IB Index: Developing a Standard Evaluation System for Intelligent Buildings

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2022

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Built Environments

University of Washington

Abstract

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Intelligent building is a rapidly growing market in the Architecture, Engineering, Construction, and Operation (AECO) industry that aims to deploy emerging technologies and leverage data-driven decision making during the whole building lifecycle. However, there is a lack of holistic understanding of intelligent buildings and more importantly, there is a gap in standard methods and criteria for evaluating intelligent buildings. Ambiguity in knowing what makes a building intelligent and how to unpack the complex concept of building intelligence limits building stakeholders' abilities to decide what technologies to implement in their buildings and to measure the effectiveness of their initiatives and strategies. This research responded to the current gaps by identifying the main components of building intelligence and used that finding as a basis for developing a tool (called the IB Index) for intelligent building evaluation. To do this, I conducted mixed-methods research consisting of actor-network theory and grounded theory to form the research theoretical foundation as well as systematic literature review and case studies for data collection and analysis. This research contributes to the body of knowledge by documenting the process and the essential elements of a standard whole-building evaluation system (including the building intelligence evaluation criteria, ontology, building performance criteria, and the weighting system). As the main outcome of the research, the IB Index provides the framework and evaluation capabilities (presented in three supplementary PDF documents) to understand the array of technological capabilities and intelligent building workflows and best practices and also to identify their impacts on building performance. Overall, the IB Index enables project stakeholders to evaluate, prove, and improve their building intelligence throughout its lifecycle.

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ACKNOWLEDGEMENTS

My doctoral journey was really an adventure full of ups and downs. It was challenging but rewarding as well. This dissertation would not have been possible without the support of my doctoral supervisory committee. First and foremost, I would like to express my sincere gratitude to my advisor and the chair of my supervisory committee, Prof. Carrie Dossick for her support and insightful guidance during this research. I had the chance to work with Prof. Dossick during my master's and PhD studies and I was always impressed by her leadership power and her enthusiasm for teaching and research. I am very grateful for all the opportunities she provided to me and the role she played to shape my professional identity as a researcher and practitioner in the field. I would also like to sincerely thank my committee member, Prof. John Messner for his thoughtful feedback which significantly helped me to improve the structure and content of my dissertation. I would like to express my great appreciation to my master's and PhD advisor, Prof. Ken-Yu Lin for her continuing support, kindness, and illuminating advice on my research. This research project could not be delivered successfully without the leadership and dedication of the project lead and my committee member, Prof. Julie Jupp and I am very grateful for her valuable guidance throughout my research. I would also like to thank my Graduate School Representative and committee member, Prof. David Ribes. I really appreciate our great discussions about research methodologies and interdisciplinary research development. I have learned so much from each of my committee members and I really enjoyed working with them during this research.

My dissertation is based on an international collaboration between multiple academic and industry partners. I'd like to express my sincere appreciation to the IB Index research team, Dr. Julie Jupp, Dr. Carrie Dossick, Shen Chiu, and Fisher Chen, also all the organizations that supported my research, as well as the subject matter experts who participated in the case studies and interviews. Finally, my enormous appreciation goes to my family for being there for me and motivating me all the time. I would like to specially thank my sister for supporting me emotionally by encouraging me to keep my faith strong, and professionally by helping me with authoring a conference paper which I later used in my dissertation.

The completion of my doctoral journey was possible because of the support I received from my advisors, family, and friends and I am deeply thankful to all of them.

Chapter 1. INTRODUCTION

1.1 INTELLIGENT BUILDINGS AND EMERGING TECHNOLOGIES

The recent trends in the AECO Industry illustrate a significant increase in deploying emerging technologies specifically for building operations and real estate development (Langhammer 2019). This has not only introduced new opportunities for collaboration between the AECO and high-tech industry sectors but also made changes in perception and realization of buildings. In addition, the gradual transition from the fragmented to more integrated project delivery approaches have facilitated communication and coordination between project stakeholders to apply performance-based design for selecting design alternatives and construction means and methods during the design and construction phases and then monitor, adjust, and optimize building performance during the occupancy phase. The increasing adoption of emerging technologies and the holistic life-cycle approach toward building operation and management have significantly influenced the building industry and served as a basis for the evolving market of intelligent buildings. According to a recent study (Ottinger et al. 2020) the intelligent building market is expected to grow at a 31.6% compound annual growth rate (CAGR) for the forecasted period through 2025 which indicates a faster growth compared to the IoT, prefabrication, and AR/VR sub-markets.

As an evolving concept in the contemporary built environment, there is still no standard definition for the concept of “intelligent building” or “smart building” (Kushal 2019) since interpretations of the term vary from region to region (Wong et al. 2005) and the key stakeholders in the building industry (e.g.,, designers, contractors, and real estate developers) point out different components for intelligent buildings based on their context-specific perceptions and priorities (De Groote et al. 2017). Comparing several given definitions reveals that in the core of this concept is the capability of generating and acting upon buildings information (i.e., its physical assets, systems' performance, and spaces' conditions) to facilitate data-driven decision-making.

An intelligent building may benefit from a collection of existing and emerging technologies. For instance, Building Information Modeling (BIM) is used to provide building owners with an accurate 3D virtual model of as-built elements and their associated information that is required for building operation. IoT technology is used in buildings to collect real-time data about a building systems while machine learning and cloud computing are used in data analytics for understanding actual building performance and predicting required operation and maintenance (O&M) actions. Taken together, digital twins provide a virtual representation of the building and key operational processes serving as a reliable source of information and a platform for holistic building management. Overall, emerging technologies play a key role in building intelligence as they facilitate achieving higher efficiency (e.g., high-performance equipment), innovation (e.g., new uses for data analytics), and building automation (e.g., operation of base building systems) (Ahmadi-Karvigh et al. 2019, Blanco et al. 2019).

As levels of technological capability and capacity intensify in the intelligent building market, there are still gaps in industry practices and academic literature in terms of a commonly accepted guidelines that clarify concepts and terminologies related to intelligent buildings, metrics that determine the applicability of different technologies in buildings, and a framework that evaluates the impacts of implemented technologies on buildings' performance. Consequently, there is a need for a standardized method of quantifying building intelligence. Also, as building owners and managers make decisions about adopting and implementing technologies, processes, and best practices for building lifecycle management, there is a need for assessment data capable of informing decision-making processes surrounding the efficiency and effectiveness of intelligent building projects. Therefore, the ultimate objective of this research is to develop a standard and technology-centered system for the documentation, quantification, and evaluation of building intelligence through developing a set of capabilities reflecting the emerging technologies' features and functions, workflows and best practices related to intelligent building management, and the characteristics of intelligent building systems.

1.2 DISSERTATION STRUCTURE

This dissertation consists of five chapters and seven appendices. The first chapter is a brief introduction of the intelligent buildings in relation to the emerging technologies. The second chapter provides a literature review aimed at conceptualizing the term "intelligent building" and to investigate the use of evaluation systems especially for intelligent building assessment. Based on the identified gaps in the knowledge, several research questions and objectives are presented at the end of the chapter. Subsequently, Chapter 3 presents the methodology developed for the research containing the process, theories, and methods of data collection and analysis. Chapter 4 discusses the research findings as the 1. process of developing an evaluation system and 2. the content of the developed evaluation system. Also, the chapter articulates the process of data validation. Finally, Chapter 5 provides a research summary, research contributions to the knowledge, and the next steps. In addition, several analyses were conducted in this research in order to achieve the research outcome. The results of those analyses (such as case studies and context analysis) were intentionally moved to the appendix section so that the body of the dissertation could stay focused on presenting the evaluation system. In addition to the description of the evaluation system provided in Chapter 4, the full content can be found in the PDF files that are provided as supplementary documents along with the dissertation file.

Chapter 2. LITERATURE REVIEW

I conducted a literature review in order to explain the terms and terminologies used as a foundation for my research and provide an overview of relevant scholarly works in the domain of intelligent buildings. The first part of the literature review aims to conceptualize and contextualize the terms “intelligent building” as a physical product and “building intelligence” as a conceptual construct that articulates the meaning and characteristics of intelligent buildings. The second part of the literature review is focused on discussing the purpose and use of evaluation systems in the field of intelligent buildings.

2.1 INTELLIGENT BUILDINGS CONCEPTUALIZATION

In this section, I explain the concept of intelligent building by presenting existing definitions for the term, discussing different approaches for defining it, articulating the concept in multiple contexts (e.g., building and infrastructure), and distinguishing it from the currently overlapping terms like sustainable buildings.

2.1.1 *Intelligent Buildings Definitions*

The concept of intelligent building has emerged in the AECO industry since the 1980s. At the time, several trends in the telecommunications market and the emergence of personal computers introduced real estate developers to new opportunities for adding to the buildings’ functionalities (Sinopoli 2010). Even though this concept has evolved over time it still does not have a clear and commonly accepted definition. In addition, the term “intelligent building” has been interchangeably used with other existing terms including smart building, high-tech building, and integrated building (Kroner 1997, Clements-Croome 2014). Table 2.1 provides the relatively well-known definitions of intelligent buildings.

Table 2.1. Intelligent buildings definitions

Definition	**Reference**
One which has fully automated building service control systems.	Cardin 1983 (cited in Wigginton 2002)
A building which totally controls its own environment.	Stubbings 1988
Any building that provides a responsive, effective, and supportive environment within which the organization can achieve its business objectives.	DEGW and Technibank 1992
A dynamic and responsive architecture that provides every occupant with productive, cost effective and environmentally approved conditions through continuous interaction among its four basic elements: places (fabric; structure; facilities); processes (automation; control; systems) people (services; users) and management (maintenance; performance) and the interrelation between them.	Conseil International du Batiment (CIB) 1995 (cited in Everett 2008)
Automated buildings with flexibility, cost-efficiency, and integrated technical performances.	Kroner 1997
One that can support advanced hardware, such as the building and personnel management systems, as well as accommodate future technologies and the anticipated level of long-term user requirements.	Hartkopf et al. 1997
One which integrates various systems to effectively manage resources in a coordinated mode to maximize: technical performance, investment and operating cost savings, and flexibility.	Intelligent Building Institution in Washington (cited in Clements-Croome 1997)
An intelligent building creates an environment that allows organizations to achieve their business objectives and maximizes the effectiveness of its occupants, while at the same time allowing efficient management of resources with minimum life-time costs.	European Intelligent Building Group (EIGB)
One that utilizes computer technology to autonomously govern the environment so as to optimize user comfort, energy-consumption, safety and work efficiency.	Callaghan 1999 (cited in Himanen 2003)
An Intelligent Building is designed and constructed based on an appropriate selection of Quality Environment Modules to meet the User Requirements by mapping with the appropriate building facilities to achieve a Long-Term Building Value.	So et al. 2001
A building which provides a productive and cost-effective environment through the optimization of its four basic elements, including structures, systems, services: and management as well as the interrelationships between them.	Intelligent Building Institute (cited in Wigginton 2002)
One in which the building fabric, space, service, and information systems can respond in an efficient manner to the initial and changing demands of the owner, the occupier, and the environment.	Arup 2003
Advanced technology combined with improved processes for design, construction and operations provide a superior indoor	Intelligent building dictionary

environment that improves occupant comfort and productivity while reducing energy consumption and operations staffing.	
A building that integrates technology and process to create a facility that is safer, more comfortable, and productive for its occupants, and more operationally efficient for its owners.	Ehrlich 2007
One that is responsive to the requirements of occupants, organizations and society. It is sustainable in terms of energy and water consumptions besides being lowly polluting in terms of emissions and waste: healthy in terms of well-being for the people living and working within it; and functional according to the user needs.	Clements-Croome 2009
One where the combination of technologies and interconnected systems supports the use of the accommodation by the building users, enables the efficient operation of the building and enables reconfiguration of the space in response to changing use.	The Institution of Engineering and Technology (IET) 2012
An Intelligent Building uses both technology and process to create a facility that is safer and more productive for its occupants and more operationally efficient for its owners.	Continental Automated Buildings Association (CABA) (cited in Hui 2016)
A smart building is highly energy efficient and covers its very low energy demand to a large extent by on-site or district-system-driven renewable energy sources. A smart building (i) stabilises and drives a faster decarbonisation of the energy system through energy storage and demand-side flexibility; (ii) empowers its users and occupants with control over the energy flows; (iii) recognises and reacts to users' and occupants' needs in terms of comfort, health, indoor air quality, safety as well as operational requirements.	Buildings Performance Institute Europe (BPIE) (cited in De Groote et al. 2017)
The ability of a building or its systems to sense, interpret, communicate, and actively respond in an efficient manner to changing conditions in relation the operation of technical building systems or the external environment (including energy grids) and to demands from building occupants.	Smart Readiness Indicator (cited in Verbeke et al. 2018)
One that creates an environment which maximizes the effectiveness of the building occupants while at the same time enabling the efficient management of resources with minimum life-time costs of hardware and facilities.	European Intelligent Building Group (cited in Hatefi 2019)

Academic scholars and industry practitioners have used various approaches to define an intelligent building and explain its characteristics. This section discusses different definitions of intelligent buildings, by highlighting common themes and ideas in the provided definitions, introducing key drivers for evolving definitions over time, and categorizing different types of definitions.

Many existing smart/intelligent building definitions share similar ideas including automation, adaptability, integration, efficiency, connectivity, responsiveness, functionality, and being occupants centric. Buckman et al. (2014) focused on “adaptability” to make distinction between the terms intelligent and smart buildings. They defined smart buildings as buildings “which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at its core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction.” By contrast, they defined intelligent buildings as buildings that “meet the drivers to building progression by focusing on intelligent systems which reactively utilize information; control, enterprise, and building materials and construction are developed largely independently of the intelligent systems.” As another example, Wong et al. (2005) considered “integration” as the key factor to define intelligent buildings: “Intelligent building accentuates a multidisciplinary effort to integrate and optimize the building structures, systems, services and management in order to create a productive, cost effective and environmentally approved environment for the building occupants”. Also, Manic et al. (2016) took “connectivity” as the main concept of smart building which was defined as the ability of a building to communicate with other buildings, the grid, utilities, energy storage units, occupants, and other smart devices.

The intelligent buildings as a concept has been constantly evolving as a reflection of emerging technologies, priorities of the global economy, and perceptions of key actors in the building industry (De Groote et al. 2017). Some studies defined intelligent building in relation to the business objectives of an organization that occupied the building. According to the DEGW and Technibank (1992), ‘‘Intelligent building is any building that provides a responsive, effective and supportive environment within which the organization can achieve its business objectives.” Also, Pennell (2013) expressed that “an intelligent building combines innovations, technological or not, with skillful management to maximize return on investment.” In comparison, the definition provided by Continental Automated Buildings Association (CABA) connects building intelligence to the perceived demands of both building occupants and owners: “an Intelligent Building uses both technology and process to create a facility that is safer and more productive for its occupants and more operationally efficient for its owners” (Hui 2016). Accordingly, the real estate entities (facility owners, facility managers, project developers, etc.) have tangibly influenced the intelligent buildings’ transformations because of their key roles in technology deployment, innovation management, and response to occupants’ demands.

The literature review indicated certain trends in the evolvement of intelligent buildings’ concept and definitions over time. To better understand the trends, Wang (2010) suggested a categorization of intelligent buildings’ definitions based on performance, services, and systems. In this literature review, I identified the following categories to better explain the highlighted characteristics of intelligent buildings in the provided definitions (Borhani et al. 2022):

- Technology-based definitions: consider intelligent building as one that leverages new (digital) technologies. The building intelligence is defined based on the functionalities of technological artifacts implemented in the building and specifically the use of data for better decision making.
- Performance-based definitions: articulate intelligent building in relation with specific aspect(s) of building performance. Like “business intelligence”, the building intelligence is defined in accordance with benefits of a high-performance building (compared to a conventional building) for its stakeholders (owner, facility manager, occupants, etc.).

- System-based definitions: identify intelligent building by characteristics of its physical and digital systems. The building intelligence is defined as an integrated system or system of systems (SoS) that manages the building technical systems and services.

The three identified categories are not mutually exclusive meaning that several definitions were found that could be included in more than one category. This categorization is useful to better interpret the multi-faceted concept of intelligent building and use the reviewed definitions as a basis to recognize intelligent buildings' characteristics and components.

2.1.1.1 Technology-based Definitions

The earlier definitions of intelligent buildings equate the term with high-tech buildings and put the emphasis on integration of advanced technologies (Kroner 1997, IET 2012). The main goal for technology integration in buildings is to achieve automation, communication, advanced controls, and analytic capabilities (Stubbings 1988, Wigginton 2002, King et al. 2017). Daissaoui et al. (2020) defined automated control system as digital systems for monitoring, control, and management of heating, ventilation, air-conditions (HVAC), fire safety, security, and energy/lighting that are integrated and interact with each other. These definitions focus on the integration of building and technology systems.

In recent years, the use of sensors and devices for data collection and computational capabilities for data analytics have been added to the characteristics of intelligent buildings. The U.S.-based Telecommunications Industry Association (TIA) defined smart building as a building that captures, manages, and uses data across its fully integrated system to provide a seamless experience to those who interact with it (TIA 2017). Similarly, the Buildings Performance Institute Europe (BPIE) expressed that smart buildings improve the productivity of people and processes by leveraging technology and actionable information to help building managers make better decisions and buildings become smart, efficient, and sustainable (De Groote et al. 2017). Ahmed et al. (2013) provided a definition for intelligent buildings that determines a range of information collected which goes beyond the building elements and systems and includes a system of detection and classification of occupants' behaviors. Such definitions highlight the aim for leveraging data in intelligent buildings.

2.1.1.2 Performance-based Definitions

Several research studies (e.g., Wigginton et al. 2002, Kaya et al. 2014) argued that early interpretations of intelligent building only considered the role of technology without any consideration of social, environmental and user interactions. In response, newer definitions of intelligent buildings provided by researchers and practitioners articulated building intelligence in terms of higher building performance in comparison with conventional buildings. In this regard, Petit et al. (2014) mentioned that smart buildings give an unprecedented insight into a building performance by integrating building systems and utilizing advanced analytics to monitor, measure and manage the building in the most efficient way. However, various factors and metrics have been proposed to represent intelligent buildings' performance. For example, Brad et al. (2014) pointed out efficient management of resources and minimization of life-cycle costs, user comfort, and capability to adapt quickly to changing needs of the users, as the determinant factors. While Clements-Croome (2014) defined intelligent buildings in terms of responsiveness to occupants, well-being of people, low resource consumption with low pollution and waste, flexibility, and adaptability to deal with change. Even though each definition contains different elements of intelligent buildings' performance, it seems the suggested elements can be categorized into environmental, social/behavioral, and economic/fiscal aspects that align with the triple-bottom line approach for defining sustainable buildings.

The literature review indicated that two themes of “energy efficiency” and “occupants’ comfort” have been used more frequently as indicators of buildings’ high performance. Regarding energy efficiency, Kiliccote et al. (2011) defined intelligent buildings as self-aware and grid-aware, interacting with a smart grid whilst focusing on the real-time demand side response and an increased granularity of controls. Also, other studies (Costanzo et al. 2012, De Groote et al. 2017) have similarly emphasized intelligent building ability to generate energy on-site or through district-system-driven renewable energy sources and manage its energy demand based on local climate conditions, users’ needs and grid requirements. In terms of occupants’ comfort and well-being, several studies investigated the impact of occupants on building performance and argued that adaptability, adjusting performance based on its occupants’ desires and requirements, should be included in the definition of intelligent building (Yang et al. 2001, Himanen 2003, Wong et al. 2005). Another definition given by Hui (2016) emphasized the ability of smart buildings to maximize the efficiency of its occupants and respond to their needs by adapting new technology or changes in the organizational structures. In addition, Bean et al. (2017) explained the aspects of building performance from occupants’ perspective that include control over energy flow, comfort, health, indoor air quality, safety, and operational requirements. Overall, the existing performance-based definitions articulate building intelligence as a combination of performance aspects as well as managerial, organizational, and technical aspects of buildings’ ecosystem.

2.1.1.3 System-based Definitions

Many scholars (Sinopoli 2010, Healey 2011, Froufe et al. 2020) defined building intelligence in relation to different building systems and how the integration between systems lead to more effective operation and management in intelligent buildings. In this context, building systems include physical and digital infrastructures (Hudson 2010) designed to provide various services to building users. Various types of systems were pointed out in intelligent buildings' definitions. For instance, Flax (1991) defined intelligent building as a unified environment based on the integration of a wide range of systems and services involving energy management systems, temperature monitoring systems, access security systems, fire and life safety, lighting control and reduction, telecommunications services, office automation, computer systems, area locating systems, LANs, management information systems, cabling and records, maintenance systems, and expert systems. While Smart Buildings, LLC (2011) provided a briefer definition highlighting the integration of building, technology, and energy systems. According to Daissaoui et al. (2020), an intelligent building integrates management systems, massive data storage and analytics to facilitate and improve energy management and electrical devices on the grid that learn habits and adapt to behaviors. Although different physical and virtual/digital building systems are included in the given definitions it is not clear how they are prioritized regarding their overall contribution to building intelligence.

In addition, some definitions conceptualized building intelligence as a supersystem (King et al. 2017) or a system of systems (SoS) that relies on communications infrastructures and computational capabilities (Cheng et al. 2009) for integration, automation, and monitoring and management of building systems. In this regard, Verbeke et al. (2018) expressed that smartness of a building refers to the ability of that building to sense, interpret, communicate, and actively respond to changing operational conditions of technical building systems, external environments, and demands from building occupants. This interpretation of building intelligence underlines the importance of data analytics in building management systems and the potential role of artificial intelligence and its relevant technologies in intelligent buildings.

The literature review indicated different approaches and trends in evolving the intelligent buildings' definitions that provide a vast range of characteristics for intelligent buildings. This highlights the need for a holistic methodology to articulate building intelligence which is a prerequisite for evaluating intelligent buildings.

2.1.2 *Intelligent Buildings' Scalability*

The concept of "intelligence" can be defined in different scales. In this regard, there is usually a distinction between intelligent residential buildings (mostly known as smart homes) and commercial buildings. It is because creating intelligent buildings and smart homes are significantly different in terms of capacity for implementation of emerging technologies, design and construction best practices, and technical and operational requirements. There is another scale of intelligence defined as intelligent/smart infrastructures and cities which have been rapidly emerging in the recent years because of the growing use of industrial IoT technologies and demands for better control of environmental impacts and energy consumption (led to emergence of the relevant term smart grid) in the current cities. The focus of this research is on commercial intelligent buildings, but the other two terms are briefly introduced in this section.

Smart homes: this concept is arising from rethinking of the innovative process of housing planning and development which involves integration of technologies into houses to provide cost-efficiency, resource efficiency, appliance interoperability, comfort, safety, and quality of life (Demiris et al. 2009, Ghaffarianhoseini et al. 2016). Other scholars defined smart homes as buildings that are "equipped with new technologies while being operative for environmental protections, economical concerns, and social issues" (Ghaffarianhoseini 2012, Hicks 2019). Such definition aims to address both intelligence and sustainability properties in homes. In addition, the smart housing market has been growing over the past few years. It is expected for this market to exhibit a CAGR of more than 34% between 2017 and 2024 (Qolomany et al. 2019). This market is important because it is evolving at the intersection of three market segments namely energy efficiency, building automation, and connected homes which have been separated before but now are merging into a single unitary market (Chow et al. 2005).

Smart cities: the concept refers to a city composed of intelligent buildings and infrastructure, intelligent business systems, and technology solutions that support city governance. The intent of such city is to guarantee the well-being of residents, sustainability, and operational efficiency (Wong et al. 2007, Brown et al. 2016). Many researchers mentioned two specific trends in evolving smart cities including 1. emphasis on technological development and diffusion of innovation and Information and Communication Technology (ICT) in a city, and 2. promotion of people and city interactions and finding the ways a smart city can fulfill social needs and improve inhabitants' quality of life (WRI 2011, Bašić et al. 2019).

2.1.3 *Intelligent Buildings versus Sustainable Buildings*

A critical part of intelligent building conceptualization is to make a distinction between this concept and the similar concepts that exist in this domain. A basic literature review indicated that the two terms intelligent building and sustainable building have considerable similarities and overlaps in terms of definitions and components. On the other hand, comparing the markets of intelligent building and sustainable building reveals tangible differences in the two concepts' interpretations, their best practices, and the involved key players (Borhani et al. 2022).

Sustainable buildings can be defined as "healthy facilities designed and built in a resource-efficient manner, using ecologically based principles" (Kibert 2012). In a broader definition, sustainable buildings are "buildings that encompass environmental, social and economic standards, together with technical aspects" (Rwelamila et al. 2000). In addition, EPA (2008) defined the term as “the practice of maximizing the efficiency with which buildings and their sites use resources- energy, water, and materials- while minimizing building impacts on human health and the environment, throughout the complete building life cycle”. All three definitions describe desired characteristics of a building with an emphasis on ecological and environmental aspects. Such a definition indicates a considerable resemblance with the performance-based definition of intelligent building (as discussed in section 2.1.1.2).

Overall, the similarities and differences between sustainable and intelligent buildings calls for a consistent approach to distinguish between the two terms. For this purpose, I initiated a fundamental research project with the goal of creating sustainable/intelligent building ontologies (i.e., the key components and the relationships between them). As the first step, the research team conducted a systematic literature review to identify the main topics used in the literature to articulate the two concepts. As a result, 13 clusters were identified which are explained as follows[1].

Design Program refers to the building responsiveness to technological and sociocultural changes as well as architectural and ecological considerations (Himanen 2003). Design for flexibility and long-term adaptability based on demands of building occupants as well as a life-cycle approach to address owners’ objectives for design intent (from constructability to operability) are among the specified requirements. In addition, this category includes passive design techniques and the use of smart materials (e.g., low embodied carbon and not listed as hazardous materials).

Safety and Security highlights the need for a safety/security plan for the whole project lifecycle containing a workflow for risk identification and mitigation. Structural reliability is

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[1] The result of the literature review was published in the ASCE Construction Research Congress proceedings, and a revised version of it is included in this section of the dissertation with permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at https://ascelibrary.org/doi/abs/10.1061/9780784483954.032

another aspect of building intelligence focusing on earthquakes and critical building structure monitoring through regular surveys or automated systems. Also, control and monitoring of building safety and security is a part of this cluster which includes utilizing a central safety and security management system for disaster response, airborne contamination detection, emergency voice communication, fire detection and protection, and alarming system (Kushal 2019). Using a unified control system for safe and secure access to buildings is another part of this cluster. Examples of required functions are monitoring and managing rooms' signage and directory information, building visitors, and access to restricted areas. Such a system consists of technologies for identity checking combined with a data analytics layer. Additionally, another layer of security applies to an organization data protection and data environment accessibility control, which is closely related to the concept of cybersecurity. In this case, a unified system is used to manage authentication and authorization of users (e.g., occupants and visitors who connect to the building internet/intranet networks).

Economic Management addresses economic repercussions in projects by adopting a life cycle cost analysis (LCCA) approach. The cost/benefit analysis includes both initial cost with added marginal cost associated with smart building initiatives and best practices, and operation and maintenance cost with consideration of smart building initiatives' cost effectiveness and strategies for long-term cost savings (Ghaffarianhoseini et al. 2016). The second aspect of economic management is related to the appraisal value and renting/selling price rates of a building that is mainly determined based on the elements of affordability for prospective building tenants and marketability for project developers to secure return on investment.

Occupants' Experience and Wellbeing promotes enhanced occupants experience in buildings through adopting an end-user need orientation. This includes building systems and architectural design, occupants' education programs, and managerial strategies that lead to better occupants' physical and mental comfort, health and wellbeing, productivity, and work satisfaction. Moreover, a part of this category is occupants' demands management which focuses on improving building services and amenities such as building web-based internal portal and in-building user interface devices to provide occupants with effective controllability over and interactivity with the building features.

Environmental and Resource Impacts specifies deployment of emerging technologies, operation, maintenance and repair (OM&R) planning, and utilization of knowledge-based systems that result in reduction of the building environmental impacts (e.g., greenhouse gas emissions and carbon emissions) and conservation of natural resources. Global warming and strategies to minimize negative impacts of design and construction such as Life Cycle Analysis (LCA) and preventing the use of harmful materials are addressed as well. Also, this cluster concentrates on using innovative solutions for building waste management including utilizing a waste management plan for efficient construction waste disposal during the construction phase and installing advanced refuse handling equipment in buildings for tenants' waste management and recycling during the occupancy phase.

Water Efficiency refers to monitoring and control of water consumption to improve water efficiency, leveraging intelligent systems for managing water supply based on various demands (potable water, water reuse for irrigation, etc.), and the building hydraulic/drainage systems' technical specifications required for achieving the building water efficiency goals (Chow et al. 2005). Water reuse and recovery is another important aspect which includes rainwater collection, greywater/blackwater recycling, and utilizing closed-loop water systems.

Operation and Maintenance (O&M) highlights the importance of life-cycle asset management planning that contains establishing performance requirements, conducting commissioning, measurement, and verification for the facility current condition analysis, and developing a proactive performance-based approach for facility management (Kushal 2019). Additionally, the cluster emphasizes on the role of intelligent monitoring-based systems with analytics capabilities for enhancing O&M work orders generation. Moreover, as a main operation activity, this cluster discusses requirements for space management which includes creating a building interior layout system that allows for flexibility and adaptability based on changing space occupancy/functionality and space utilization conditions. Also, it includes space monitoring and optimization using performance analysis and post-occupancy evaluation (POE).

Construction/Property Technologies articulates building emerging digital technologies (e.g., IoT, digital twin, and robotics) and the relationship between the high-tech incorporation and building lifecycle management. There are multiple use cases for these technologies such as implementing IoT sensors and devices for real-time energy and water metering, occupancy detection, and building system monitoring and condition assessment. In addition, technology deployment applies to use of artificial intelligence and machine learning for data analytics and pattern detection which is proven to be beneficial for building stakeholders. For example, it helps facility managers to understand their building actual performance, predicts occupants' demands more accurately, and makes more informed decisions about the building O&M. A key part of property technologies is building automation/management which explains technical features and functions of building management systems (BMS) and building automation systems (BAS). The primary functions of these systems include controlling and management of building physical systems and zones, system integration and interoperability (for interaction with the building systems), automated monitoring of building performance/condition, faults detection and diagnostics, and utility management (King et al. 2017).

Building Systems and Equipment identifies technical specifications for high-performance and intelligent building systems, devices, and commercial equipment. In this context, “high-performance” is determined in terms of utilities’ cost effectiveness, while “intelligent" depends on interoperability, and integration with building management systems. The frequently discussed building systems include bathroom/kitchen fixtures (energy- and water-efficient appliances), building envelope (dynamic and interactive façade system), electrical system, lighting system (intelligent and controllable fixtures), conveying system (energy efficient and programmable elevators, escalators, and lifts). While among different building systems, there is an emphasis on high-performance and intelligent HVAC systems. The cluster provides detailed discussions on building standards and industry best practices (e.g., Froufe et al. 2020) that specifies required HVAC system features and configurations for flexible and efficient heating, cooling, and ventilation as well as constant system monitoring and optimization based on the actual building usage and occupants’ behaviors.

Location and Infrastructure discusses requirements for the building location such as walkability and accessibility as well as the quality of the landscape and outdoor spaces. Other factors related to selecting the building location include protecting natural lands and historic/cultural sites. In addition, the cluster introduces strategies for reducing the building ecological impacts such as leveraging existing infrastructure, remediating brownfield and contaminated lands (to use them as the building site), and reusing available soil resources.

Parking and Transportation generally associates building intelligence and performance with the project location in terms of ease of parking and accessibility to public transportation. The analysis indicated two specific elements for this cluster. First, smart parking which is defined as a parking facility that provides users with sufficient information sharing, finding and booking parking spots conveniently, and allows for planning commutes in advance and remotely. Second, the availability of electric vehicle (EV) charging stations that promote environmental friendliness by reducing dependency on fossil fuels.

<u>ICT Network</u> provides the specifications and best practices for an information technology (IT) infrastructure that is required for adoption and implementation of intelligent building technologies and systems. The main elements include wired and wireless information networks (broadband internet, fiber-optic network, etc.), data governance system, and network coverage stabilization. Also, it identifies the requirements for an effective telecommunication system in buildings such as video-conferencing equipment and integrated audio/visual systems.

<u>Energy Efficiency</u> refers to monitoring and control of energy consumption to achieve energy efficiency, using renewable energy sources (solar panels, geothermal, etc.) and limiting building dependency on fossil fuels, and leveraging intelligent management systems for energy demand predictions and energy efficiency optimization. In addition, the cluster describes smart practices for acquisition, distribution, and stabilization of power as well as management and optimization of the power supply system in a building. Key elements of this component include leveraging distributed energy resources (DER), using uninterrupted power supply (UPS), and integrating to smart grid.

<u>Indoor Environmental Quality (IEQ) Efficiency</u> determines the relevant requirements in a building to ensure occupants’ thermal, acoustic, and visual comfort. It also requires zone-based IEQ monitoring and control and making balance between natural and artificial/mechanical indoor air supply, lighting, and ventilation. In addition, this cluster emphasizes on protecting indoor air

quality by requiring activities like controlling mold and moisture, smoking, and other types of air pollution inside buildings.

The identified clusters serve as a foundation for identifying sustainable building and intelligent building components through a comparative analysis. The result of the analysis and the identified components of intelligent buildings are discussed in section 4.1.1.

2.2 BUILDINGS EVALUATION SYSTEMS

In general, a building evaluation system is developed as a standard method of assessing building (e.g.,, systems, performance, services, etc.) against a list of criteria to ensure that the building meets the owners' and users' project goals, and the constructed building is in compliance with the intended design (Hatefi 2019). An evaluation system may be developed for products, homes, commercial buildings, or cities (see Appendix D for a list of existing evaluation systems). For buildings, an evaluation system may address a single aspect of building (e.g., energy efficiency or IT and connectivity) or multiple aspects for the purpose of evaluation (Gabe et al. 2019). Currently, numerous evaluation systems exist in the AECO industry (e.g., LEED, BREAM, WELL) mostly focused on sustainable buildings' evaluation and certification. By contrast, only a few evaluation systems exist for intelligent buildings. However, the sustainability evaluation systems can be investigated as part of the process of creating an evaluation system for intelligent building since the same logical method of evaluation and framework for the evaluation system can be used even though the content and evaluation criteria will be different.

This section presents the results of the literature review on building evaluation systems in terms of purposes of using evaluation systems for commercial buildings, the standardized structure and method of evaluation, and a review of existing evaluation systems for intelligent buildings.

2.2.1 *Purpose of Evaluation Systems*

Researchers explain the purposes of building evaluation systems mostly with two approaches of identifying benefits of evaluation systems for different stakeholders and discussing evaluation systems as a supporting tool for more informed decision making within an organization.

2.2.1.1 Evaluation Systems' Benefits and Use Cases

An intelligent building stakeholder may benefit from an evaluation system in many ways depending on its role and level of involvement in a building project as well as its own experience and expertise in the field of intelligent buildings. Overall, all stakeholders may use an intelligent building evaluation system to better understand the components of building intelligence and learn about relevant available technologies and best practices. Below is an overview of perceived benefits and use cases for each type of building stakeholders:

Real estate owners, developers, and investors: as the primary beneficiary of evaluation systems, owners may use an evaluation system during the design phase to measure their new building level of intelligence based on the given design intents and allocate resources accordingly. Also, they can use the evaluation system as a marketability tool to demonstrate the advantages and added sales/renting value of their intelligent buildings compared to the conventional buildings in the market (King et al. 2017). Facility owners may use evaluation systems for building retrofit and optimization during the occupancy phase. Existing buildings have potentially a significant share of the intelligent building market. A study (Bean et al. 2017) shows that “up to 90% of the existing European building stock will still be standing and in use in 2050”. Therefore, it is necessary to identify intelligent building strategies and practices that are applicable to existing buildings. Currently, the building retrofit planning is mostly based on the budget availability, old system replacement, or implementation of trending intelligent buildings' initiatives rather than a long-term asset optimization plan. Developing such a plan requires a holistic understanding of the current building condition, alternatives for optimization, and the added value of each alternative. An evaluation system can provide required information to facility owners and help them to choose the retrofit/optimization option that best fits their goals and objectives. In addition, intelligent buildings tend to transform the business model in real estate and present it as a customer service platform which enhances user experience (Ottinger et al. 2020). In this case, real estate developers use evaluation systems to clearly communicate their options and services to non-expert clients.

Facility managers and operators: intelligent buildings require more intelligent facility management that addresses new issues such as mitigating cybersecurity risks in buildings and managing integrated and automated building systems (AON 2017). By using an evaluation system, facility managers can learn about such issues through investigating different aspects of building intelligence and develop appropriate facility/asset management strategies based on their priorities and impacts of their initiatives. In addition, considering the recent changes in the information and operation technology (IT-OT) market in terms of new business models (e.g., building connectivity-as-a-service) and new end-to-end technology solutions (Fletcher et al. 2018), facility managers may use evaluation systems to increase their awareness about available options and complete their technology stack based on their actual needs.

General and specialty contractors: evaluation systems help contractors to educate themselves about the intelligent building technologies and practices related to their specific field of expertise and improve their in-house capabilities accordingly to meet the clients’ needs. Also, as one of the main executors of the evaluation system aimed criteria, contractors can use it to facilitate communication and collaboration with other team members regarding selection of building systems, equipment, and technologies (and their potential impacts on the construction project management) during the project delivery phase.

Technology vendors: new technologies are in the core of intelligent buildings. IT and software companies have recognized the high demand for automation and digitalization in the building industry (Ottinger et al. 2020). They may use an evaluation system to communicate the details of the existing demand for their technology solutions to their different clients. For instance, they refer to relevant criteria (in an evaluation system) as potential use cases for design-oriented digital technologies in communication with architects and contractors while using other criteria to show potential areas of technology deployment for achieving energy efficiency and automation in building operation in communication with owners and asset/facility managers. Also, technology vendors can revise their marketing approach (e.g., advertising strategies) and optimize their products and services based on the measured impacts of their technologies through analyzing the evaluated/certified buildings.

Designers and engineers: based on the principles of parametric performance-based design, evaluation systems may serve as a basis for generating different design alternatives and comparing them based on their (economic, environmental, and social) impacts on the building performance and intelligence. Moreover, similar to general- and sub-contractors, designers use evaluation systems as a tool for better communication and collaboration while working with their clients to choose desired building intelligence criteria and achieve a design intent that best fit the project goals and requirements.

Building tenants and occupants: intractability, adaptability, and responsiveness are among the primary features of intelligent buildings (Al Dakheel et al. 2020). This means that an intelligent building can interact with its occupants and tenants, and it adapts based on the user behaviors and interactions. In this regard, evaluation systems benefit building occupants in two ways. On one hand, the building project team recognizes and focuses on building intelligence areas that specifically enhance building intractability as well as occupant experience including comfort, safety, and productivity (Brown et al. 2016). On the other hand, building occupants learn about the building controls and services available to them as well as their behaviors that impact building performance and intelligence. Moreover, prospective buildings tenants may use evaluated buildings as a benchmark in the market and choose based on the measured (versus claimed) capabilities of buildings.

<u>Local governments and public agencies:</u> One benefit of evaluation systems for governments is to develop and regulate standards in the areas highlighted by intelligent building evaluation systems. Also, they may conduct a statistical analysis on evaluated buildings to better understand the status and trends in the intelligent building market. Another benefit is promoting intelligent building, infrastructure, and city policies through the evaluation systems. For example, multiple energy tariffs, demand-response, and grid integration programs can be incorporated into an evaluation system criteria (Potter et al. 2018).

2.2.1.2 Evaluation Systems for Informed Decision Making

During the lifecycle of a building project, the project team uses an evaluation system while making a decision between two design alternatives, about purchasing a technology solution, or initiating an asset optimization effort (as discussed in the previous section). This section provides a theoretical discussion on the concept of “decision-making” to justify the use of a building evaluation system as a needed tool for data-driven and more informed decision making.

As a general definition, decision making is “an artistic endeavor in which facts, data, experience, faith, intuition, and bias are combined to make a selection from a number of alternatives" (Abdun-Nur 1970). In a more formal view, decision making is a process that includes identifying the elements of decision variables, objectives, alternatives, uncertainties, consequences, and associated risks (Nik Bakht et al. 2015). Accordingly, there are several decision making approaches as shown in Figure 2.1.

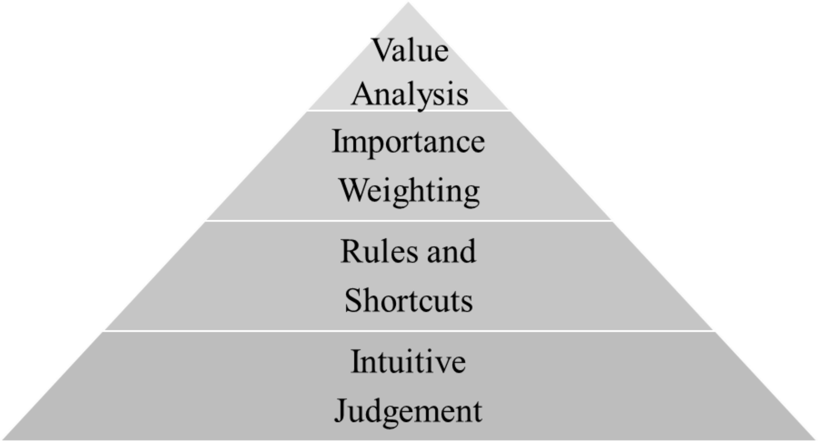

Figure 2.1. The pyramid of decision approaches (adopted from Schoemaker et al. 1993)

In the first level, decisions are made based on managers intuition and overall understanding of a subject and its context. In the second level, some rules and criteria for decision making are defined based on the attributes of the subject and better understanding of the context conditions. In the third level, a weighting system is created to reflect decision makers priorities and preferences regarding the criteria. The last level is used for complex and important decisions and includes more comprehensive assessment of criteria as well as a value analysis on their impacts on the decision makers goals and objectives.

In the contemporary building industry, organizational decision making is more complicated than ever for many reasons. For example, a typical building project involves many stakeholders with different objectives that need to make decisions collaboratively. Traditionally, the end-users and late project stakeholders (e.g., facility managers) were not a part of the process of decision making. But nowadays, integrated project delivery approaches require consideration of all stakeholders’ priorities and feedback in decision making (Fletcher et al. 2018). In addition, there are multiple decision-making milestones during the project lifecycle (e.g., design decisions, building system selection, and O&M decisions) and each milestone needs a different set of information gathering and evaluation of decision criteria (Al Waer et al. 2012). Finally, the rapid emergence of digital technologies has added to the decision analysis complexity since it requires decision makers to decide on different technology solution options while some stakeholders may not have the knowledge and expertise needed to understand their requirements and options. For all these reasons, achieving intelligent buildings is comprised of making complex decisions throughout the project life cycle. In response, the pyramid of decision approaches shows that an evaluation system can be a sophisticated tool which addresses all key aspects of decision-making approaches. Ideally, an intelligent building evaluation system is a standard rule-based and consistent system for conceptualization and evaluation of building intelligence. It can educate stakeholders about the existing technology solutions by breaking down their features and functions into the evaluation criteria. Although the building assessment for certification is typically intended to be performed during the occupancy phase, the evaluation system supports all decision-making milestones as it covers both the process of intelligent building development and the products for intelligent building operation and management. Moreover, decision makers can conduct value analysis for decision making using the evaluation system that quantifies the values of available options based on their relative importance, alignment with the stakeholders’ goals, and impacts on the building.

2.2.2 *Evaluation Systems’ Method and Structure*

Using an evaluation system for assessing and certifying buildings is a relatively new concept (compared to other industry sectors like consumer goods certification in manufacturing). Simple qualitative auditing templates and assessment checklists were used for an overall building evaluation before developing evaluation systems (Inkoom et al. 2016). Advances in construction-technology and property-technology as well as growing global awareness about buildings' performance and impacts led to emergence of more standardized methods of building evaluation in the 1990s. researchers and practitioners have provided various characteristics to describe a standard evaluation system (IISD 2009, Al waer et al. 2010, Al waer et al. 2012, Van Rooijen et al. 2013):

- Informativeness: building project stakeholders should be able to use the evaluation system as an education tool and learn about the aspects of the building that are being evaluated. The evaluation systems should specifically inform the users about the evaluation criteria and the options they can choose from.
- Simplicity: the evaluation system should ideally be usable by different users without requiring significant background knowledge. The interface of the evaluation system should also be clear and user-friendly.
- Comparability: the provided criteria should be comparable with other standards. Also, it should enable users to use the evaluation system for making a comparison between the certified and non-certified conventional buildings.
- Measurability: the given qualitative and quantitative evaluation criteria should be measurable and quantifiable so that users can receive an objective and overall result for their building evaluation.
- Comprehensiveness: the evaluation systems should address all key aspects of the topic (that is being evaluated). Also, it should be usable in different phases of the building lifecycle.

- Actionability: the provided criteria should lead to practical action items. The evaluation system should also contain information for improvement and optimization related to the evaluating topic.
- Transparency: the intent for the provided criteria should be clearly communicated. Also, the process and method of building evaluation should be transparent. All potential conflicts of interest, uncertainties, and assumptions should be disclosed and accessible to the users.

The structure of the building evaluation systems entails several elements including, method of evaluation, scope/areas of evaluation, evaluation criteria, weighting system, alternatives/options, and approach of rating/certification.

The method of evaluation is the primary element of an evaluation system. It is also significantly different in the existing evaluation systems. One interpretation of the method of evaluation concept is a method or formula for measuring an evaluation criterion. For instance, energy consumption is a criterion in the many evaluation systems, but they have different methods for measuring and quantifying it, such as calculating annual energy-related utility cost, amount of energy saving (compared to a benchmark), and level of Energy Use Intensity (EUI). In some evaluation systems, method of evaluation refers to the factor(s) used for selection between identified alternatives. In this context, alternatives may be design options, building systems, or even different evaluating buildings. An evaluation system may use a single factor or multi factors for selection. Examples of single selection factors include cost-benefit calculation (Rodríguez López et al. 2011), Magnitude of systems’ integration (Arkin et al. 1997), Net Present Value (NPV), and life-cycle cost (Wong 2007). In more recently developed evaluation systems, method of evaluation means a procedure for evaluating the level of sustainability/intelligence in one whole building. Such assessment is mostly based on multi-criteria analysis (aka. Multi-Criteria Decision

Analysis (MCDA)) which allows for taking a range of evaluation criteria and their correlation into account and applying mathematical algorithms to calculate and quantitatively report the result of evaluation (Medineckiene et al. 2015). As a brief explanation, MCDA is a widely used method to create rating systems. Neb et al. (2019) explain this method with eight steps including defining the decision problem, identifying some alternatives, determining the target system, developing a hierarchy of factors, defining preferences and values of decision makers, creating a weighting system for factors, performing the analysis method to aggregate and rank the alternatives, and finalizing the decision making and reporting the result. Moreover, there are various techniques for performing MCDA including Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and fuzzy Multiple Attribute Utility (MAUT) (VillarinhoRosa et al. 2013, Kaya et al. 2014). A drawback of using a detailed mathematical approach is increased complexity and intense data requirements for evaluation which diminish the usability of the evaluation system (cf. Engelsgaard et al. 2020). Many comprehensive evaluation systems implement the MCDA framework to some extent but exclude alternatives, and users' goals and objectives from the evaluation process.

A main part of the evaluation systems is identification and classification of evaluation criteria. The goal is to develop clear and measurable criteria for building evaluation that represent key components of the building sustainability/intelligence. ISO 21929-1 standard (2011) provided an explanation of different types of criteria including 1. assessed information such as planned or calculated values as well as actual data, 2. degree of the influence on evaluating topic (direct vs indirect), and 3. criterion content such as qualitative, descriptive and quantitative. Also, several evaluation systems use binary types of criteria meaning that evaluation is based on a yes/no answer to the question of whether the evaluating building meets the single requirement that is set by the criterion. In this regard, some criteria may be defined in the form of compliance with building regulations, norms, and codes (Leiringer 2020). On the other hand, a few evaluation systems created a level of maturity/advancement for a given criterion using some indicators sorted from less advanced to more advanced (in terms of sustainability/intelligence) to enable a more accurate evaluation. A potential benefit of this model is allowing for evaluating a building based on its current conditions while giving a clear view of future possible targets (Al Dakheel et al. 2020). Overall, there is no commonly accepted approach for creating evaluation criteria and each approach has certain advantages and disadvantages.

Weighting system is another element of the evaluation system structure. Although it may be considered as an internal step of the MCDA method it can be discussed separately since many evaluation systems contain this element even though they do not implement MCDA method. The weighting system is necessary simply because some identified evaluation criteria are more important than others in terms of their impacts on the building sustainability/intelligence and this fact should be addressed in the evaluation system. Therefore, a weighting system aims to determine the relative importance of the evaluation criteria using a coefficient given to each criterion. The weighting system may also determine the relative importance of different groups of criteria. For instance, Wong et al. (2006) grouped the evaluation criteria based on the building systems and divided the building systems into primary and secondary based on their relative importance while it represented the impacts of each building system on the overall building intelligence. A challenge for creating the weighting system is the lack of an objective and theoretical method for determining and validating the weighting system (Ding 2008, Mahmoud et al. 2022). The existing evaluation systems use different methods and approaches to create a weighting system. Part of the reason is that the weights of criteria may depend on various factors such as regional priorities, project circumstances, building type and occupancy, and stakeholders’ goals and requirements.

Rating and certification are other elements of the evaluation systems structure. Rating system refers to the visualization of the building evaluation outcome based on pre-determined levels of sustainability/intelligence. For example, LEED evaluation system has four levels (certified, silver, gold, and platinum) while each level has a range for the calculated evaluation score. The way of achieving the score is usually not fixed and users have the flexibility to select a combination of criteria to achieve a desired score (Ade et al. 2020). In general, there are two rating approaches including self-evaluation and third-party evaluation which usually provides a formal building certificate. In addition, different evaluation systems certify a building at different points of the project lifecycle such as at the end of design phase or during the post-occupancy phase.

2.2.3 *Existing Intelligent Buildings’ Evaluation Systems*

The main structures of existing intelligent buildings evaluation systems have been adopted from the sustainability evaluation and certification systems. However, creating a standard system for intelligent buildings evaluation has been proven to be a complicated task due to ambiguity in definition and components of building intelligence, the variety of technologies available, and building performance expectations for building systems and services.

This section provides a brief summary of existing evaluation systems created by both academic scholars and industry practitioners. Several formal intelligent buildings evaluation systems as well as research studies were found during the literature review while each evaluation system used different components and methods of evaluation. The Asian Institute of Intelligent Buildings (AIIB) developed an intelligent building index with 10 modules and 327 criteria questions for building assessment (Chow et al. 2005). Another research initiative (Kaya et al. 2014) proposed an intelligent building assessment system with the following main attributes: engineering (e.g., responsiveness), economical (e.g., life-cycle costing), environmental (e.g., energy consumption), socio-cultural (e.g., human comfort), and technological (e.g., work efficiency). The Building Research Establishment (BRE) developed a smart building evaluation matrix tool. It aimed to distinguish between building intelligence and building automation and measured the level of building intelligence based on five groups of performance indicators (Kolokotsa et al. 2007). Wong et al. (2006) took a different approach and defined building intelligence as the intelligence of its physical and digital systems (e.g., building automation system, HVAC system, lighting system, and information and communication network system) and developed a conceptual model for the selection of intelligent building systems based on a set of attributes and sub-attributes. Also, the Building Intelligence Quotient program created a web-based tool containing 315 questions in order to determine the value of intelligent building with a focus on building technologies and operation practices (Katz et al. 2009, Kushal 2019). Similarly, Ghaffarianhoseini et al. (2016) emphasized on the importance of intelligent building technologies although they tried to broaden the area of evaluation by including environmental and social components. Their work provided a review of key features and performance indicators of intelligent buildings as well as four main components (along with sub-components) of intelligent buildings including smartness and technology awareness, economic and cost efficiency, personal and social sensitivity, and environmental responsiveness. A recent initiative supervised by European Commission Services proposed a rating system (called Smart Readiness Indicator aka. SRI) that identifies 112 smart services within 10 domains, accounting for their levels of functionalities, and their impacts (Verbeke et al. 2018). A unique characteristic of this evaluation system is that it separates building intelligence from building performance while making a connection between intelligence indicators and performance impacts. Additionally, SmartScore is a relatively new evaluation system that evaluates intelligent buildings based on user functionality and technological foundation (WiredScore 2021). It seems that this evaluation system aims to connect the technical functionalities of a building (with a focus on the ICT system) with its performance (from the building occupants' perspective). Another new evaluation system is SPIRE which provides a web-based tool for building self-assessment (official certification is possible too) using 6 categories including sustainability although it refers to the conventional sustainability evaluation systems (e.g., LEED, BREAM, and WELL) to determine the score of that criterion (Soncodi 2021).

The overall review of the existing evaluation systems reveals that there is a significant discrepancy in the evaluation systems in terms of selected components and evaluation criteria as well as method of evaluation. To make a more detailed comparison between the existing evaluation systems, I selected six comprehensive formal evaluation systems namely IBI Manual V.3.0, MATOOL, BiQ V.2.0, SRI, SmartScore, and SPIRE. The result of this comparison was used as a basis for identifying components of building intelligence. A summary of these evaluation systems' metadata is presented in Table 2.2 (Chow et al. 2005, Kolokotsa et al. 2007, Katz et al. 2009, Batov 2015, WiredScore 2021, Soncodi 2021). Providing an analysis of real-world implications of these evaluation systems is difficult since the three of them (IBI, MATOOL, and BiQ) are not being actively used anymore and the other three are so new that there is very little empirical data regarding their implementations.

Table 2.2. An overview of the existing intelligent buildings evaluation systems

Evaluation System Name	**Organization**	**Country of Origin**	**Year**	**Areas of Evaluation**	**Rating System**
Intelligent Building Index (IBI)	The Asian Institute of Intelligent Buildings (AIIB)	China	2002	Green, Space, Comfort, Working efficiency, Culture, High-tech image, Safety & structure, Management practice & security, Cost effectiveness, Health & sanitation	Overall IBI Score in the range of 1-100
MATOOL	Building Research Establishment (BRE)	UK/EU	2004	Built environment, Responsiveness, Functionality, Economic issues, Suitability	Bad: <50, Good: 50 ~80, Very Good: 80 ~100, Excellent: 100~125
Building Intelligence Quotient (BiQ)	Continental Automated Buildings Association (CABA)	Canada	2009	Systems overview, Power distribution, Voice and data systems, Connectivity options, Intelligent building system features, Facility management applications, Degraded mode operation, Building automation environment	Silver: 51-69%, Gold: 70-84%, Platinum: 85-100%
Smart Readiness Indicator (SRI)	Flemish Institute for Technological Research NV (VITO)	EU	2018	Heating, Domestic hot water, Cooling, Controlled ventilation, Lighting, Dynamic building envelope, Energy generation, Demand side management, Electric vehicle charging, Monitoring and control	7 Classes: A-G based on the overall score in %
SmartScore	WiredScore	US	2021	Individual and collaborative productivity, Health and wellbeing, Community and services, Sustainability, Maintenance and optimization, Security, Digital connectivity, Building systems, Landlord integration network, Governance, Cybersecurity, Data sharing	Certified, Silver, Gold, Platinum
SPIRE	TIA and UL	US	2021	Connectivity, Health and wellbeing, Life and property safety, Power and energy, Cybersecurity, Sustainability	-

2.3 SUMMARY AND POINT OF DEPARTURE

In this research, I conducted literature review in two areas including a conceptualization of intelligent buildings and introduction of building evaluation systems. First, I discussed the concept of intelligent building in terms of its definitions (technology-based, performance-based, and system-based) and scalability (intelligent home, building, and city). Moreover, I provided a discussion on the differences between sustainable buildings and intelligent buildings. Subsequently, I conducted a literature review on evaluation systems in the building industry. I identified purposes for implementing evaluation systems including benefits for different stakeholders and using evaluation systems as a decision-making tool. Also, I explained the structure of an evaluation system and its key elements. Finally, I provided a comparative review of the existing evaluation systems for intelligent buildings.

During the literature review, I found some gaps in research which I discuss in this section. I use these gaps as a basis to form my research questions. Also, I explain the boundaries and expected limitations of my research.

2.3.1 *Research Gaps*

Overall, three specific gaps were found as the result of the literature review.

Research gap 1: there are gaps in general and commonly accepted definition and articulation of “Intelligent Building”.

Based on the literature review, there is no commonly accepted definition of intelligent buildings. There is also a significant overlap between the concepts of intelligent building and sustainable building in terms of definitions and characteristics. This is due to the lack of a holistic understanding of intelligent building components to articulate building intelligence, to distinguish it from other similar concepts, and to be used as a basis for intelligent building evaluation. Overall, the methods used for determining components are divergent in the current literature. On one hand, Cempel et al. (2013) defined two types of components for intelligent buildings including active components, as their performance can be improved through better maintenance, operations or upgrades, and passive components, such as architectural design, building location, and materials that once constructed rarely change and hence are not a part of the building intelligence. On the other hand, other studies (Chow et al. 2005, Omar 2018) considered elements like building location and orientation as intelligent building components. Thus, there is a need for determining components of intelligent building with a consistent, scientific, and transparent method.

Research gap 2: there are gaps in technology-centered standard systems for building intelligence assessment.

The ultimate goal of identifying intelligent building components is to develop a standard evaluation system that helps different building projects stakeholders to understand intelligent building technologies, systems, services, and practices. Through the comprehensive literature review and comparative analysis of current evaluation systems, the following gaps and limitations were found:

- Generic and ambiguous criteria: some criteria (e.g., office automation or system integration) are too general and subject to different interpretations.
- Inconsistency in the framework/ontology of the proposed systems: in some systems, a criterion (e.g., energy efficiency) was categorized under a single category (e.g., environmental) while it is correlated with other existing categories (e.g., economical) as well. Also, such inconsistency may cause double counting in the evaluation system.

- Sector-dependent evaluation system: some evaluation systems (mostly industry-based) define the concept of intelligent building and its associated criteria (e.g., building automation) based on a specific sector (e.g., mechanical and HVAC systems or building security). Although the outcome might be detailed and accurate it does not holistically address all aspects of building intelligence.
- Static weighting and rating systems: Many evaluation systems do not recognize and address the relative importance of evaluation criteria (as discussed in section 2.2.2). Also, some criteria (e.g., mechanical air ventilation system) may have higher/lower importance for some types of buildings or climates. However, many proposed systems have static and inflexible weighting systems that do not reflect the regional priorities and requirements.
- Intangible and unmeasurable criteria: while some aspects of building intelligence (e.g., occupant comfort and productivity) are hard to be objectively quantified, some systems did not provide any qualitative or quantitative metric/method for evaluating these criteria.
- Binary evaluation system: Many systems evaluate the criteria by “exist/ not exist” options while in many cases the quality and extent of adopting a technology or practice have significant impacts on its functionality and consequently the building intelligence.

Accordingly, there is a need for a standard evaluation system that resolves these issues.

Research gap 3: there are gaps in the systematic study of how building intelligence impacts building performance.

The literature review indicated the important role of emerging technologies in intelligent buildings. In the current intelligent building market to maintain competitiveness, property owners need to adopt and implement emerging technologies, processes, and best practices that support required digital transformations and demand changes whilst also ensuring that the marketability of intelligent building projects can be secured. However, low professional capacity to incorporate technologies, lack of knowledge in developers and owners on impacts of their initiatives, and lack of information on the opportunities and benefits of technologies are among top barriers to the promotion of intelligent buildings (cf. Kua et al. 2002). Currently, there are gaps in existing evaluation systems regarding addressing the technologies, processes and best practices and providing a clear method for measuring their contributions to the building performance.

2.3.2 *Research Questions*

In response to the three identified gaps in research, I developed the following research questions.

Research question 1: what is an intelligent building and what are the main components of building intelligence?

The first research question raised from the existing gap in consistency and comprehensiveness of the definition of intelligent building as a concept and components identification and the increasing demand for it in both academia and industry sectors especially because of the current confusing overlaps between different concepts. Therefore, this question seeks to not only identify the intelligent building components in a consistent way but also clearly distinguish between components of intelligent building and sustainable building.

Research question 2: what is a standard method for building intelligence assessment?

According to the explained gaps in the existing intelligent buildings' evaluation systems, the second research question focuses on the idea of creating a rule-based, context-sensitive, and sector-independent evaluation system with a consistent framework and ontology that uses measurable, unambiguous, and context-tested criteria that cover all aspects of building intelligence, and with an focus on addressing emerging technologies in the evaluation system that helps users to use this system as a decision making tool (specifically for deploying emerging technologies) during the whole building lifecycle.

Research question 3: what are the intended impacts of building intelligence on building performance?

The third research question was developed based on the current gaps in the systematic assessment of impacts of intelligent building technologies, services, and practices on building performance that enables building owners and managers to make more informed decisions. A pre-requisite for answering this question is creating a framework for articulating building performance and connecting it to the identified building intelligence evaluation criteria in the developing evaluation system.

2.3.3 *Research Limitations*

Based on the identified gaps in knowledge and the identified research questions and objectives, this research aims to develop an evaluation system for the articulation and documentation of building intelligence components, evaluation of intelligent buildings' technologies, systems, services, and practices, and quantification of building intelligence impacts on the overall building performance. Since it is an ambitious goal, it is important to determine the scopes of the work and clarify the limitations and boundaries of the research clearly:

- Developing an evaluation system contains various tasks. This research is focused on determining evaluation criteria based on identified building intelligence components and creating a framework for evaluation including the method of evaluation and the weighting system. However, creating a certification mechanism (e,g, self-evaluation versus third-party evaluation) is excluded since it depends on the process and business plan for commercialization of the evaluation system. Similarly, designing a user interface and a specific tool (web-based or standalone software) for utilizing the evaluation system are excluded from this dissertation.

- Creating a weighting system that addresses the relative importance of evaluation criteria is a part of this research. However, one may argue that the identified coefficients may need to be adjusted depending on different types of buildings (e.g., commercial office versus educational facility) or different regions (with different priorities). There is an ongoing debate regarding this issue and how realistic it is to create multiple weighting sets (since each building project may have different goals, priorities, and requirements that affect the importance of the evaluation criteria). Also, this issue is related to the certification mechanism to some extent since the coefficients might be adjusted by the end users in the self-evaluation approach. Even though the framework of the evaluation system has the flexibility to adjust the weighting values, developing multiple weighting systems for different types of buildings/regions is beyond the scope of this research.
- Related to the third research question, the scope of the work includes creating a framework to identify the intended impacts of building intelligence on the building performance. This work could be accomplished with different levels of detail such as 1. determine the main areas of building intelligence impacts, 2. determine research-based expected impacts of the identified evaluation criteria on the building performance, and 3. determine impacts of identified evaluation criteria quantitatively based on validated empirical data. This research aims to perform this task using the second approach. In this regard, the term “intended impacts” was used intentionally (instead of “actual impacts” or “validated impacts”) to convey that these impacts are designed aspects of the components but need to be further field verified.

Chapter 3. RESEARCH METHODOLOGY

In this chapter, I explain the research methodology including design of a framework for addressing the research questions and the process of conducting the research. Also, it introduces the methods and theories used during the research process.

3.1 RESEARCH DESIGN

Based on the identified research gaps and questions, the scope of the study included identifying the building intelligence and performance components, developing a standard evaluation system, and creating a framework for measuring the impacts of building intelligence on building performance. While the first scope is the pre-requisite for achieving the second one and the third scope has a complementary role for the second one since it enhances the method of evaluation in the developing evaluation system.

This research was based on an international collaboration between several academic and industry partners led by the International Intelligent Building Organization (IIBO). The project was initiated by the University of Technology, Sydney (UTS) in Sydney, Australia and the University of Washington (UW) later joined the project to lead the study in the United States. The project entailed practical R&D focused on developing the evaluation system (called IB Index) and a web-based software application to enable end-users to implement the evaluation system. While this PhD research was based on the IB Index project in terms of content and workflow it included some additional scholarly steps (e.g., the preliminary literature review), on one hand, and excluded the IB Index business model development and commercialization process, on the other hand. The overall research process is shown in Figure 3.1.

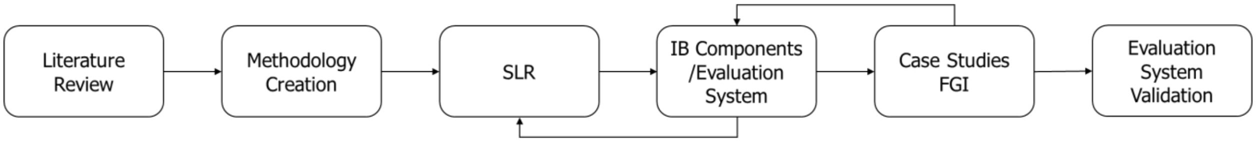

Figure 3.1. The overall process of the research

The process started with a literature review to provide the fundamental knowledge of the research topic as well as identify research gaps and questions. It is followed by the research methodology creation which includes appropriate theories and data collection/analysis methods with the expected research outcome in mind. Subsequently I conducted a systematic literature review (SLR) to investigate intended areas and topics (first, related to the building intelligence components, and second, the evaluation system). In the next step, a draft of the IB Index evaluation system was created which then was tested using two case studies. Through an iterative process, the evaluation system was revised based on the results of the cases information, focus group interviews (FGI) and further SLR. In the last step, the developed IB Index went through a final validation process.

Since the scope of the study for this research was slightly different from the scope of the work for the IB Index project performed by the research team[2] and also to be transparent regarding my contributions to the research, I summarized the major activities of the research (as shown in Table 3.1) and indicated whether they were completed through individual, or collaborative works.

Table 3.1. Individual vs. collaborative completion of the major research activities

Activity	**Individual Work**	**Collaborative Work**
Literature review	X	
Methodology development	X	
Intelligent/sustainable building components identification		X
Systematic literature review	X	
Case study/interviews 1		X*
Case study/interviews 2	X	
Context Analysis	X	

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[2] The other research team members include Dr. Julie Jupp, Dr. Carrie Sturts Dossick, Shen Chiu, and Fisher Chen.

IB Index structure revision	X	
IB Index weighting system creation		X
IB Index ontology creation	X	
IB Index Catalogue/guidance development	X**	
IB Index validation	X	
For all individual works, the research team provided significant support through reviews and revisions. *The first case study was conducted by UTS, and the result was used as the secondary source of data in this research. **The IB Index Catalogue version 1 was created by UTS. The final version presented in the dissertation is the 4th version of the Catalogue.		

To gain a better understanding of development mechanism for the IB Index evaluation criteria, the two relevant general approaches are discussed in detail. The “top-down” and “bottom-up” concepts (Oltean-Dumbrava et al. 2014) are used to explain these approaches (as summarized in Figure 3.2).

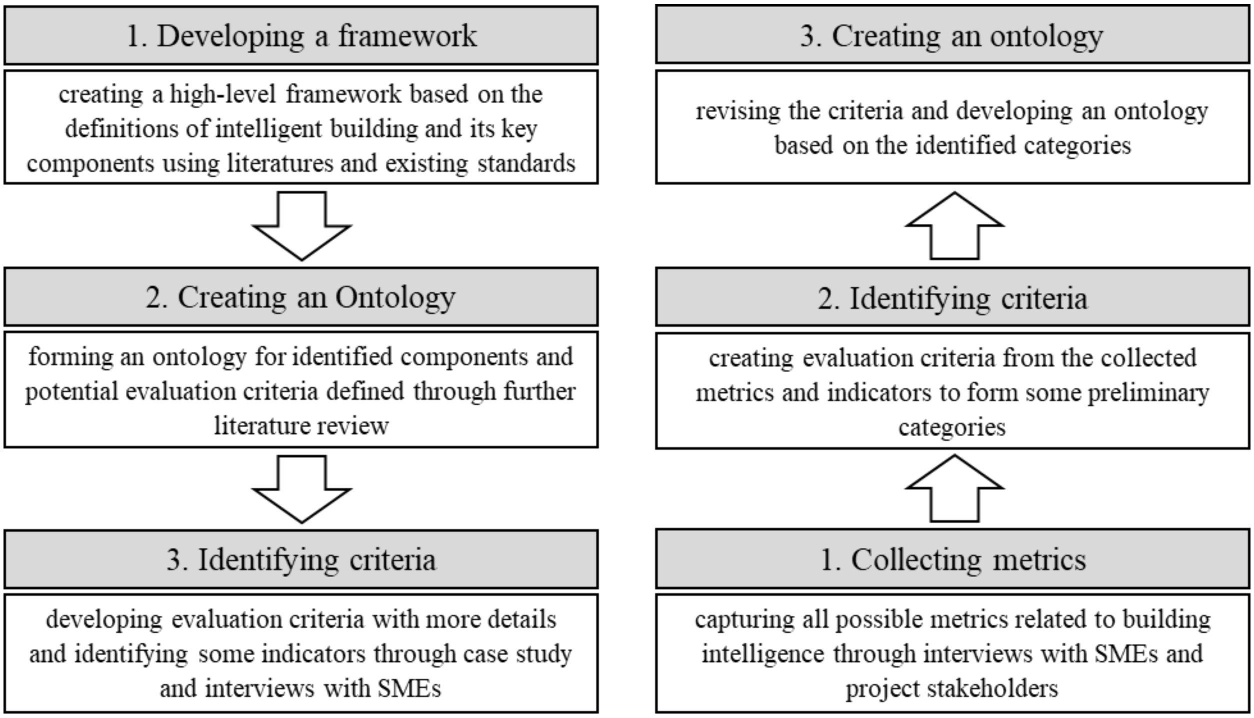


Figure 3.2. Top-Down (left) and Bottom-Up (right) approaches for developing intelligent buildings evaluation criteria

The bottom-up approach starts with collecting all relevant data using a case study. The researcher uses ethnographic methods and semi-structured focus group interviews with subject matter experts (SMEs) and project stakeholders (of the selected case study). The captured data may include workflow of an intended technology, daily practices of SMEs, and description of an implemented intelligent building initiative. In this level, the collected metrics may not be consistent or documented with a formal structure. Next, the researcher uses metrics as a basis for creating quantifiable criteria (with more generalized and consistent language). In addition, the criteria are sorted into higher-level categories. Finally, an ontology is created to organize the evaluation criteria and their categories within a standard hierarchy.

Unlike the organic process of the bottom-up approach, the top-down approach aims to provide a standardized and systematic process of criteria development. First, the researcher determines the main aspects of building intelligence. Next, the researcher divides the aspects into more detailed components and possibly quantifiable criteria using systematic literature review (i.e., examination of related documents/standards, deep search in academic/industry publications, and learning about intended technologies, practices, and building systems). Further, a logic-based ontology is developed to organize the identified criteria. Finally, the researcher uses findings of previous analyses along with the interviews with SMEs for revision and validation of the developed criteria and measurable metrics for building evaluation.

In the process of developing the intelligent building components and evaluation criteria, the research team used the bottom-up approach to create the first version of the IB Index with the intention of capturing all aspects of building intelligence. Subsequently, the research team revised and standardized the IB Index evaluation criteria and ontology based on the top-down approach.

3.2 THEORIES AND METHODS

There are two theories underlying the logical methodology of this research. The first theory is Actor-Network Theory (ANT) which is used to interpret and deconstruct the complex concept of building intelligence. The second one is grounded theory which is used to form the process of creating the research end-products. The two theories are discussed in this section. In addition, this research utilizes mixed-methods analysis mainly by combining systematic literature review and case studies including focus group interviews. This section articulates these methods and the ways they are deployed.

3.2.1 *Actor-Network Theory*

Actor-Network Theory (ANT) is one of the social theories that was adopted by other domains to conceptualize and contextualize new concepts such as information systems and emerging technologies. Latour (1996) introduced ANT to study the characteristics of human–technology relationships. This theory is mainly concerned with "the way various people, ideas and things come together within networks and are held in place or become disassociated and reconstituted" (Harty 2008). ANT is unique since it considers the non-human elements (e.g., objects, ideas, and artifacts) at the same level as humans in the social context (Latour 2005). In other words, ANT considers a complex system as a network of system elements, their producers, maintainers, and consumers, as well as the social relationships between them (Dusek 2006). By rejecting a distinction between human and non-human, ANT adheres to an ontological symmetry where system elements and human actors are constituted or disassociated through interactions (Harty 2008). In addition, ANT emphasizes the continual reconfiguration and transformation of the network through interaction between the actors, artifacts and practices (Latour 2005, Harty 2008). So, a researcher can study the process of formation of a system/artifact and position it in its current network in accordance with its surrounding connected elements.

ANT is not completely new to the domain of the built environment. Several researchers mentioned ANT as an analytical technique to be used in areas like exploring construction project network organizations (Pekericli et al. 2012), articulating diffusion of innovation in construction

(Hajj et al. 2021), and creating a sociotechnical system for BIM implementation in projects (Sackey et al. 2015). In addition, some researchers used ANT as the main framework for their analysis of their intended subject. For example, Rydin (2013) used ANT to explore the relationships between different actors involved in planning and regulating commercial development. Also, Frank et al. (2022) developed an ANT diagram for identifying challenges of creating a sustainable building certificate by focusing on the relevant actors and their connections. Other studies employed the theory to provide a theoretical understanding of complex phenomena such as collaboration in housing construction (London et al. 2017) and stakeholders engagement in projects (Missonier et al. 2014) where it is critical to investigate multiple human/non-human elements and dynamic relationships between them. In summary, research studies in the domain of built environment use ANT mainly for two purposes including 1. to explore a complex system by creating a network of primary actors and their connections, and 2. to understand the formation and reformation of a system over time by studying its influential actors and their interactions. Overall, these approaches align with the intentions for ANT and its applications in other domains.

In the case of intelligent buildings, the goal of ANT is to create a network of key human and non-human actors related to building intelligence that may be identified within an industry, organization, or project. Also, it makes connections between different actors to investigate the nature and quality of their relationships.

Even though ANT is an effective and useful theory for interpreting complex systems, it is not flawless. Some scholars criticized this theory because of its lack of generalizability (Star 1991). They argue that a network developed by this theory is case-specific and cannot be generalized to articulate the relationships and interactions between intended actors in similar circumstances. In response, this theory does not aim to generate an objective source of “truth” in studying a social phenomenon or system, but it rather tries to provide an "effective" method to observe and interpret it (Gad et al. 2010). In the context of this research, I would argue that the above-mentioned criticism concerns the established actor-network models (mostly developed in social sciences) and not the credibility and applicability of the theory itself. To investigate the concept of building intelligence, I used ANT as a basis to identify and interpret the relevant elements and it can be continuously used to capture the transformations and dissociations of them which will be incorporated into the evaluation system. In fact, all existing evaluation systems are subject to change because of changes in their core concepts (e.g., the way that sustainability certifications like LEED have been periodically updated to reflect the transformation of the concept of sustainability in the built environment). Thus, deploying ANT is beneficial to create the evaluation system and update it in the future more efficiently and systematically. Figure 3.3 provides a conceptual visualization of ANT model I developed to explore the building intelligence.

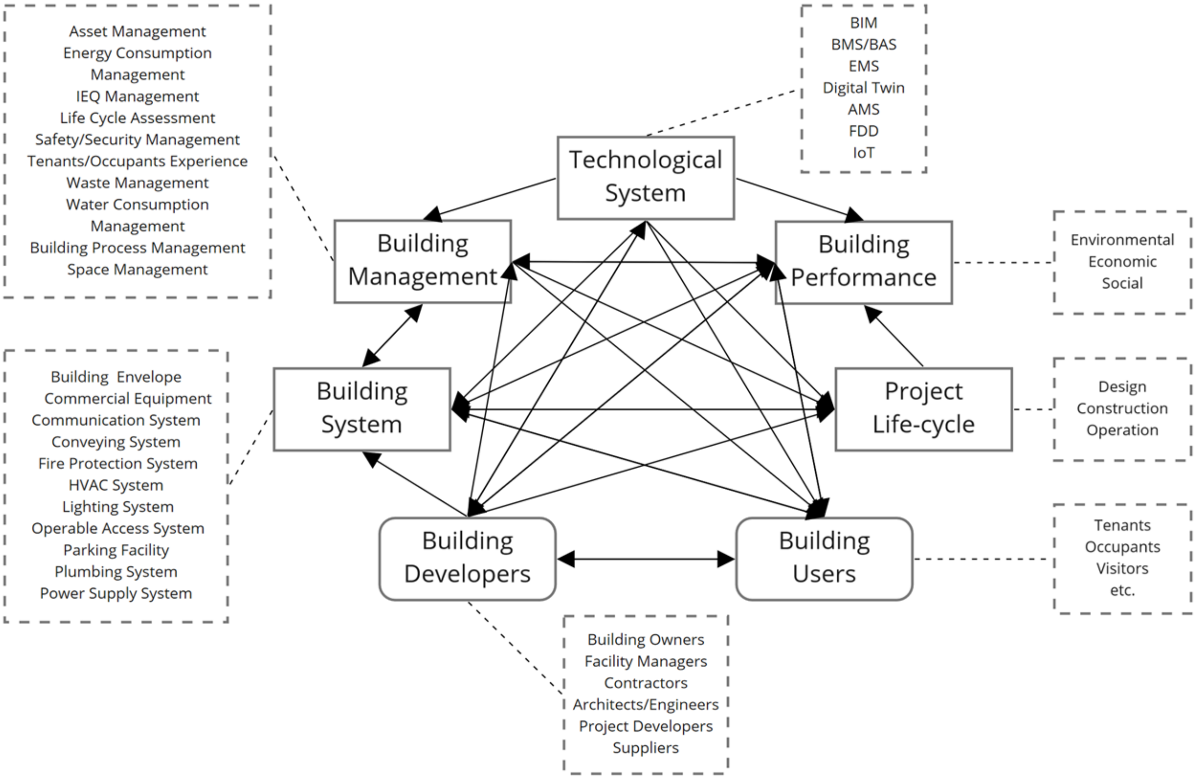


Figure 3.3. The ANT model for developing the building intelligence framework

This model shows the connections between different areas of building intelligence that are based on three primary actors namely human (building developer and users), building (defined by its life-cycle, base systems, managerial activities, and performance characteristics), and technology (used as a general term referring to physical devices, digital technology solutions, and technological knowledge). Moreover, the model depicts many-to-many relationships including human-technology, human-building, and building-technology interactions. For instance, one can focus on the connection between building developers\facility managers and building management\energy consumption management to identify what activities are performed by the FM team and how they impact building intelligence. Consequently, the ANT model serves as a basis for identifying and organizing the building intelligence components as well as criteria of the intelligent buildings evaluation system.

3.2.2 *Grounded Theory*

Howell (2013) defined grounded theory as a way of building theory through the collection and analysis of rich data. Grounded theory can be described as a research method that seeks to develop theory that is grounded in systematically gathered and analyzed data, and the interplay between data collection and analysis continuous during the research process (Pulla 2014). The process of conducting grounded theory involves collecting data systematically, coding data, creating categories and clusters, theoretical sampling, performing comparative analysis and building substantive theory (Howell 2013, Pulla 2014). A product of this process can be an ontological framework for the investigated domain.

In this research, I used grounded theory regarding building intelligence components, evaluation criteria, and ontology which I developed and standardized through iterative processes.

For instance, to develop the evaluation criteria, the process started with data collection. In this case, data points were the metrics and criteria of building intelligence identified during the systematic literature review and focus group interviews. As criteria emerge through data sampling and analysis, the relationships between criteria are used to form the categories and sub-categories. The types of relationships were divided into primary (related to a characteristic of the building intelligence that is articulated by the intended criterion) and secondary (related to a different characteristic that has a connection with or an impact on the intended criterion). For example, a criterion that measures controllability of a lighting fixture (to balance between natural and artificial lighting) has a primary relationship with the building lighting system and secondary relationships with energy efficiency and building management system. The developed criteria were continuously compared with each other to ensure consistency and find redundant concepts. The process was repeated until getting to the point of data saturation (i.e., no more building intelligence criteria were found during the case study or literature review that had not been already included in the evaluation system).

3.2.3 *Case Study and Focus Group Interview*

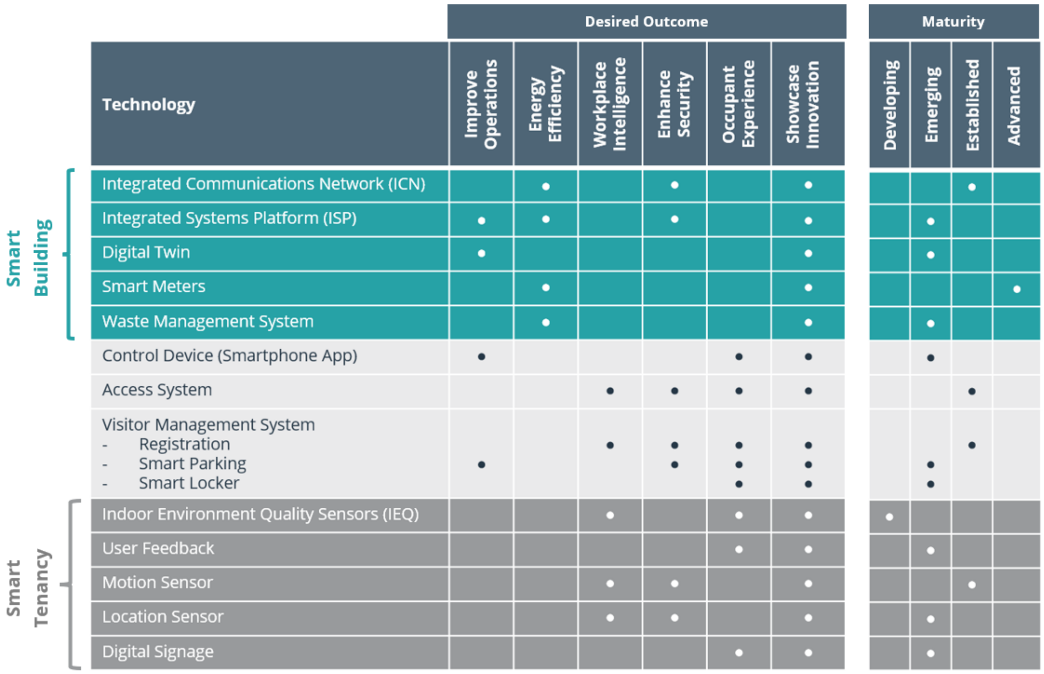
Case study is defined as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clearly evident." (Yin 1984). Case study produces context-dependent knowledge (Flyvbjerg 2001) answering the questions of "why an event happens" and "how an event happens" (Yin 1984). So, a case study is mostly useful when a researcher wants to develop a theoretical proposition by going to the field and observing how people act, apply a tool in a specific way, and interact with other people (Taylor et al. 2001). During a case study, a researcher may use different methods to collect evidence including documentation (e.g., letters, memoranda, and meeting minutes), archival records (e.g., service records and organizational records), direct observation, participant observation, physical/cultural artifacts, and interviews (Yin 1984).

In addition, Weiss (1994) defines Interviewing as a tool that gives a researcher access to learn about others' experiences, what they perceived from an event, how they interpret it, and how that impacted their thoughts and feelings. In the context of technology adoption, an interview allows a researcher to obtain first-hand knowledge about adoption processes, implementation practices, impacts, and challenges of a technological artifact by conducting a focus group interview (Gill et al. 2008) with a group of technology experts. Also, interviewing multiple members of a social setting (e.g., a specific technology practitioner) helps researchers to gain different perspectives of the phenomenon (Roulston et al. 2018).

In this research, the research team used a case study method (a selected building and its specifications, implemented technologies, smart initiatives, etc.) to test and calibrate the developed evaluation method and criteria in terms of the clarity, consistency, and comprehensiveness as well as the accuracy and functionality of the weighting system. Also, as one of the main methods of data collection, the focus group interviews (FGI) were made with different groups of subject matter experts (SMEs) within the case study to examine and validate the created evaluation system.

The research team conducted two case studies. The first one took place in Sydney, Australia and a high-rise commercial office building was selected for the study. In the process of case selection, the research team performed a preliminary analysis to make sure the intended building could be considered as an intelligent building based on possessing basic elements like building technologies, building systems, and basic tenants-building interactions. Specifically, the research team listed major technologies (already implemented or targeted by the facility owners/managers) and the owner intentions and desired outcomes for using those technologies.

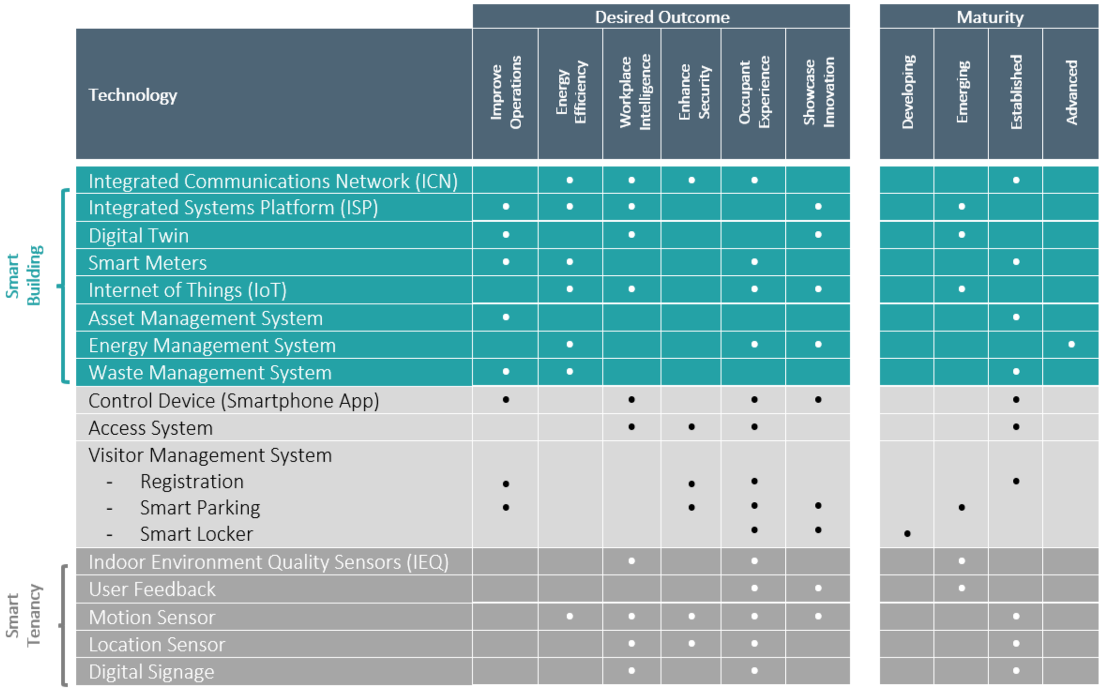
Also, the technologies were divided based on the use cases (enhancing performance of building systems or experience of building tenants). Moreover, the analysis captured the relative maturity of the technologies (reported by facility managers). Figure 3.4 shows a summary of this analysis (see Appendix B for the case study 1 analysis' report).



		Desired Outcome						Maturity			
	Technology	Improve Operations	Energy Efficiency	Workplace Intelligence	Enhance Security	Occupant Experience	Showcase Innovation	Developing	Emerging	Established	Advanced
Smart Building	Integrated Communications Network (ICN)		•		•		•			•	
	Integrated Systems Platform (ISP)	•	•		•		•		•		
	Digital Twin	•					•		•		
	Smart Meters		•				•				•
	Waste Management System		•				•		•		
	Control Device (Smartphone App)	•				•	•		•		
	Access System			•	•	•	•			•	
	Visitor Management System										
	- Registration			•	•	•	•			•	
	- Smart Parking	•			•	•	•		•		
	- Smart Locker					•	•		•		
Smart Tenancy	Indoor Environment Quality Sensors (IEQ)			•		•	•	•			
	User Feedback					•	•		•		
	Motion Sensor			•	•		•			•	
	Location Sensor			•	•		•		•		
	Digital Signage					•	•		•		

Figure 3.4. Case study 1 preliminary analysis

I was the primary researcher on the Seattle-based research team that conducted a second case study in Seattle, Washington, United States. After going through the preliminary analysis (result is shown in Figure 3.5) two specific office buildings were selected on a corporate campus because of their occupancy (which is comparable to the building of case study 1) and implemented technologies. In addition to collecting the buildings' data and documentations, I created a semi-structured interview tool containing the topics, related IB index categories, list of question areas, and the potential groups of interviewees (see Appendix A). Next, I interviewed 21 subject matter experts from the organization who participated in the case study (see Appendix C for the case study 2 analysis' report).



	Technology	Desired Outcome: Improve Operations	Energy Efficiency	Workplace Intelligence	Enhance Security	Occupant Experience	Showcase Innovation	Maturity: Developing	Emerging	Established	Advanced
	Integrated Communications Network (ICN)		•	•	•	•				•	
Smart Building	Integrated Systems Platform (ISP)	•	•	•			•		•		
	Digital Twin	•		•			•		•		
	Smart Meters	•	•			•				•	
	Internet of Things (IoT)		•	•		•	•		•		
	Asset Management System	•								•	
	Energy Management System		•			•	•				•
	Waste Management System	•	•							•	
	Control Device (Smartphone App)	•		•		•	•			•	
	Access System			•	•	•				•	
	Visitor Management System										
	- Registration	•			•	•				•	
	- Smart Parking	•			•	•	•		•		
	- Smart Locker					•	•	•			
	Indoor Environment Quality Sensors (IEQ)			•		•			•		
	User Feedback					•	•		•		
Smart Tenancy	Motion Sensor		•	•	•	•	•			•	
	Location Sensor			•	•	•				•	
	Digital Signage			•		•				•	

Figure 3.5. Case study 2 preliminary analysis

The results of the case studies/FGIs were used to further develop and revise the IB Index evaluation system as well as to help the organizations participating in the research to learn about the impacts and effectiveness of their intelligent building initiatives and gain a better understanding of the actual level of intelligence in their buildings.

As the last step of the research process, I conducted 9 interviews with subject matter experts to validate the developed IB Index evaluation system. This round of the interviews was mainly focused on validating the comprehensiveness and clarity of the evaluation criteria as well as validating a part of the weighting system that addresses the relative importance of the evaluation criteria (see Section 4.1.8 for more information about the validation workflow).

3.3 SUMMARY

As mixed-methods research, this study benefited from multiple theories and methods to answer the research questions. The actor-network theory provided a basis for identifying building intelligence components and developing a standard and rule-based system to evaluate them. Also, several methods were used for data collection and analysis including case study, focus group interview, and systematic literature review. While grounded theory puts all methods into an iterative process of analysis, reflection, and revision to achieve the research outcomes. Additionally, the combination of ANT and grounded theory helped to cover the potential weakness of ANT theory and to ensure the validity and generalizability of the research outcomes. Table 3.2 summarizes the research objectives (responding to the associated research questions), the related research theories/methods, and the phases they were implemented according to the research process.

Table 3.2. Summary of the research methodology

Research Objectives	Theories and Methods	Research Process
Identifying components of building intelligence.	Actor-Network Theory Grounded Theory	Systematic Literature Review IB Components Development
Developing a standard system for intelligent buildings' evaluation.	Actor-Network Theory Grounded Theory Case Study and Interview	Evaluation System Development Case Studies/FGI
Creating a framework to connect intended impacts of building intelligence on building performance.	Case Study and Interview	Case Studies/FGI Evaluation System Validation

Additionally, Figure 3.6 illustrates a conceptual visualization of the research methodology and the way methods and theories are connected to each other and being used to accomplish the research objectives.

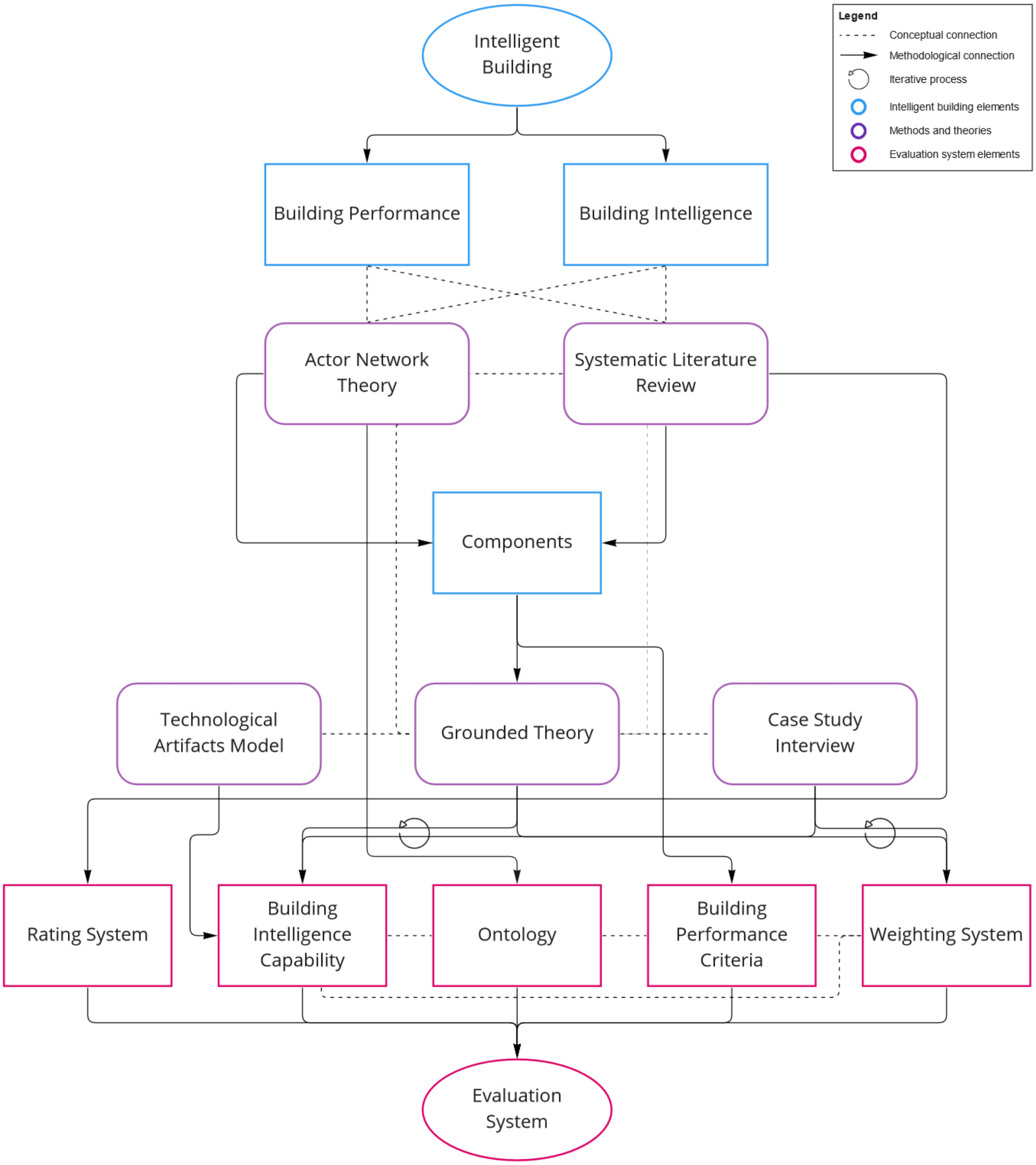


Figure 3.6. A conceptual visualization of the research methodology

Furthermore, the current version of the IB Index was developed through a process of revision and validation. To better understand this process, Table 3.3 provides a timeline of the IB Index development containing the main research activities leading to creation of each version of the IB Index evaluation system (see Section 4.1.8 for more details).

Table 3.3. The IB Index development timeline

Items	2019	2020			2021				2022		
	Au.	Wi.	Sp.	Au.	Wi.	Sp.	Su.	Au.	Wi.	Sp.	Au.
Preliminary literature review[1]	▨	▨									
IB Index v.1		▨									
Context analysis[2]		▨	▨								
Case study/FGI 1[3]			▨	▨							
Systematic literature review				▨		▨			▨	▨	
IB Index revision (v.2)				▨							
Technological artifact model development[4]					▨	▨					
Neural network ontology development[5]					▨	▨	▨				
IB Index Components development[6]					▨	▨	▨	▨			
IB Index revision (v.3)							▨				
Case study/FGI 2[7]							▨	▨			
IB Index validation (v.4)[8]										▨	▨

The timeline is based on the academic calendar year. Au.: Autumn, Wi.: Winter, Sp.: Spring, Su.: Summer.

IB Index revisions included revising all main components of the IB Index such as the Catalogue, guidance, and the qualitative/quantitative coefficients in the weighting system.

[1] See Sections 2.1 and 2.2 for the results of literature review.

[2] See Section 4.1.3 for more information. Also, see Appendix F for the analysis report.

[3] See Appendix B for the case study report.

[4] See Section 4.1.5 for more information.

[5] See Section 4.1.7 for more information.

[6] See Sections 2.1.3 and 4.1.1 for more information. Also, see Appendix E for the tables of components.

[7] See Appendix C for the case study report.

[8] See Section 4.1.8 for more information. Also, see Section 4.2 for the IB Index Catalogue v.4.

Chapter 4. ANALYSIS

This chapter presents the main outcome of the research namely the IB Index in three sections including the IB Index framework which explains the process of the evaluation system development, the IB Index Catalogue that provides a detailed discussion on the evaluation criteria, and the IB Index validation which articulates the procedure for the evaluation system revision and validation.

4.1 IB INDEX OVERVIEW AND FRAMEWORK

4.1.1 *Building Intelligence Components*

Identifying components of building intelligence is the first step of developing a standard intelligent building evaluation system. As discussed in Section 2.1.3, the research team conducted an ontological analysis to find the building intelligence components in comparison with the building sustainability[3]. Actor-network theory was employed as the basis for this activity. The research team created a framework containing key areas of building intelligence and the sociotechnical relationships between them. Subsequently, the key areas were used to locate publications for a systematic literature review during which the research team analyzed 58 publications (containing academic papers and industry technical reports and best practices), and 29 formal sustainable/intelligent building evaluation systems to identify specific components. For the concept of sustainable building, the research team mainly analyzed formal evaluation systems and developed a unified ontology to make comparison between them. The selected evaluation systems

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[3] The result of the analysis was published in the ASCE Construction Research Congress proceedings, and a revised version of it is included in this section of the dissertation with permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at https://ascelibrary.org/doi/abs/10.1061/9780784483954.032

for in-depth analysis include LEED, LBC, DGNB, BREAM, EDGE, and WELL (see Appendix D for the full list of the reviewed evaluation systems). For intelligent building, the research team focused on academic/industry literature (37 papers were used to extract intelligent building components) along with the following four formal evaluation systems IBI, SRI, BiQ, and SmartScore (these evaluation systems were introduced in Table 2.2).

The comparative ontological analysis showed a substantial overlap between the intelligent and sustainable building components. Also, it identified the specific areas of similarity and difference. Accordingly, energy/water efficiency, indoor environmental quality, and occupants (health and wellbeing) are the clusters with higher similarities. On the other hand, topics like IT infrastructure and building automation/management systems are mostly addressed by smart building components while physical infrastructure and materials are mostly discussed as sustainable building components. These findings are visualized in Figure 4.1.

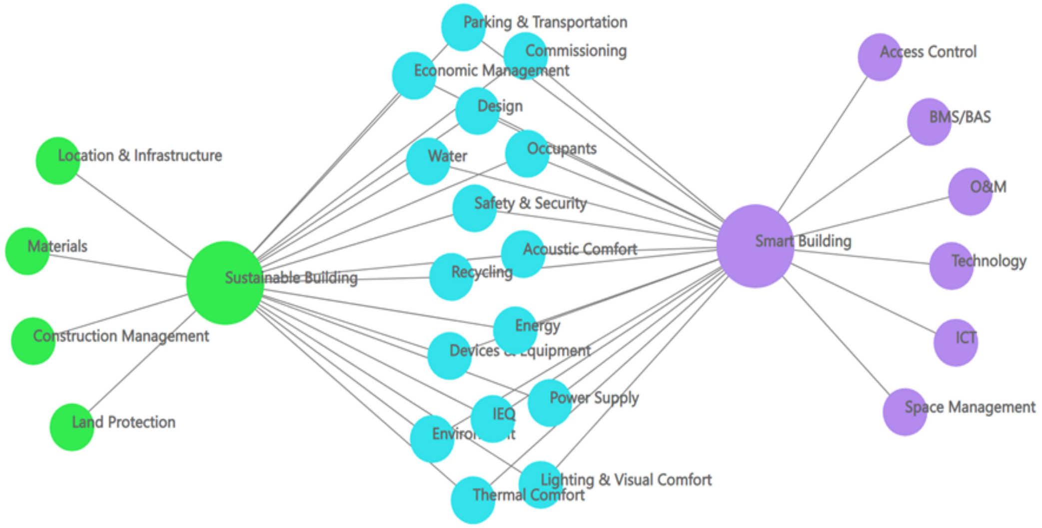


Figure 4.1. An overall comparative analysis of the intelligent and sustainable building components

As a result of this analysis, the building sustainability components were identified containing 18 clusters and 103 components. Moreover, the building intelligence components were identified containing 18 clusters and 79 components (see Appendix E for more details).

The findings of this analysis can be used to clearly distinguish between the building sustainability and intelligence components. First, a significant underlying theme was found in the building intelligence specific components. It specifies the emerging technologies and how they are implemented in intelligent buildings. Moreover, it contains the use of data analytics during the entire project lifecycle for more effective monitoring, control, management, and decision making. Second, a contextual difference was found in the way that components are defined. While one type of components describes “outcomes”, another type describes “actions” required for producing such outcomes. For example, one component may address the topic of thermal comfort as an indicator of building sustainability/intelligence by defining a required level of indoor air temperature and humidity (to be considered comfortable for the occupants), while the other component determines the technical specifications of the HVAC system that leads to that level of thermal comfort. Currently, most of the intelligent/sustainable building literature includes both types of components without acknowledging the difference between them.

To further develop this idea, it is important to understand how building intelligence is contently and structurally different from building sustainability. Theoretically, the concept of sustainability consisted of environment/ecology, society/culture, and economy/business aspects according to the triple bottom line theory (Papajohn et al. 2016). In comparison, building intelligence can be conceptualized based on the process, product, people methodology. In this regard, the element of people refers to the building occupants, their experience and interactions with the building, and their behaviors effects on the building performance; process is defined as overall design and construction processes and workflows as well as organizational settings and best practices for facility/asset management; and finally, the element of product consists of building physical and digital/virtual systems, adopted technology solutions, and required technological knowledge (cf. Alwaer et al. 2010). Based on this assumption, the building sustainability components should be of outcomes type that determines the desired building performance. On the other hand, the building intelligence components should be of actions type which discusses how the desired level of intelligence and consequently level of performance can be achieved in a building through implementing proper processes and workflows, technologies, and best practices. Therefore, it is concluded that building sustainability specifies elements of building economic, environmental, and social performance based on stakeholders' desired objectives and benchmarks set by the industry, while building intelligence focuses on articulating people, processes, and products in a building and their dynamic relationships.

4.1.2 *IB Index Typology and Structure*

To design a proper framework and structure for an evaluation system, its applicability areas should be determined. In this regard, Figure 4.2 demonstrates the typology of the IB Index based on the key factors used to distinguish between building evaluation systems.

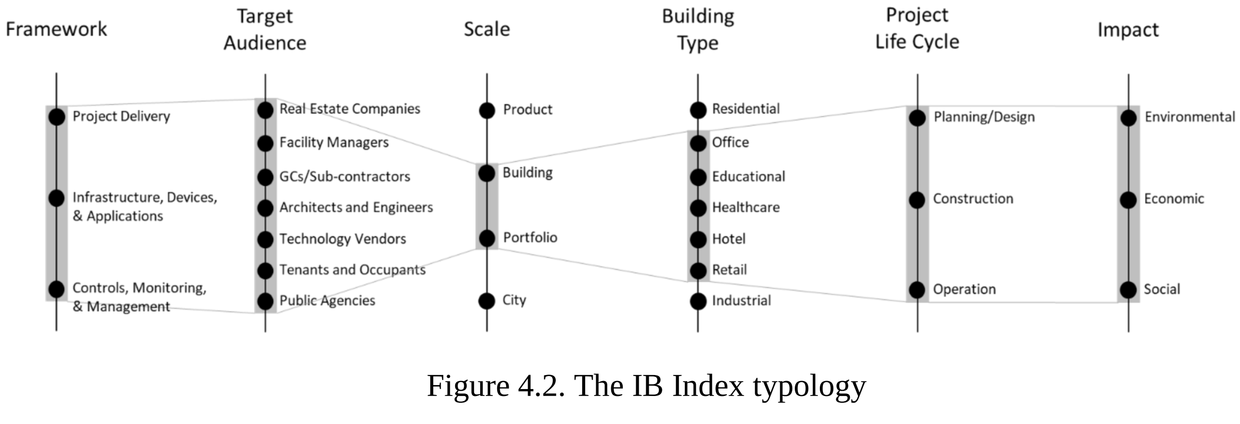


Figure 4.2. The IB Index typology

By default, the IB Index evaluation criteria are organized into three categories aligned with the design, construction, and operation phases of a project although the end-users can change the framework (see Section 4.1.7 for more information). All building stakeholders are among the target audience of the IB Index since it is a research-based whole building evaluation tool and different stakeholders may benefit from its technical guidance and supplementary documents to learn more about the intelligent buildings' opportunities and make more informed decisions (also a discussion on stakeholders' specific benefits was provided in Section 2.2.1.1). This evaluation system was originally designed for commercial buildings and portfolio of buildings (e.g.,, educational institute campus) evaluation. Also, it may be implemented during all major phases of a building project (from planning and design to operation). Unlike many existing evaluation systems, the IB Index makes a distinction between building intelligence and performance while making a connection between them by providing a framework to assess the impacts of building intelligence on building performance. To achieve this goal, a unique structure was created for the IB Index Catalogue which serves as the core element of the IB Index evaluation system. It contains all criteria used to understand and assess building intelligence. The overall hierarchy of the IB Index Catalogue is shown in Figure 4.3.

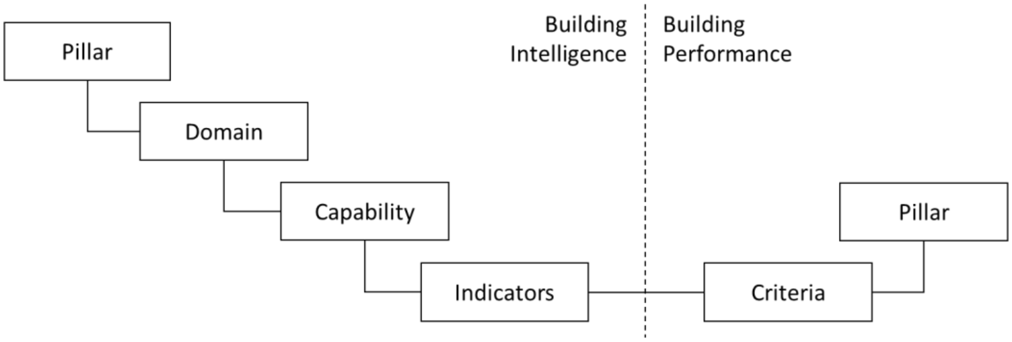


Figure 4.3. The structure of the IB Index Catalogue

As an overview, the building intelligence and performance have a 4-level and 2-level hierarchy, consecutively. In the building intelligence side, a pillar is at the top of the hierarchy. Each pillar has a number of domains, which in turn have capabilities that represent building intelligence evaluation criteria. The indicators then measure the level of intelligence within each capability. The building performance hierarchy is simpler. It has the pillar at the top and each pillar contains multiple criteria that specify aspects of building performance in more detail.

In the IB Index, a ‘Pillar’ represents the highest level of categorization of building intelligence/performance. There are two types of pillars defined in the IB Index Catalogue. The first type organizes the capabilities that conceptualize building intelligence components. The following three Pillars were defined in this group to support the whole life-cycle approach:

- Project Delivery (PD): it addresses all processes and practices’ specifications required for design and delivery of an intelligent building.
- Infrastructure, Devices, and Applications (IDA): it contains all building physical and virtual systems required for realizing an intelligent building.
- Controls, Monitoring, and Management (CMM): it includes all control & monitoring systems as well as management services required for effective operation, maintenance, and optimization of an intelligent building.

The second type of Pillars represents the impacts of building intelligence on the building performance and building occupants. In this group, the following pillars were defined based on the concept of triple-bottom line framework:

- Environmental: it shows the ways a building may impact the environment such as conservation of natural resources and waste generation.

- Economic & Fiscal: it addresses the building economic and fiscal impacts (during its lifecycle) related to the building stakeholders such as reduced delivery cost and savings on energy consumption.
- Social & Behavioral: it includes sociocultural and behavioral impacts on building users (e.g., tenants, occupants, visitors) such as increased occupants' productivity and comfort.

The second level in the building intelligence hierarchy is 'domain,' which was defined to provide a more detailed organization and classification of building intelligence capabilities. In addition, a "capability" is the most detailed representation of building intelligence. Capabilities aim to address all functions and characteristics of a system, technology, or service (identified as a domain). Finally, an "indicator" defines the levels of intelligence, maturity, or technology attainability for an intended capability. The IB Index Catalogue allows for up to five indicators for each capability (levels 0-4) to provide sufficient granularity for defining indicators. Figure 4.4 shows an example of a capability in the IB Index Catalogue.

Input Pillar: Project Delivery

Domain: PD-01 Project Planning & Specification

PD-01-PPS

CODE	CAPABILITY	DOMAIN										INPUT PILLAR				
PD-01-PPS-01	PPS-01 Integrated & Intelligent Design Program	PD-01 Smart Building Specification										Project Delivery				
LEVEL OF INTELLIGENCE INDICATORS		IMPACT/ OUTCOME PILLARS & DOMAINS														
		EFI-01 Reduced Project Delivery Time and Cost	EFI-02 Savings from Facility and Asset Management	EFI-03 Savings from Higher Water and Energy Efficiency	EFI-04 Increased Appraisal Value and ROI	EFI-05 Savings from Capital Expenditure	SBI-01 Increased Safety, Security, and Emergency Response	SBI-02 Increased Access to Information and Occupants Control	SBI-03 Increased Comfort and Convenience	SBI-04 Improved Equity, Diversity, and Inclusion	SBI-05 Increased Productivity, Health and Wellbeing	ENVI-01 Reduced Waste Generation	ENVI-02 Increased Use of Renewables and Grid Stability	ENVI-03 Efficient Use of Natural Resources	ENVI-04 Improved Environmental Impacts	ENVI-05 Increased Water Efficiency and Demand Control
level 0	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
level 1	Conventional design program	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
level 2	Integrated design program	+	0	0	0	+	0	0	0	+	+	0	0	0	0	0
level 3	Level 2 + incorporating owners' general/operational requirements specification	++	0	0	0	++	0	0	0	++	++	0	0	0	0	0
level 4	Level 3 + incorporating intended technology execution plans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.4. An example of a capability in the IB Index Catalogue

In addition, the capabilities and indicators were developed through an iterative process containing the following activities:

- Compare between capabilities to ensure that all aspects of a technology, practice, or system are addressed by the capabilities.

- Balance between generalizability and customizability of capabilities to achieve a globally adoptable standard. This means to provide a clear explanation for a capability and its indicators while avoiding being too descriptive in defining context-dependent terms and terminologies or including a specific technology solution that could be outdated or changed in the near future.
- Examine the logical hierarchical connection between capabilities and their domains to ensure that identified capabilities are categorized correctly and consistently.
- Use only one metric of measurement for each capability. This means to ensure that each capability is measuring and evaluating only one function of a system/technology. For example, the level of integration, automation, and interoperability of a Building Management System (BMS) must be evaluated by three separated capabilities.

4.1.3 *Context Comparison*

Since the IB Index is targeted at creating a global standard it is critical to ensure that it is usable in different markets. For this purpose, the research team conducted a context comparison analysis on the two countries that were involved in this research project namely Australia (AU) and United States (US) in order to find similarities and differences between their contexts. In this regard, the "context" is defined by the intelligent building market, AECO industries, and related professional communities in a country or region (e.g., North America). The results of the analysis indicated a discrepancy between the two contexts which may cause issues for applicability of capabilities and ultimately adoptability of the evaluation system.

In summary, the analysis consists of making comparisons between the two contexts in terms of domains, capabilities, and indicators of the IB Index Catalogue using various resources such as relevant industry standards/guidelines/technical reports published by public agencies and private organizations in each country, technology solutions and practices available in each market, and major local projects and initiatives related to intelligent building. As a result, a number of differences were identified in areas like intelligent building specification, electrical power supply, and physical/cyber security controls (see Appendix F for the full report). In addition, the following categorization was made based on the type and nature of the discrepancies:

- Terminology: difference in terms and terminologies used to specify similar concepts. For example, the document that determines Building Information Modeling (BIM) implementation requirements is called "BIM brief" in the AU and "BIM execution plan" in the US contexts.
- Framework: difference in processes and frameworks for articulation of a capability. For example, the AU and US contexts are different in terms of determining asset information requirements and associated standards. In addition, there is a difference between the framework of asset information specification and classification (e.g., UniClass and COBie).
- Evaluation: Conceptualization and evaluation criteria for a capability and its level of intelligence. For example, there are different components and evaluation criteria for information validation and verification planning in the AU and US contexts.
- Technology: difference in level of technology/system deployment and trends in the market. For example, the two markets are different in terms of the range of renewable energy sources (solar panels, biofuels, wind, etc.) and energy distribution systems adoptable for commercial intelligent buildings.

In response to the context discrepancies, different solutions provided by research studies such as adding, omitting, or adjusting criteria based on regional priorities, alteration and integration of the weighting system depending on location and project, and tailoring evaluation criteria by content and value (Suzer 2015). Based on the results of the analysis, the research team took several strategies to align and calibrate the IB Index Catalogue including revising the language of capabilities and indicators to ensure generalizable descriptions, transferring all specific technology examples from the IB Index Catalogue into the technical guidance, and planning for a flexible and customizable weighting system.

4.1.4 *Layers of Analysis*

The IB Index Catalogue was developed to capture all capabilities of building intelligence specifically with respect to emerging technologies. However, there are some elements which are not explicitly captured by any buildings or its systems attributes but are still considered as an element of building intelligence. Unlike several existing evaluation systems that include such elements as new capabilities, the IB Index addresses them as “layers of analysis” that is applied to the existing capabilities. Two examples of layers of analysis are explained below.

The first example indicates the capabilities that are dependent on an agent competency and performance. An agent may be a system operator, facility manager, or an O&M technician. An organization ability to leverage technologies for its intelligent building depend not only on availability and applicability of technology solutions but also on availability of skillful in-house staffs to implement technologies properly. Therefore, an agent qualification may affect the technology effectiveness as well as the correlation between the technology intended impacts and the building performance. This example of a layer of analysis also reveals the potential areas for process automation (i.e., replacing the manual agent-based workflows with automated AI-based workflows when applicable and beneficial).

The second layer of analysis indicates the capabilities that are dependent on/related to occupant behaviors. Some research studies (Burpee et al. 2016) have shown the relationship between occupant behaviors (regarding using the building spaces and services) and the building performance. Therefore, this analysis helps to determine the potential needs for tenants/occupants education (e.g., fostering pro-environmental behaviors) and building automation (i.e., replacing occupants-controlled equipment/appliances with centralized automated controls when it is applicable and beneficial).

The flexibility of the layers of analysis model is that new layers can be defined and added as the intelligent building market as technologies evolve. For example, the model can be used to identify capabilities that are related to intelligent space management and infectious diseases control, providing a layer of analysis capable of supporting the intelligence of a building response to epidemics and pandemics.

4.1.5 *Technological Artifact Model*

Emerging digital technologies are at the core of building intelligence. However, creating capabilities for technology assessment is a challenging task because it requires 1) a deep understanding of technical features of the technology and options provided by different vendors, and 2) a holistic understanding of the technology ecosystem, which supports integration between multiple technologies and synergetic benefits of it. Beside technical understanding about a technology, one should be able to translate that knowledge into quantifiable metrics for evaluation to avoid either double-counting or overlooking the technology elements that are contributing to the building intelligence. For example, showing that an IoT system is being implemented in a building and specifying its technical features are necessary but not sufficient to prove the building intelligence in that regard. The evaluation system should not only check the existence of the technology (e.g., a network of IoT sensors and gateways) but also it should determine the specific building systems leveraging that technology and the types of data that are fed into the IoT analytics system.

To properly create technology assessing capabilities, I developed the "technological artifact model" (shown in Figure 4.5) that provides a generic map of technology elements that require investigation and evaluation through the IB Index.

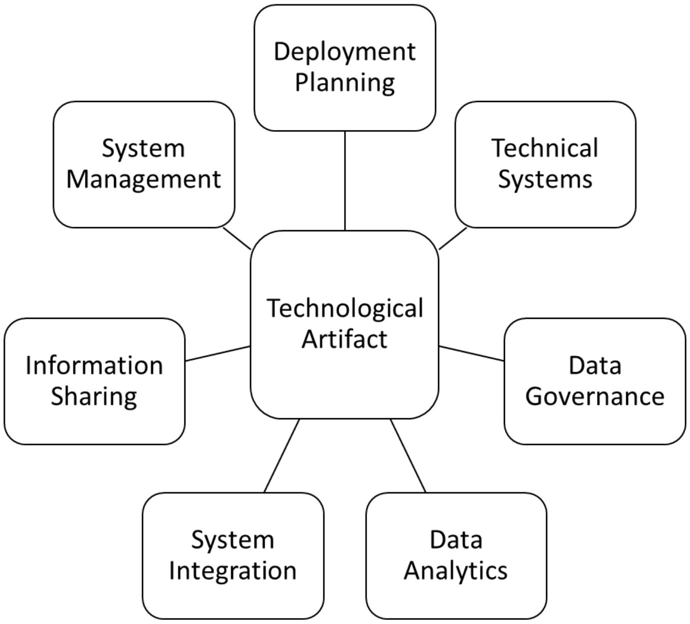


Figure 4.5. The technological artifact model

The seven elements of the model are briefly explained below:

- Implementation planning includes specification of programs, roadmaps for technology adoption, plans for physical/digital asset auditing and optimization, and standards for project delivery and owner requirements.
- Technical system discusses technical features of different options available in the market for purchasing a technology solution. A technical system may be a physical system, a

virtual/digital system, or a combination of both (e.g., an elevator system with its operation and fault detection software application)

- Data governance includes the processes for data collection, storage, validation & verification, exchange, and management.
- Data analytics refers to using computational methods (simulations, AI/ML, etc.) for analyzing data in digital systems mainly for data-driven system operation and decision-making as well as system performance analysis and prediction.
- System integration includes connection/communication between base building systems as well as connection to centralized virtual systems (e.g., BMS).
- Information sharing means visualization and communication of information (regarding buildings performance and services) with various stakeholders including tenants, visitors, facility operators, and owners.
- System management contains physical and virtual systems performance audit and base building systems operation control and optimization.

The technological artifact model was used to identify potential capabilities so that each element of the model may be translated into one or multiple capabilities for an intended technology. It also helped with understanding the type of capabilities, which assist with alignment and categorization of new capabilities in the ontology developed for the IB Index Catalogue.

4.1.6 *Weighting System*

In IB Index, the weighting system consists of two parts including 1. the impacts of building intelligence on the building performance, and 2. relative importance of the developed capabilities. Regarding the first part, the created building intelligence indicators had to be connected to the building performance criteria. To do this, the research team determined fifteen performance criteria categorized based on the building performance pillars (as shown in Table 4.1) by extracting reported benefits/intents of the given indicators from literature and formal evaluation systems and translating them into consistent non-overlapping criteria. In terms of weighting the capabilities' indicators, the system uses qualitative scoring (i.e., from 0, +, ++, +++, ++++ equivalent to the range of 1.0-2.0 with 0.25 intervals) to determine the impacts of each indicator. This scoring is to calculate the impacts of each domain of building intelligence (see Appendix B and C for more details).

Table 4.1. The building performance criteria

Domain	Criteria	Description
Economic and Fiscal	Reduced project delivery time and cost	Delivering the building project faster and with lower initial cost (e.g., through better collaboration, value engineering, and lower number of RFIs).
	Savings from facility and asset management	Reducing lifecycle cost especially O&M costs through proactive maintenance, building automation, and asset optimization strategies.
	Savings from higher water and energy efficiency	Reducing building utility costs by enhancing water and energy (thermal and electricity) efficiency.
	Increased appraisal value and ROI	Achieving higher asset appraisal value (based on better marketability and tenancy) and desired ROI for stakeholders.
	Savings from capital expenditure	Increasing cost savings and assets' added value due to better capital and financial plannings related to building retrofit and management.
Social and Behavioral	Increased safety, security, and emergency response	Increasing occupants' safety and security through better risk mitigation and utilizing advanced building management and emergency response systems.
	Increased access to information and occupants' control	Providing occupants with proper control over building systems and access to building information needed for better interactions with the building.
	Increased comfort and convenience	enhancing occupants' experience regarding level of comfort (thermal, visual, etc.) and convenience in the building.
	Improved equity, diversity, and inclusion	Improving EDI through better space accessibility and sharing as well as equal

		access to the building amenities (high-speed internet, smart appliances, etc.).
	Increased productivity, health and wellbeing	Supporting occupant health and wellbeing through better facility management (e.g., IEQ improvement and IWMS) and providing occupants' behaviors improvement program.
Environmental	Reduced waste generation	Reducing waste generation by better design and construction planning and applying proper waste management plan/technologies.
	Increased use of renewables and grid stability	Supporting grid integration and stability by deploying related technologies (e.g., DER and PV panels) and energy efficiency programs.
	Efficient use of natural resources	Enhancing use of natural resources through better design/construction planning and management and deploying intelligent building systems (e.g., HVAC and envelop).
	Improved environmental impacts	Improving the building environmental impacts by adopting and implementing related technologies (e.g., LCA tool) and plans (e.g., GHG emissions reduction).
	Increased water efficiency and demand control	Increasing water efficiency by applying DSM workflows and utilizing proper technologies like water reuse systems and water meters.

In addition, the second part of the weighting system aims to address the relative importance of capabilities because in each domain a capability may be more important than another meaning it has a more significant contribution to the overall building intelligence. For example, the capability that evaluates an energy management system is more important than the capability that examines the existence of a dashboard for visualizing building energy consumption. Therefore, in the weighting system, a number (as a weight) was assigned to each capability to represent its relative priority and importance (see Appendix G for the IB Index Scorecard that contains the capabilities' weighting coefficients). The research team initially determined the numbers (in the range of 1.0-2.0 with 0.25 as interval) based on the types of the capabilities and their contents (in order to ensure an alignment between the developed weighting system and findings about capabilities' impacts/importance extracted from the relevant literature and evaluation systems). Subsequently, the numbers were verified through interviews with subject matter experts (see Section 4.1.8 IB Index Validation for more information).

Although the developed weighting system has both default coefficients for capabilities and impacts coefficients for indicators it still has the flexibility to be customized based on the building type, regional priorities, project requirements, and users' needs. Such customizability depends on the evaluation system rating method too. In the self-evaluation method, the coefficients may be modified by the users. However, in the third-party certification model, the ability for customization is limited since all buildings must be evaluated using a constant benchmark and method of evaluation so that the result can be used by the market to compare between intelligent buildings (or between certified versus non-certified buildings). In this case, an effective solution for the issue is to create multiple versions of the weighting system (e.g., for different regions or types of buildings) so the users can select the right system for their projects.

4.1.7 *Neural Network Ontology*

In evaluation systems, the criteria are organized using an ontology that defines the logical hierarchy (of categories and sub-categories) and the relationships between the criteria. As discussed in the previous sections, IB Index organizes and classifies the capabilities based on a 4-level hierarchy. However, I replaced that structure with a neural network-based ontology in the later phases of the project. As a definition, a neural network data structure is used to map the complex relationships between buildings and their equipment, spaces, and actions (Willow 2020). This approach focuses on the relationships between the elements of a system (e.g., an intelligent building) rather than the hierarchical classification of the elements (e.g., UniFormat and MasterFormat) which has been the traditional approach in the AECO industry for categorizing building assets. In the context of evaluation systems, it gives the IB Index a unique advantage compared to other evaluation systems which is a dynamic and interactive user interface for the evaluation tool that allows for sorting, organizing, and visualizing the capabilities based on the end-users' needs. Such flexible ontology facilitates the use of IB Index as an effective decision-making tool. For instance, an end-user may want to evaluate building intelligence according to a specific base building system (HVAC, lighting, etc.) while another end-user may want to evaluate a specific technology before purchasing to understand its contributions to the building intelligence or its impacts on the overall building performance. Figure 4.6 demonstrates a conceptual visualization of the IB Index neural network ontology. In this figure, each color represents a different aspect of the building intelligence used to organize the building intelligence capabilities (the grey dots).

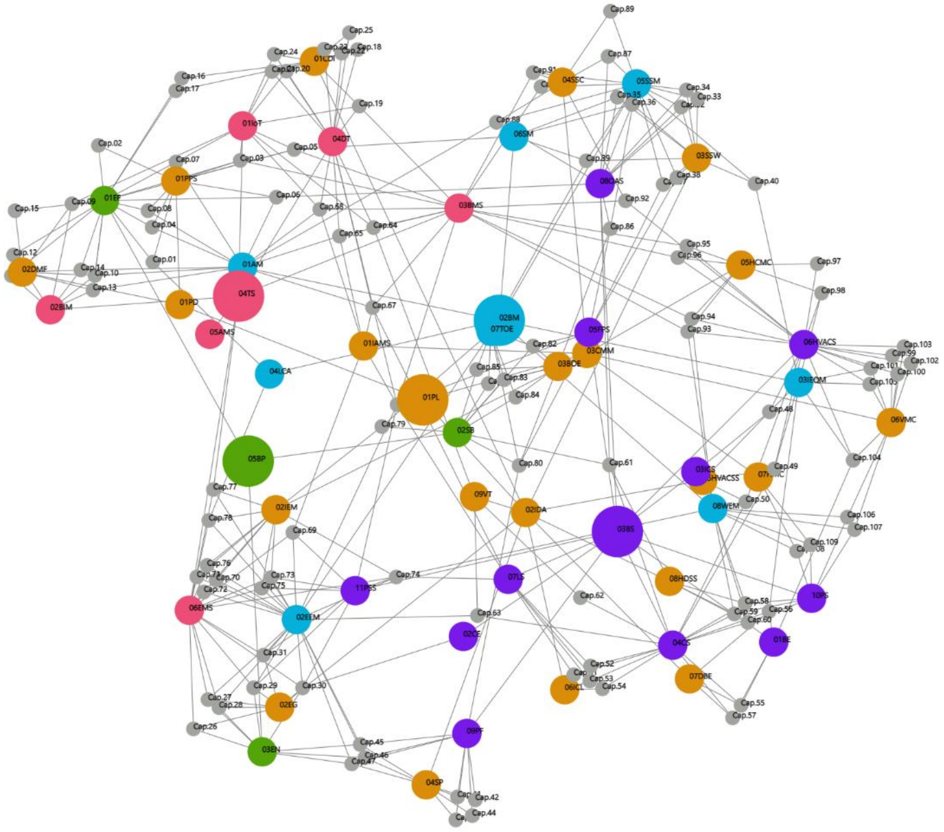


Figure 4.6. The IB Index neural network ontology

Accordingly, the ontology makes connections between the capabilities and the following five main aspects of building intelligence (these are in alignment with the non-human actors of the developed ANT model):

- Project Lifecycle organizes the capabilities based on their relevance to the phases of the project including the project delivery phase, infrastructure, devices, and applications installed during the construction phase, and controls, monitoring, and management activities take place during the operation phase (it was the original IB Index ontology)
- Building Management organizes the capabilities using their relations to the building managerial actions such as energy efficiency, safety and security, IEQ, space, tenants and occupants, asset, and water efficiency management.
- Building System organizes the capabilities based on their association with primary/base and secondary building systems such as communication, fire protection, HVAC, power supply, and conveying systems.
- Technology Solution organizes the capabilities depending on their connections to various intelligent building technology solutions like BMS/BAS, digital twins, IoT, EMS, CMMS, AMS, and BIM.
- Building Performance organizes the capabilities using their intended impacts on different building performance aspects including environmental, economic and fiscal, and sociocultural and behavioral.

The IB Index end-users may select each of the five options as an interchangeable mode to reorganize capabilities and review only the relevant capabilities at a time. As a clarification, in a UI designed based on this ontology, the categorization/organization of the capabilities changes however, the content of the capabilities and their indicators remains unchanged.

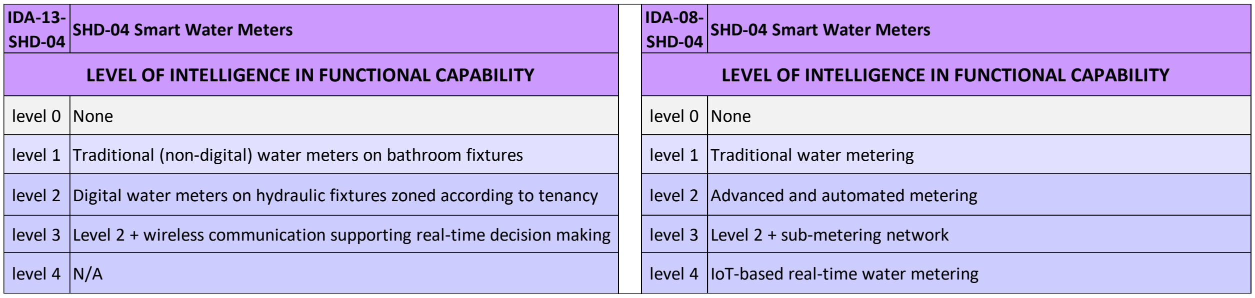
4.1.8 *IB Index Validation*

The last essential element of the IB Index framework is the validation of the developed Catalogue. This section explains the process of IB Index multiple revision and validation phases and the specific IB Index elements that have been validated through the process. In general, the research findings were validated through data triangulation (using mixed-methods research and comparing analyses to show consistency in results). Also, the IB Index was validated in terms of:

- Comprehensiveness of the Catalogue: to make sure that the Catalogue has addressed all components of the building intelligence (processes and workflows, technologies, best practices, and occupants’ interactions) and all aspects of them are being measured by the developed capabilities.
- Accuracy of the weighting system: to review and verify the weighting system regarding the coefficients given to the capabilities as their relative importance.
- Clarity of the catalogue and guidance: to verify the IB Index content (i.e., description of capabilities and indicators, and terminologies used in the Catalogue) in terms of clarity, sufficiency of explanations, and consistency of language to ensure the end-users can understand and implement the tool successfully.
- Independence of the capabilities: to make the capabilities inclusive but technology-neutral which means developing capabilities in a way that all relevant technology solutions are included by the indicators maturity level, but the requirements/metrics are not too prescriptive about using a specific system or technology solution (e.g., 4G/5G internet protocols). Also, to make sure that capabilities will still be applicable as technologies and intelligent building industry evolve.

- Effectiveness of the ontology: to verify the created dynamic ontology in terms of structure and hierarchy, naming of pillars/domains/capabilities, and the logical relationships between the capabilities and their domains/pillars.

The catalogue/guidance presented in the next section is the fourth version of the IB Index. The first revision of IB Index was based on the results of case study 1 and the context analysis. The major changes in this version (IB Index V.2) included revising terms and definitions and excluding several domains and capabilities from the Catalogue. IB Index V.3 was developed based on additional literature review and in-depth research on selected topics (using the technological artifacts model). Also, the dynamic ontology was created and applied to organize the IB Index capabilities in this phase. The Catalogue was validated through the case study 2 during which the capabilities were discussed with the subject matter experts. As a result, several domains and capabilities were merged and modified. Figure 4.7 shows an example of capability modification.



IDA-13-SHD-04	**SHD-04 Smart Water Meters**
LEVEL OF INTELLIGENCE IN FUNCTIONAL CAPABILITY	
level 0	None
level 1	Traditional (non-digital) water meters on bathroom fixtures
level 2	Digital water meters on hydraulic fixtures zoned according to tenancy
level 3	Level 2 + wireless communication supporting real-time decision making
level 4	N/A

IDA-08-SHD-04	**SHD-04 Smart Water Meters**
LEVEL OF INTELLIGENCE IN FUNCTIONAL CAPABILITY	
level 0	None
level 1	Traditional water metering
level 2	Advanced and automated metering
level 3	Level 2 + sub-metering network
level 4	IoT-based real-time water metering

Figure 4.7. An example of a capability modification

According to this figure, the following changes were made to the capability: shorten the indicators and providing the details in the guidance section, add the sub-metering system as a new indicator (which was suggested by a SME during the interviews), and replace the level 3 indicators' content with the equivalent consistent terminology (namely IoT-based) and remove the decision-making function from it since it has been addressed by another capability in the CMM pillar.

In addition, the weighting system was revised by comparing the information collected from the evaluated buildings and their intelligence/performance scores. Since sharing and verifying the research findings with research members and research subjects (e.g., interviewees) is a way to increase the data validity (Yilmaz 2013), another round of data validation was performed through 9 interviews (about half the interviewees participated in the case study 2 and half were new SMEs). During this phase, some capabilities were revised, and some explanations were added to the guidance to increase its clarity although no major changes were found needed (all minor changes were incorporated into IB Index V.4). Moreover, the capabilities' weights were validated by the interviewees. Overall, the coefficients given by the experts were in alignment with the existing numbers in the weighting system. One reason for discrepancies as raised by one of the interviewees was the issue that capabilities should be divided into mandatory and selective since some capabilities are not necessarily more important, but they may be considered as prerequisites for technologies and workflows addressed in other capabilities. Also, several interviewees confirmed that the capabilities' coefficients might change depending on the project type and origin and the weighting system could be flexible when the IB Index is used as a self-evaluation tool. Table 4.3 summarizes the revision and validation process of the IB Index.

Table 4.2. The process of IB Index Catalogue revision and validation

IB Index Version	Catalogue Information			Catalogue Modifications
	Domain	Capability	Indicator	
V. 1	30	221	663	-
V. 2	27	203	612	major changes in terms and definitions, 1 domain was deleted.
V. 3	18	105	344	major changes in capabilities and the ontology, 2 domains were added, 3 deleted, and 12 merged.
V. 4	18	109	361	minor changes in capabilities and definitions, no change in domains.

4.2 IB INDEX CATALOGUE AND GUIDANCE

The content of IB Index (i.e., the developed capabilities and indicators) is presented by the Catalogue which is currently composed of three Excel documents. The "project lifecycle" was selected as default ontology for organizing the capabilities so each Excel document contains one pillar and its domains. The current version of IB Index consists of 18 domains and 109 capabilities. Table 4.2 shows the pillars and domains.

Table 4.3. The IB Index Catalogue pillars and domains

Pillars	Domains	
1 Project Delivery (PD)	01 Project Planning and Specification (PPS)	02 Data Management Framework (DMF)
2 Infrastructure, Devices & Applications (IDA)	01 Communication and Data Infrastructure (CDI)	02 Energy Generation (EG)
	03 Safety, Security, and Well-being (SSW)	04 Smart Parking (SP)
	05 HVAC Systems and Sensors (HVACSS)	06 Intelligent and Connected Lighting (ICL)
	07 Dynamic Building Envelop (DBE)	08 Hydraulic Devices, Systems & Sensors (HDSS)
	09 Vertical Transport (VT)	
3 Controls, Monitoring & Management (CMM)	01 Intelligent Asset Management Systems (IAMS)	02 Intelligent Energy Management (IEM)
	03 Building Occupants' Experience (BOE)	04 Safety and Security Controls (SSC)
	05 Heating/Cooling Monitoring and Control (HCMC)	06 Ventilation Monitoring and Control (VMC)
	07 Hydraulics Monitoring and Control (HMC)	

Several concepts were used for creating many indicators of building intelligence. These concepts are intentionally selected for naming the indicators because they are frequently used by academic scholars and industry practitioners in articulating overall characteristics of intelligent buildings, paradigms of technology maturity and advancement, as well as diffusion of innovation in asset and facility management. This makes it easier for the IB Index users to understand capabilities and differentiate between the levels of indicators. On the other hand, these concepts could be misleading since they are generally used interchangeably with different meanings and in different contexts. Therefore, below are brief definitions of these concepts in the context of intelligent buildings, in general, and IB Index Catalogue, in particular.

Asset/Facility Management: IB Index uses asset and facility management as a general term including any managerial activity related to design, construction, operation, maintenance, and optimization of a facility asset throughout its lifecycle. Also, the term asset may refer to a range of entities from a single building system to a portfolio of multiple buildings. This definition is different from the typical definition of the facility management (FM) which mostly includes O&M activities during the occupancy phase of the building.

Physical and Virtual Systems: physical systems refer to different disciplinary equipment, devices, and physical elements in a building (e.g., HVAC and lighting systems). Also, virtual systems include digital technology solutions (e.g., BMS and FDD systems) implemented in a building. Moreover, technical systems are defined as the combination of physical systems, virtual systems, as well as digital devices used in a building (e.g., middleware, gateway, meter) that cannot be included in a specific building disciplinary system.

Interoperability: this concept refers to the ability of a system to communicate with other systems in a building in order to send and receive data. The end-user of the data may be a machine or human. Such ability is critical for intelligent building systems because on-time accessibility to reliable data can resolve many existing inefficiencies in facility management (CABA 2015). In IB Index, the concept of interoperability is used to describe the data/information exchange between two virtual systems as well as data transfer from digital devices (e.g., sensors and data loggers) into virtual systems. Various communication protocols (open and proprietary) and system architectures may be developed to enable interoperability between two or more systems.

Automation: IB Index Catalogue uses this term to convey the following meanings: 1. automating data interoperability (e.g., using BACnet as a standard communication protocol to automate data transfer between multiple devices), 2. automating implementation of existing tasks and workflows related to asset/facility management which are typically manual and agent-dependent, and 3. automating the process of data analysis and visualization (e.g., using machine learning techniques to detect patterns in a database and generating reports for the end-users automatically). Automation in intelligent buildings is achieved through integrating technical systems into a building automation tool.

Integration: in general, two entities can be integrated on a granular level (from a sub-system to an enterprise integration). However, IB Index considers two essential components for integration including connection and controllability. A two-way connection between two entities is a pre-requisite for their integration. This connection may happen in different forms such as communication between devices (e.g., actuators and occupants' mobile applications), data synchronization between systems, and electricity transmission between power sources (grid integration). Additionally, controllability means that there must be a system of systems (SoS like BMS or digital twin) that controls and manages the integrated system(s). This second component implicitly requires an integration between IT and OT systems as a foundation for other technical systems' integration.

Optimization: building optimization is the process of improving a building systems and performance (e.g., energy optimization) in comparison with the building current condition. The IB Index Catalogue uses this term specifically in referring to physical system re-configurations, long-term system modifications (e.g., technology upgrades), and building utilization enhancement in order to produce positive impacts on the building performance. In addition, optimization implies taking a proactive approach in making changes to assets to enhance its functionality and performance and to generate added asset value.

Demand analysis: the concept is defined in relation to consuming resources (e.g., water, electricity, and heating/cooling) and a user-defined level of building performance (e.g., lighting comfort). The real-time data collection from both building users and systems as well as data analysis are essential parts of identifying a building actual demand.

The following sections provide detailed explanations of capabilities and indicators of IB Index. Regarding the format of these sections, each pillar is discussed in a section that contains the domains of the pillar and under each domain, capabilities are articulated based on the “Capability Intent” and “Indicator Description”, while the capability intent is a sentence that explains the intent for including the capability in the evaluation system and the Indicator Description is a paragraph that aims to provide succinct descriptions and more contexts to the developed indicators. Also, the IB Index consists of various types of capabilities that are introduced as follows:

- Capability with progressive indicators: this is the standard and default type of capability. The indicators represent a level of maturity for the evaluated criterion based on a one- or two-dimensional logic. For example, a lighting control may be evaluated based on the level of automation or level of automation + level of coverage.
- Capability with accumulative indicators: in this case, a higher level/indicator consists of the previous level/indicator and an additional characteristic or requirement. For example, an asset management planning is evaluated from basic to advanced based on several characteristics each provided in an indicator. In this type of capability, the number of indicators may exceed the standard levels (0-4). Also, the order of indicators does not necessarily represent relative importance or advancement.

- Capability with rule-based indicators: this capability considers two rules for evaluation. The first one specifies the characteristic/requirement related to the evaluating criterion that is provided by the indicators. The second rule specifies cases/systems to which the capability applies. For example, the quality of a virtual system adoption plan is evaluated using the characteristics articulated by the indicators. Also, based on the second rule, the capability-required adoption plan must be applied to at least 50% of the intended virtual systems. In this case, the end-user needs to provide a list of all virtual systems they intend to adopt and implement in the building.

Defining different types of capabilities with different methods for assessing building intelligence enables building evaluators to accurately measure the depth and breadth of implementing technologies, leveraging data, and applying intelligent building best practices.

4.2.1 *Project Delivery*

This pillar is comprised of two domains:

4.2.1.1 Project Planning and Specification

This domain explains processes and plannings created at early stages of a project and are required for developing and maintaining an intelligent building during its lifecycle.

PPS-01 Integrated & Intelligent Design Program	
Level 0	None
Level 1	Conventional design program
Level 2	Integrated design program
Level 3	Level 2 + incorporating owners' general/operational requirements specification
Level 4	Level 3 + incorporating intended technology execution plans

Capability Intent: To evaluate developed design program in terms of responding to intelligent buildings’ lifecycle requirements and accommodating technologies that are intended to be deployed in the building.

Indicator Description: Building design program should be prepared collaboratively by the project team to address project main goals and needs. Level 1 refers to a conventional building design brief/program that specifies base building systems and the main design intent. It is mostly developed through a fragmented project delivery system, and it may not be reviewed by important stakeholders including facility managers and end users. Thus, it is subject to more design mistakes and ambiguities. Level 2 refers to an integrated and performance-based design program that defines performance goals for the building and applies different analysis and reviews (e.g., engineering, constructability, life-cycle cost, and energy analyses) to minimize discrepancy between designed and actual building performance. Level 3 improves integrated design program by incorporating owners and end-users' perspectives and requirements. This level needs a shared understanding about the intelligent building elements and life-cycle requirements. This design program enables project owners to effectively communicate their expectations from the project as well as their organizational standards for project delivery and building O&M to project stakeholders. Level 4 adds another layer of integration by identifying potential technologies to be adopted and implemented in the intelligent building, specifying how they improve the designed building systems, and ensuring that the developed design brief/program and the intended technologies' execution plans align properly. This level allows for any required changes in design and customization of purchasing technology solutions.

PPS-02 Project Delivery Systems	
Level 0	None
Level 1	Fragmented system
Level 2	Semi-integrated system
Level 3	Integrated system

Capability Intent: To ensure that the selected system for project delivery enables the project team to meet the project goals and requirements by having an effective collaboration and communication during the project delivery phases.

Indicator Description: in general, project delivery system refers to strategies for delivery (DBB, CMAR, IPD, etc.), types of procurement (lump sum, GMP, target price, etc.) and methods of selection (low bid, QBS, Best Value, etc.). The differences in project delivery systems are mainly due to phasing and sequencing (i.e., to determine each project stakeholder involvement in the phases of the project delivery process), roles and responsibilities (i.e., to define each project stakeholder roles and responsibilities for project delivery), and risk allocation and management (i.e., to identify most capable project stakeholder for managing each type of project risks and to determine how project risks/interests are allocated to project stakeholders). Accordingly, Level 1 refers to a traditional and fragmented approach to project delivery. The owner usually holds separate contracts with other project stakeholders and there is usually no or limited collaboration between different project stakeholders. Level 2 requires some integration in project delivery. In this system, project stakeholders (e.g., contractor and facility managers) have some involvement in the design phase and work together more collaboratively. Level 3 defines an integrated system in which the owner plays an active role in project delivery by taking risks and responsibilities to achieve higher efficiency and benefits in the long term. Also, all project stakeholders share project risks and interests.

PPS-03 Intelligent Technology Adoption Roadmap	
Level 0	None
Level 1	Separated technology execution plans
Level 2	Integrated technology execution masterplan
Level 3	Holistic roadmap for technology adoption
Level 4	Control program (with KPIs) to track progress and revise the roadmap

Capability Intent: To measure project team abilities and preparedness for successful adoption and implementation of technologies in intelligent buildings.

Indicator Description: a technology execution plan is defined as a document that contains the technology solution features/function, information of the technology provider, and any technical details specified by the project team related to the technology execution. Level 1 defines a conventional approach that investigates technology solutions separately. The project team may create several execution plans for technologies that it intends to use. Level 2 refers to creating a masterplan to achieve synergies between different technology solutions. The technology execution masterplan determines technical considerations for integrating multiple technologies and identifies benefits of using them in a specific combination (e.g., adopting an IoT network that is connected to a BMS). Level 3 defines a holistic roadmap for technology adoption that considers the project team organizational and managerial factors. It is comprised of several phases for adopting intended technologies along with goals, priorities for technology selection, and resources (time, budget, staff) related to each phase. Level 4 defines a tracking method with some KPIs to track the progress in the roadmap and make required adjustments.

PPS-04 Asset Management Planning	
Level 0	None
Level 1	O&M planning
Level 2	Level 1 + SAMP
Level 3	Level 2 + capital planning & decision making

Capability Intent: to evaluate organization life-cycle asset management planning and implementation.

Indicator Description: asset management consists of all strategies and approaches for managing (operating, maintaining, repairing, improving, etc.) physical and non-physical owner assets. Accordingly, level 1 refers to the more traditional approach towards asset management that is equal to facility operation and maintenance containing O&M work orders and facility critical services planning. Level 2 requires developing a Strategic Asset Management Plan (SAMP) that includes the owner goals, responsibilities, long term planning, and alignment between asset management and other organizational requirements (e.g., sustainability). Level 3 considers financial factors and risk assessment for asset management and includes asset management goals/requirements in the organization decision-making process.

PPS-05 Operation and Maintenance Strategy	
Level 0	None
Level 1	Reactive O&M strategy
Level 2	Preventive O&M strategy
Level 3	Performance-based O&M strategy

Capability Intent: to evaluate organization strategies for facility operation and maintenance

Indicator Description: level 1 is the conventional approach that an O&M work order is generated as a reaction to a system failure. While level 2 requires a proactive approach that aims to avoid system failures by utilizing pre-scheduled preventive O&M work orders. Level 3 provides a more efficient and lean approach by identifying the system condition and real-time performance and generating O&M work orders accordingly.

To be clear about what this capability measures, one should note that among different types of work orders, this capability considers work orders related to operation, maintenance, and repair of physical building systems. Therefore, the regular periodic work orders (such as cleaning and garbage removal) are excluded for this O&M strategy categorization.

PPS-06 Physical Systems Specification and Plan	
Level 0	None
Level 1	System characteristics and elements specification
Level 2	Level 1 + digital panel and interoperability specification
Level 3	Level 2 + commissioning guideline
Level 4	Level 3 + management and optimization plan

Capability Intent: to measure existence and quality of physical system plans and specifications to be used during the project life cycle.

Indicator Description: the indicators are defined through an accumulating approach which each level takes place in a phase of the project lifecycle. Level 1 requires detailed system design and specification that documents all system elements and characteristics. Level 2 refers to specification of data interoperability and how the intended system exchanges data with other building physical/virtual systems. Level 3 provides a guideline for commissioning (system testing, verification, and as-built documentation) before the project close-out. Level 4 defines a plan for periodic system condition assessment and strategies for better system management and optimization during its life cycle.

As a basic definition, building physical systems include Building Envelope, Commercial Equipment, Communication System, Conveying System, Fire Protection System, HVAC System, Lighting System, Operable Access System, Parking Facility, Plumbing System, and Power Supply System.

PPS-07 Virtual Systems Specification and Adoption Plan	
Level 0	None
Level 1	Technical features and functions specification
Level 2	Level 1 + use cases and best practices documentation
Level 3	Level 2 + roles and responsibilities determination
Level 4	Level 3 + management and optimization procedures

Capability Intent: to measure existence and quality of virtual/digital system plans and specifications.

Indicator Description: level 1 specifies all technical features of the system (in the user interface) that are available to the users. It also explains different functionalities of the system. Level 2 provides existing use cases for the system and best practices developed by peer organizations and system developers which lead to more efficient system utilization. Level 3 determines roles and responsibilities within the organization to operate, customize, maintain, and optimize the system. Level 4 defines procedures and plans for management and optimization of the system in coordination with the system developer and end users.

Building virtual/digital systems include but not limited to Internet of Things (IoT) analytics platform, Computerized Maintenance Management System (CMMS), Building Information Modeling (BIM), Integrated Workplace Management System (IWMS), Building Management System (BMS)/Building Automation System (BAS), Digital Twin, Fault Detection and Diagnosis (FDD), and Energy Management System (EMS).

PPS-08 Building Portfolio Evaluation & Management Plan	
Level 0	None
Level 1	Standard protocols and requirements
Level 2	Life-cycle planning
Level 3	Level 2 + training and supports for building users
Level 4	Level 3 + auditing and optimization plan

Capability Intent: to measure existence and quality of building portfolio management plans.

Indicator Description: level 1 refers to a standard plan for 1) identification of potential risks and demands related to the building systems, operators, and occupants, 2) specifying management protocols (e.g., performance KPIs) and responsibilities, as well as determining technical requirements (e.g., data analytics, incident response, best practices, etc.). Level 2 defines a lifecycle plan those positions portfolio management activities in different phases of the project lifecycle. Level 3 requires providing guidelines and training to building managers for proper implementation of protocols as well as providing training and education to building tenants/occupants for proper compliance of requirements. Level 4 defines a plan for audit and optimization of the developed strategies, protocols, and activities.

Building portfolio management includes Energy Efficiency & Management, Indoor Environmental Quality (IEQ) Management, Life Cycle Assessment (LCA), Safety & Security

Management, Space Management, Tenant & Occupant Experience, Waste Management, and Water Efficiency & Management.

4.2.1.2 Data Management Framework

This domain includes strategies and best practices related to using, governing, and managing data.

DMF-01 Information Management Plan	
Level 0	None
Level 1	System-based information management
Level 2	Organization data flow map
Level 3	Enterprise data management

Capability Intent: to evaluate the organization information exchange and management plan.

Indicator Description: information management plan aims to determine what and how information is being managed (management may refer to information sharing, accessibility, validation and verification, and governance). It covers all organization-based and project based that is being exchanged within an organization and between organizations. Level 1 is conventional system-based information management. In this approach each database is managed within the system that produces or receives information. This approach is usually associated with manual information exchange, significant need for information quality control as well as need for legacy information management. Level 2 requires an organization data flow map that identifies all data exchanged organizationally/inter-organizationally with data producer, data owner, data receiver, technical properties, and management protocol. This allows for more efficient data interoperability and creation of standardized and more reliable databases. Level 3 defines an enterprise data management approach that integrates hardware, software, data standards, and people for developing an unified database with a single information management protocol.

DMF-02 Specification and Use of Common Data Environment (CDE)	
Level 0	None
Level 1	Document based file sharing and information exchange

Level 2	Project-based conventional EDMS
Level 3	Partially integrated CDE
Level 4	Fully integrated life cycle CDE

Capability Intent: to promote the use and specify the characteristics of the Common Data Environment (CDE).

Indicator Description: level 1 refers to the traditional method of information exchange namely sharing physical documents. Level 2 requires some extent of digital information exchange (mostly project documents) using conventional Electronic Data Management Systems (EDMS). Level 3 is the start point of using the Common Data Environment as a single platform for data sharing and governance that is accessible by all project teams. The partial integration requires sharing and maintenance the most updated version of the critical project documents. Level 4 is the full integration to the CDE for access to the project documents and project teams' required information throughout the project lifecycle.

DMF-03 Data QA/QC Plan	
Level 0	None
Level 1	Data QA specification
Level 2	Level 1 + data QC technical procedures
Level 3	Level 2 + QA/QC workflow agreement

Capability Intent: to evaluate organization plan for data quality assurance and checking.

Indicator Description: access to reliable, accurate, and updated data is critical for the success of a project. For this purpose, the indicators are defined in a cumulative manner including level 1, specifying the data assurance by the owner and sharing the requirements by the project teams, level 2, creating a technical procedure by the owners to check the quality of data/documents received from the project teams, and level 3, an agreement on QA/QC workflow that determines QC milestones, roles and responsibilities, and QC review meetings.

DMF-04 Data QA/QC Automation	
Level 0	None

Level 1	Document-based data quality checking
Level 2	Digital agent-based quality checking
Level 3	Rule-based automated quality checking
Level 4	AI/ML-enabled quality checking

Capability Intent: To measure the level of automation in the Data QA/QC workflow.

Indicator Description: level 1 is the document-based quality checking (QC) during which a specialist reviews and verifies the quality of data received as physical documents or digital but not machine-readable documents. Level 2 refers to agent-based quality checking using digital tools. Although the QC tools provide some levels of automation, the whole process of data verification is performed manually by a specialist. Level 3 requires rule-based QC in which quality checking rules are defined by a specialist and the digital tool performs the quality checking on documents automatically. Level 4 refers to advanced emerging QC tools that employ artificial intelligence and machine learning (AI/ML) for data quality checking.

DMF-05 Asset Information Requirements & Specification	
Level 0	None
Level 1	Data attributes' requirements specification
Level 2	Level 1 + physical systems' information requirements
Level 3	Level 2 + virtual systems' information requirements
Level 4	Level 3 + organizational information requirements

Capability Intent: To ensure existence and completeness of specifications on asset information requirements.

Indicator Description: asset data has generally heterogeneous sources and includes a variety of data types. In this regard, level 1 specifies the basic asset data requirements including delivery of asset technical and spatial information. Level 2 considers basic asset information requirements along with the information requirements specific to each building physical system (it may include design information, building codes compliance, etc.). Level 3 adds the virtual systems information requirements (e.g., types and format of data that is entered into a digital twin or BMS platform). Level 4 defines additional information requirements specific to organizational data (e.g., financial and managerial information).

DMF-06 Asset Information Interoperability Standards	
Level 0	None
Level 1	Data repositories with proprietary formats
Level 2	Data repositories with standard classification schemas
Level 3	Level 2 + data repositories with open data standards

Capability Intent: to evaluate interoperability standards the organization uses for asset information exchange.

Indicator Description: data interoperability is a critical and potentially challenging task with significant impact on the project resources and performance. Therefore, it is important for project teams to use a shared standard for data interoperability. Level 1 refers to the traditional approach of using data repositories with Proprietary formats that is easy to use but provides limited compatibility with other formats and data platforms. Level 2 defines a standard classification schema (e.g., UniFormat, UniClass, and OmniClass/COBie) that identifies required data types, attributes, and formats based on the schema of databases in the intended virtual/digital systems. Level 3 promotes the use of open data standards that enables easier and more effortless information exchange between different data platforms.

DMF-07 Proposal Assessment During Bidding	
Level 0	None
Level 1	Descriptive and qualitative proposal evaluation of bidding proposals
Level 2	Qualitative and descriptive criteria for the proposed technical systems
Level 3	Level 2 + business proforma for the proposed technical systems

Capability Intent: to ensure that the owner has a proper proposal assessment mechanism that supports its intelligent building goals and plans

Indicator Description: Owners need to evaluate the quality of companies and their proposals against the intelligent building requirements during the bidding process. Accordingly, level 1 refers to a general descriptive and qualitative evaluation of the proposal (e.g., company experience with intelligent building in the past projects). Level 2 needs the owner to have some specific criteria (qualitative/descriptive) for evaluating the technical systems (both physical and virtual/digital). Level 3 adds the requirement of including a business proforma in the proposal (a quantitative analysis of the proposed technical systems with a rough estimate of LCC and expected ROI). It is important to note that the assessment required by this capability is in addition to the standard proposal evaluations and it focuses on the technological aspects of the proposed building physical and virtual systems.

4.2.2 *Infrastructure, Devices, and Applications*

This pillar includes the following nine domains:

4.2.2.1 Communication and Data Infrastructure

This domain contains technical requirements and specifications of the ICT system installed in an intelligent building.

CDI-01 Communication Network Infrastructure	
Level 0	None
Level 1	Separate cable networks
Level 2	Converged network infrastructure
Level 3	Universal Connectivity Grid (UCG)

Capability Intent: To evaluate a building communication network in terms of connectivity and available functionalities.

Indicator Description: the communication network is an important component in buildings since it provides the infrastructure for deploying intelligent building digital technologies and best practices. To define the quality of a communication network, level 1 refers to the traditional approach of separation between communication networks installed for different services (Wi-Fi system, access control, power, A/V system, LED lighting, etc.). While level 2 requires a converged cabling infrastructure that provides a more unified network capable of supporting different applications. Level 3 is achieved by using the universal connectivity grid that maximizes network scalability (based on actual demands), accessibility to users, and efficiency in terms of life cycle cost.

CDI-02 Communication Cabling Network Architecture	
Level 0	None
Level 1	Unstructured cabling design
Level 2	Structured cabling design
Level 3	Level 2 + standardized network components

Capability Intent: to evaluate a building communication network in terms of structure and design.

Indicator Description: design of cabling network (vertical/backbone and horizontal cabling systems and sub-systems) has a substantial impact on communication network maintenance and operational costs. Regarding cabling network maturity, level 1 refers to traditional unstructured cabling design. While level 2 refers to structured cabling design that provides a comprehensive communication network infrastructure with consistency in design of components of networks installed for different services. Level 3 requires level 2 and adds compliance with standards for installation and maintenance of cabling networks (cabling types and categories, system configurations, grid size, etc.) in intelligent buildings.

CDI-03 Integrated Communications Network Infrastructure	
Level 0	None
Level 1	Multiple proprietary communication networks
Level 2	A non-singular IP-based network designed to connect main building systems
Level 3	A single IP-based network designed to connect all technical systems

Capability Intent: to ensure building information and communication network infrastructure allows for integration between technical systems.

Indicator Description: level 1 describes the traditional approach for design of communication network infrastructure that consists of multiple proprietary communication networks (with different protocols and standards) added gradually to the infrastructure as different building systems are installed in the building. Level 2 aims to provide some level of integration by providing a communication network (non-singular IP) that enables integration between main building systems. Level 3 refers to a single IP communication network that allows for connection between all technical systems.

Technical systems include physical/digital building systems (lighting system, HVAC, operable access, security system, conveying system, fire protection, building envelope, etc.), devices (sensors, meters, etc.), and virtual systems (BMS, DT, FDD, AMS, etc.)

CDI-04 Level of Integration between Technical Systems (Quantity)	
Level 0	None
Level 1	Separate systems
Level 2	Partial integration between systems
Level 3	Full integration between systems

Capability Intent: To evaluate the integration of disparate technical systems for centralized control of systems and efficient use of resources.

Indicator Description: level 1 refers to having separate technical systems with limited and manual data exchange between them. Level 2 requires higher compatibility and interoperability between systems and technology solutions. To achieve this level, at least 40% of the building technical systems must be integrated. Level 3 refers to integration between all technical systems to create a single source of truth for all databases and systems. To achieve this level, at least 75% of the building technical systems must be integrated.

Although an integrated centralized system has many benefits, it may also have potential risks (e.g., increasing cyber security risks and life safety). Therefore, technical systems with sensitive data (e.g., access control and security systems) may be excluded from this capability evaluation if significant risks and technical issues are identified by the building owner.

CDI-05 Level of Integration between Technical Systems (Quality)	
Level 0	None
Level 1	One-way data interoperability
Level 2	One-way data interoperability and functions control
Level 3	Two-ways data interoperability
Level 4	Two-way data interoperability and functions control

Capability Intent: To evaluate the quality of integration between two virtual systems.

Indicator Description: the integration and connection between two systems (e.g., CMMS and DT) are not binary concepts and their quality can be defined by different levels. Accordingly, level 1 refers to a one-way data transfer (from one system to another without the ability to push back or share data). level 2 adds the ability to access and control features and functions of one system from another system user interface. Level 3 refers to a two-ways data transfer between systems (both sending and receiving data). Finally, Level 4 allows for both data accessibility/interoperability and functions control in the two systems.

CDI-06 IoT and Internet Connectivity	
Level 0	None
Level 1	Short range connectivity
Level 2	Long range connectivity
Level 3	Short + Long range connectivity

Capability Intent: to evaluate the existence of different wired and wireless connectivity protocols in a building.

Indicator Description: providing different ranges of connectivity in a building is critical to support successful deployment of technical systems. Level 1 refers to the existence of short-range connectivity options (e.g., Wi-Fi, Bluetooth, Zigbee, Z-Wave). Level 2 refers to the existence of long-range connectivity options (e.g., 3G, 5G, LTE, LMT-M, LPWAN, and NB IoT). Level 3 refers to the existence of long- and short-range connectivity options.

CDI-07 A/V Cabling and Interface	
Level 0	None
Level 1	Conventional A/V cables with proprietary interface
Level 2	High-definition A/V cables with proprietary interface
Level 3	High-definition A/V cables with single universal interface

Capability Intent: to evaluate the quality of audio/video systems.

Indicator Description: level 1 refers to conventional A/V cables (e.g., VGA, Coaxial, and RCA) with proprietary connection interface. Level 2 refers to high-definition A/V cables (e.g., HDMI and DVI) with proprietary connection interface. Level 3 refers to high-definition A/V cables (e.g., HDBaseT) which have a universal connection interface.

CDI-08 In-Building Wireless (IBW) System	
Level 0	None
Level 1	Macro Wi-Fi coverage
Level 2	Standard Wi-Fi cabling infrastructure
Level 3	Scalable IBW Solutions

Capability Intent: to evaluate existence and quality of the IBW system to support better wireless connectivity and coverage.

Indicator Description: level 1 relies only on Macro Wi-Fi and the building indoor spaces may not receive adequate network coverage. Level 2 provides in-building Wi-fi cabling infrastructure that complies with existing standards (mainly in terms of selected cable category). Level 3 requires in-building wireless solutions that are scalable based on the building demand. Current IBW solutions include Distributed Antenna Systems (DAS), Distributed Radio Systems (DRS), and Distributed Small Cells (DSC).

CDI-09 IoT Network Architecture	
Level 0	None
Level 1	Basic IoT platform
Level 2	Level 1 + middleware capabilities
Level 3	Level 2 + integrated connectivity
Level 4	Level 3 + ubiquitous computing

Capability Intent: to measure the quality and maturity of the building IoT network based on the evolving IoT features and functions.

Indicator Description: this accumulative capability aims to address the various elements of an IoT system architecture that would enhance its functionality. Level 1 describes a basic IoT platform containing the essential elements of an IoT network namely sensors, devices (hardware like processor and storage), application, actuators, and gateways if needed. Level 2 adds the utilization of middleware to facilitate big data governance, security management, and cloud services. Level 3 requires integrated connectivity that mainly unifies the information standards/protocols and methods of data transfer (e.g., a converged universal gateway) for a smooth connectivity between the IoT elements as well as the management enterprise solution. Finally, level 4 adds the feature of ubiquitous computing which is critical to real-time and constant data collection and processing in the intelligent buildings with a complex network of occupants and systems (producing data points).

CDI-10 Data Infrastructure Monitoring System	
Level 0	None
Level 1	Traditional monitoring system
Level 2	Proactive monitoring and management system
Level 3	Automated Infrastructure Management (AIM) system

Capability Intent: to ensure uninterrupted and high performance of data/communication network during its life cycle.

Indicator Description: Complexity of cabling and network architecture in smart buildings needs a system for monitoring and management of communication network infrastructure. In this regard, level 1 refers to a traditional monitoring system through which a technician monitors the communication network (usually once the system failed) to identify connectivity errors and data exchange challenges. Level 2 aims to provide a proactive approach by better documentation of the network architecture and maintenance manuals as well as continuous monitoring of network and generating reports to detect potential risks. Level 3 requires using the Automated Infrastructure Management (AIM) system that is an integrated hardware and software platform for automated real-time monitoring/management of cabling infrastructure, running network devices, and active ports/connections in a building.

4.2.2.2 Energy Generation

This domain specifies systems and equipment required for leveraging renewable energy and power distribution to ensure energy efficiency.

EG-01 On-Site Renewable Energy Production	
Level 0	None
Level 1	10% of TAEC
Level 2	25% of TAEC
Level 3	>50% of TAEC

Capability Intent: To evaluate on-site technologies and systems utilized for renewable energy production.

Indicator Description: the indicators are defined based on the question of what percentage of total annual energy cost (TAEC) in the building is covered by on-site produced renewable energy. This percentage is calculated using the following formula:

$$x = \frac{\text{(Equivalent) cost of onsite produced energy}}{\text{Total annual energy cost}}$$

The table below is used to determine the requirement of each indicator:

Indicator	Requirement
Level 1	X >= 5%
Level 2	X >= 10%
Level 3	X >= 15%

Systems and technologies used for onsite renewable energy production include but are not limited to Photovoltaic (PV) panels, in-building wind turbines, geothermal systems, and biofuels.

EG-02 Green Energy Procurement	
Level 0	None
Level 1	10% of TAEC
Level 2	25% of TAEC
Level 3	>50% of TAEC

Capability Intent: To ensure that building energy demand is procured from renewable sources.

Indicator Description: this capability promotes the use of green energy (energy generated from renewable sources) as a main source of energy in the building. To qualify for this capability, the building owner needs to hold an annual contract to procure a certain amount of energy from a local green energy provider (there is no minimum requirement regarding the distance between the energy generation site and the building location). The indicators are defined based on the following formula and table:

$$\mathrm{x} = \frac{\text{Total annual cost of purchased green energy}}{\text{Total annual energy cost}}$$

The table below is used to determine the requirement of each indicator:

Indicator	Requirement
Level 1	X >= 10%
Level 2	X >= 25%
Level 3	X >= 50%

The source of the green energy may be purchased from the competitive clean electricity market and does not need to be generated by a specific renewable source.

EG-03 Smart Energy Metering & Benchmarking	
Level 0	None
Level 1	Periodic energy metering
Level 2	Advanced and automated metering infrastructure
Level 3	IoT-based real-time energy metering
Level 4	Level 3 + sub-metering

Capability Intent: to evaluate a building ability to measure and benchmark its actual energy consumption.

Indicator Description: Traditionally, there has been a discrepancy between designed and actual building performance in terms of energy consumption and efficiency. Smart metering aims to fill this gap by identifying actual energy consumption in a building that helps owners for more effective energy management. To define a level of maturity for smart metering, level 1 refers to installing temporary energy meters in the building high load areas/systems to develop a portfolio for the building energy usage. Level 2 requires an advanced metering infrastructure that is defined as an automated two-way communication (between control center and end users) network of energy metering devices. Level 3 refers to using IoT technology for energy metering that enables an automated real-time system for energy usage data collection, storage, and analysis. Finally, level 4 adds the requirement of having sub-metering at the building system level which is a pre-requisite for developing an accurate portfolio for energy consumption.

EG-04 Energy Storage & Distribution	
Level 0	None
Level 1	Onsite-energy storage
Level 2	Distributed Energy Storage System (DESS)
Level 3	Dynamic grid integration

Capability Intent: To measure functionality and efficiency of energy storage and distribution system in a building.

Indicator Description: energy storage and distribution are critical parts of efficient energy management. Level 1 refers to the basic need for having a conventional energy storage system (e.g., electricity storage batteries and thermal energy storage) in the building to increase the security of energy supply. To meet the Level 2 requirement, the building must have systems such as distributed energy storage system (DESS) needed for using distributed energy resources (DER) as a source of energy (that could be controlled by a local micro-grid system) along with central sources of energy supply. Level 3 is based on the idea of smart grid integration and requires the building to have systems needed for distributing energy to adjacent buildings or back to the grid as well as grid stabilization.

EG-05 Uninterruptible Power Supply	
Level 0	None
Level 1	Manual back-up power
Level 2	Integrated UPS system

Capability Intent: To ensure consistent electricity supply for critical building systems.

Indicator Description: the uninterruptible power supply (UPS) includes electricity storage units, and power backup, stabilization and distribution systems. Level 1 refers to a conventional UPS system that needs to be regulated manually. While this UPS prevents building systems' shut-down and long interruption in services some data loss and system disturbances may still happen. Level 2 defines a system that is capable of automated disturbance-free electricity supply at the time of power outage. Other functionalities of the automatic UPS system include automatic main failures detection, BMS integration, and automatic voltage regulation.

There are different UPS systems such as standby off-line system, double conversion on-line, and Rotary system. The size, type, and capacity of the system is determined based on the building needs and is excluded from the UPS system intelligence assessment.

EG-06 Power Over Ethernet	
Level 0	None
Level 1	Conventional POE network
Level 2	Level 1 + LED lighting fixtures
Level 3	Level 2 + Wi-Fi access points
Level 4	Multi-purpose POE network

Capability Intent: To examine existence and functionalities of the Power Over Ethernet (POE) system in a building.

Indicator Description: Power over ethernet (POE) transmits both data and power using a distributed cable infrastructure. Level 1 requires a standard POE network that simplifies management of connected devices. Level 2 combines POE with LED lighting that uses distributed low voltage power and is considered as a high-performance and efficient lighting fixture. Level 3 refers to adding Wi-Fi access points to the POE network to provide better Wi-Fi coverage in the building. Finally, Level 4 defines a multi-purpose POE that uses one cabling network to serve multiple purposes including IP surveillance cameras, access control devices, and digital displays.

There are different types of POE cabling such as type 1 (PoE, 2-pair PoE), type 2 (PoE+), type 3 (4-pair PoE, PoE++, UPOE) and type 4 (higher-power PoE). Choosing the proper type depends on the connected devices and other building requirements.

4.2.2.3 Safety, Security, and Well-being

This domain determines technical systems needed for cyber and physical security and well-being of occupants inside an intelligent building.

SSW-01 Building Access Administration	
Level 0	None
Level 1	Discretionary access management
Level 2	Role-based access management
Level 3	Rule-based access management

Capability Intent: to evaluate the strategy for building physical access administration that fit the building safety and security requirements.

Indicator Description: In general, there are several approaches for administering building access control that are different based on complexity and the logic used for granting access permission. Even though these models are applicable to cyber-physical systems, access control, this capability measures the physical access administration only. Level 1 is discretionary access management which provides significant authority to the administrator to control and modify the level of accessibility given to building users. A drawback of this approach is that it is more difficult to manage the access level for different users consistently. It is also more vulnerable to unauthorized access. As a more restrictive approach, level 2 defines a role-based access management which provides access permissions to users based on their roles in the organization. In addition, level 3 uses pre-defined rules to determine the level of accessibility for users. This approach may be more accurate because different users with the same role may need different access privileges. Also, some building areas may require specific access controls regardless of the users' roles.

SSW-02 Access Control Integration	
Level 0	None
Level 1	Single non-integrated access control
Level 2	integrated access control network

Capability Intent: to evaluate the level of integration of the access control system used for interior doors and building entrances.

Indicator Description: the level of integration between access control devices is important since an integrated system makes the access management easier and allows for an on-time system response at the time of security breach. Accordingly, level 1 is based on having the access control units at each entrance/controlled door while these units are not interoperable. On the other hand, level 2 requires all access control units to be in a connected network which is integrated into a management system.

SSW-03 Access Control Systems	
Level 0	None
Level 1	Physical card/tag-based access control
Level 2	Smartphone/device-based access control
Level 3	Level 2 + multi-methods authentication

Capability Intent: to ensure that a right access control system is used for the building based on the building occupancy and security risks.

Indicator Description: there are various technologies used to confirm users' identity for the purpose of access control. Level 1 refers to having card readers at entrances. In this case, users use physical cards/tags as an access ID card. This option is not very secure due to the possible card theft and fake ID cards. Because of the security issues of the previous option, level 2 requires using electronic devices (e.g., smart phone applications) to check the user identity. This method is not ideal either because of increasing cyber-attacks. A more reliable solution is using a combination of methods for identity authentication. The methods for user identity control include but are not limited to physical cards, digital ID cards, two-factor authentication mobile apps, and biometrics devices.

SSW-04 Surveillance Systems	
Level 0	None
Level 1	Surveillance cameras at building entrances
Level 2	Surveillance cameras at strategic locations
Level 3	Integrated surveillance system
Level 4	Level 3 + real-time analytics system

Capability Intent: to evaluate the surveillance system needed for building safety and security.

Indicator Description: level 1 requires surveillance cameras at the building entrances which is used for a basic security checking. Level 2 aims to provide a higher level of security by installing cameras at any location that needs surveillance coverage. Level 3 requires integration between the installed surveillance devices and the building management systems (including access control system, safety and security system, and alarming system). Level 4 adds the data analytics capability to the surveillance system that allows for real-time analysis of surveillance footage and automated decision-making.

There are important ethical and sociocultural considerations regarding use of surveillance systems in buildings that facility managers need to take into account. The specific approach for balancing between protecting safety and security of the building occupants and respecting their privacy depends on each project circumstances.

SSW-05 Occupancy Detection System

Level 0	None
Level 1	People counting at the building entrances
Level 2	Occupancy detection at public spaces
Level 3	IoT-based occupancy detection network
Level 4	Level 3 + occupancy pattern and behavior tracking

Capability Intent: to measure existence and quality of occupancy detection system used for enhanced occupants' experience and building management.

Indicator Description: occupancy detectors are used in buildings for various reasons such as demand side management, access control, and emergency response. Facility managers need occupancy detection system with sufficient coverage to take full advantage of occupancy data. In this regard, level 1 refers to using traditional people counters at the building entrances. This approach can be used for a high-level analysis of total building occupancy (based on in/out numbers) including number of occupants at different times of the day and peak of occupancy. Level 2 requires occupancy detection at public spaces that enables a more accurate occupancy analysis since the total occupancy numbers are calculated for public spaces which should have different systems' configurations (e.g., in HVAC and access control systems) compared to other types of spaces in an intelligent building. To meet the level 3 requirement, an IoT network with occupancy sensors is required which is considered as a more sophisticated technology with two specific benefits including real-time occupancy analysis, and more customized occupancy data for different building spaces. Finally, level 4 adds the ability of detecting occupancy patterns and tracking occupant behaviors related to building usage.

In general, several occupancy detection technologies are available in the market including people counting devices, occupancy sensors (e.g., PIR, RFID, ultrasonic, acoustic based sensors), CCTV with image processing technology, and Wi-Fi-enabled detectors. This capability does not prescribe any specific solution as long as the requirements of the indicators are met.

SSW-06 Fire Prevention System	
Level 0	None
Level 1	Standalone smoke detectors
Level 2	Smoke detector network connected to fire control panel
Level 3	Level 2 + heat detectors
Level 4	Integrated fire prevention and suppression system

Capability Intent: to ensure that proper detection and control equipment exist in the intelligent building that provides fire safety and prevents indoor air pollution.

Indicator Description: level 1 is simply installing smoke detectors in the building. Level 2 ensures better coverage of fire safety system by requiring a network of smoke detectors in the building that is connected to the fire control panel. Level 3 adds heat detectors as an additional layer of fire protection. To comply with level 4, the fire detection and alarming system must be integrated into the fire suppression system which is typically achieved using an IoT network. Also, having a fire suppression system in the building is not enough to meet this capability requirements since installing fire sprinklers and extinguishers are mandatory by most building codes.

SSW-07 Carbon Monoxide Detection System	
Level 0	None
Level 1	Standalone carbon monoxide detectors
Level 2	Carbon monoxide detector network connected to gas control panel
Level 3	Integrated carbon monoxide detection system

Capability Intent: to ensure that proper detection and control equipment exist in the intelligent building that provides carbon monoxide safety and prevents poisoning.

Indicator Description: like the previous capability, level 1 is installing standalone carbon monoxide detectors in the building. Level 2 ensures better coverage of safety system by requiring a network of carbon monoxide detectors in the building that is connected to the gas control panel. Level 3 refers to an IoT-based carbon monoxide detection system integrated into the BMS.

SSW-08 Visitor Management System	
Level 0	None
Level 1	Analogue check-in/ visitor registration

Level 2	Digital visitors' registration application
Level 3	Integrated visitor registration and management system

Capability Intent: to measure the existence and quality of a visitor management system as part of the intelligent user experience and occupants/tenants' management.

Indicator Description: visitor management is a part of the occupants and tenants' management as well as space management in single/multi-tenants' intelligent buildings. In general, the maturity of a visitor management system is based on the ways visitor information is collected and utilized for management purposes. In this regard, level 1 refers to a basic analogue system (typically available at the building entrance) for visitors' registration. Level 2 uses a digital system which can be either administered or self-check in. In this case, the visitor data is mainly used for security/access management as well as sending notification to building occupants. Level 3 requires an integration between the visitor management and BMS which allows for using the visitor data for analytics used for more effective room bookings and space management, occupancy management, and relevant integrated workflows.

SSW-09 Indoor Environment Monitoring System	
Level 0	None
Level 1	Single IEQ element monitoring
Level 2	Multi IEQ elements monitoring
Level 3	IoT-based IEQ monitoring system
Level 4	Integrated IEQ monitoring system

Capability Intent: to evaluate the IEQ data monitoring system in terms of data acquisition comprehensive and technology advancement.

Indicator Description: Indoor environmental quality data has a critical role in intelligent facility management and performance optimization. Thus, this capability aims to define levels of advancement for an IEQ monitoring system. Accordingly, level 1 is a system that captures a single IEQ element while level 2 defines a system that can collect multiple IEQ elements. Level 3 requires an IoT-based system that enables real-time monitoring and customized IEQ data tracking for specific building zones. Level 4 aims to integrate the IEQ monitoring system to other virtual systems (mainly BMS) to use the collected data for all applicable analyses and decision making.

The IEQ elements include but are not limited to acoustics and noise pollution, air quality (odors, toxins, dust, carbon dioxide, etc.), temperature, VOCs, and humidity. The end user needs to determine what IEQ elements are considered for this capability evaluation.

4.2.2.4 Smart Parking

This domain provides specifications of availability and quality of parking and electric vehicle charging stations used by the intelligent building occupants.

SP-01 Parking Guidance System	
Level 0	None
Level 1	External parking signage
Level 2	External detailed parking signage (total counts + type of available lots, zones)
Level 3	Level 2 + internal signage and indicators

Capability Intent: to enhance usability of a parking facility by installing external and internal signage systems.

Indicator Description: digital signage systems tend to facilitate finding available car lots in a parking facility. Level 1 defines the minimum requirement as installing digital signage boards with current number of available parking lots at the parking entrances. Level 2 refers to installation of external boards that show detailed information including total number of available lots, types of available lots (e.g., compact vs. van vehicles) and their zones. Level 3 requires providing signage and empty parking lot indicators inside the parking facility.

SP-02 Unauthorized Occupancy Detection System	
Level 0	None
Level 1	Manual parking audit
Level 2	Automated detection system
Level 3	Integrated detection and reporting system

Capability Intent: To ensure safe and secure use of the parking facility.

Indicator Description: unauthorized use of parking facility or parking in the reserved areas is a current challenge that could be addressed more efficiently through deploying new technologies. Accordingly, level 1 set the minimum requirement as the traditional approach of having a person conducting daily manual parking auditing. While level 2 provides automated parking occupancy detection by implementing new technologies (CCTV cameras and image processing for vehicle detection, automated license plate reader, etc.). Level 3 requires the integration between the parking occupancy detection system and other building management systems for reporting unauthorized occupancy to facility managers and vehicle owners.

SP-03 Parking Payment System	
Level 0	None
Level 1	Manual payment
Level 2	Onsite vending machine
Level 3	At-gate payment system
Level 4	App-based payment

Capability Intent: To efficiently manage parking tickets payments.

Indicator Description: level 1 refers to the manual payment option that needs a person at the parking entrance for handling payment transactions while the next levels provide more automated and ticketless payment options. Level 2 requires installing vending machines inside the parking facility. While level 3 refers to a more secure option of having self-serving at-gate payment system.

SP-04 Parking Mobile Application Services	
Level 0	None
Level 1	Parking occupancy information
Level 2	Parking Booking Services
Level 3	Parking navigation services
Level 4	EV charging information

Capability Intent: to provide more flexibility and convenience to users and managers of the parking facility.

Indicator Description: Many activities related to parking usage can be done by mobile devices that provide more convenience to parking users and more control and trackability to managers. In this regard, this capability identifies four primary services that can be accessed through a mobile application including 1. parking occupancy information such as number of empty cars lots based on type of the vehicle, 2. booking services for reserving a parking lot or paying parking tickets (regular parking lots, electric vehicle car lots, disability parking spaces etc.) 3. parking navigation services like pathfinding feature to find an available car space based on car location or finding near exit/entrance door, and 4. access to current information of a parked electric vehicle and its charging status.

SP-05 On-site EV Charging Station	
Level 0	None
Level 1	Public EV charging pole
Level 2	Building designated EV charging Pole

Capability Intent: To promote using electric vehicles.

Indicator Description: providing accessible EV charging stations is a general indicator of intelligent buildings that contributes to multiple capabilities (e.g., energy efficiency). Accordingly, this capability requires access to on-site charging stations through either level 1 which is a public EV charging pole in the building parking facility or a nearby parking facility that is available to all building occupants or level 2 namely building designated EV charging pole that secures access for the building occupants.

SP-06 On-Demand Charging	
Level 0	None
Level 1	Dumb charging
Level 2	Dumb charging for set time
Level 3	Adaptive time charging

Capability Intent: To determine technical requirements for installed EV charging stations.

Indicator Description: level 1 refers to charging EC battery as it is plugged (aka. Dumb charging). More efficient options are described in next levels. Level 2 is dumb charging while charging station allows for setting a charging time while level 3 is adaptive time charging that includes setting charging station on/off based on collected information such as time duration and grid balance. It also provides more insights to electricity usage and charging costs.

SP-07 EV Charging capacity	
Level 0	None
Level 1	Low charging capacity
Level 2	Medium charging capacity
Level 3	High charging capacity

Capability Intent: To determine technical requirements for installed EV charging stations.

Indicator Description: This capability defines three levels of 1. low, 2. medium, and 3. high charging capacities to address different vehicles needs and charging efficiency in an EV charging station. To evaluate this capability, the exact capacity parameters (electricity voltage, charging speed, etc.) for the indicators are defined based on the local market and product options.

4.2.2.5 HVAC Systems and Sensors

This domain explains technical requirements for the HVAC system of an intelligent building.

HVACSS-01 Heating/Cooling Emission Control Equipment	
Level 0	None
Level 1	Thermostatic valves
Level 2	Digital controller
Level 3	BMS-integrated controller

Capability Intent: to ensure that the heating and cooling emissions of the HVAC equipment are controlled in order to minimize environmental impacts and maximize energy efficiency.

Indicator Description: heating and cooling emission is a typical issue in the HVAC equipment and contemporary HVAC systems have a controller to minimize the emissions. Accordingly, level 1 describes a HVAC system that uses the thermostatic valves to control heating/cooling. Although this may be sufficient for some buildings it usually does not provide the flexibility needed for intelligent buildings. To comply with level 2, the HAVC system should have a programmable digital controller which allows for adjustment of heating/cooling setpoints based on pre-determined factors. Level 3 requires a controller which can be integrated to the building BMS so that heating/cooling setpoints can be automatically adjusted based on the actual HVAC system performance and analyzed indoor air quality.

HVACSS-02 Air Flow Rate and Pressure Configuration	
Level 0	None
Level 1	On/Off time configuration
Level 2	Multi-stage configuration
Level 3	Automatic flow rate/pressure configuration

Capability Intent: to evaluate the HVAC equipment in terms of the controllability and configurability of the air flow rate and pressure.

Indicator Description: level 1 refers to the traditional HVAC device in which the air flow rate and pressure are adjusted by turning the air generator on and off. If level 1 is considered as a two-stage configuration, then level 2 requires a multi-stage configuration which provides more accurate adjustments. Finally, level 3 defines a HVAC system with automatic system configurability (using BAS) that adjusts the air flow rate and pressure based on the actual HVAC system performance and the analyzed indoor air quality.

HVACSS-03 Distribution Pumps in Network	
Level 0	None
Level 1	On/Off time configuration
Level 2	Multi-stage configuration
Level 3	Automatic speed configuration

Capability Intent: to evaluate the HVAC equipment in terms of the controllability and configurability of the distribution pumps.

Indicator Description: this capability is like the previous one except that it measures the HVAC system controller regarding the distribution pumps in the network. Accordingly, level 1 refers to the traditional HVAC device in which the air flow rate and pressure are adjusted by turning the air generator on and off. If level 1 is considered as a two-stage configuration, then level 2 requires a multi-stage configuration which provides more accurate adjustments. Finally, level 3 defines a HVAC system with automatic system configurability (using BAS) that adjusts the air flow rate and pressure based on the actual HVAC system performance and the analyzed indoor air quality.

4.2.2.6 Intelligent and Connected Lighting

This domain specifies features and functions of the lighting system of an intelligent building.

ICL-01 Lighting Control Coverage	
Level 0	None
Level 1	Floor level-based control
Level 2	Room-based control
Level 3	Zone-based control
Level 4	Fixture-based control

Capability Intent: to measure the controllability of the lighting infrastructure.

Indicator Description: the coverage of lighting control in this context refers to the FM team strategy for controlling a part of the lighting infrastructure separated from the other parts. Although this factor is not equally important in all types of buildings, having control over individual parts of the lighting system is generally preferred since it allows for better space, energy, and facility management. Accordingly, level 1 requires a control unit per floor, while level 2 requires lighting control for each room. Level 3 allows for controlling lights in different zones of a room (e.g., depending on distance to windows with natural lighting or areas with different types of lighting fixtures). Finally, level 4 needs each installed (set of) lighting fixtures to be controlled individually.

ICL-02 Lighting Control Automation	
Level 0	None
Level 1	Manual on/off switch
Level 2	Programmed control
Level 3	Automated single-factor control
Level 4	Automated multi-factor control

Capability Intent: to measure the level of automation in interior/exterior lighting control.

Indicator Description: related to the previous capability, another aspect of lighting control is the capability of turning lights on/off or dimming automatically based on the building and occupants’ real needs. Level 1 refers to the manual on/off lights switch that is used in typical buildings which does not offer any level of automation. Level 2 requires programmable lighting fixtures, so a semi-automated control is achieved by using the conventional BAS. Typically, a programmed control changes the lighting condition based on the time of the day (e.g., end of working hour in office and educational buildings). Level 3 and 4 require fully automated factor-based control which is defined as using a BMS to control lighting based on real-time changes in pre-determined factors (e.g., time, energy use, luminance, and occupants’ presence). Accordingly, level 3 needs a system that performs a single-factor control while level 4 needs a system capable of multi-factor control.

ICL-03 Lighting Control Flexibility	
Level 0	None
Level 1	Manual on/off switch
Level 2	Multi-illuminance level control
Level 3	Level 2 + multi-lighting fixtures controls
Level 4	Luminaire-Level Space Lighting Control (LLLC)

Capability Intent: to evaluate the installed lighting controls in terms of the level of controllability and flexibility of luminous flux.

Indicator Description: besides lighting controls coverage and automation, flexibility of lighting controls enables even more improvement of energy efficiency and occupants experience. In this regard, Level 1 is a manual switch that only turns light on and off. Level 2 provides the option of dimming the light. While level 3 adds the turning on/off and dimming controls for each group of lumens in a lighting fixture (this is applicable to lighting fixtures with multiple lighting arrays which is commonly used in commercial buildings). Moreover, level 4 encourages using LLLC which is a fixture-based lighting control solution that allows for incremental control at different luminaire levels.

ICL-04 Interior Lighting Fixtures	
Level 0	None
Level 1	Traditional lighting fixtures (non-LED)
Level 2	LED lighting fixtures
Level 3	Level 2 + dimmable lighting fixtures
Level 4	Level 3 + color tunable lighting fixtures

Capability Intent: to evaluate the in-use lighting fixtures in terms of quality, controllability, efficiency, and luminance.

Indicator Description: functions of the lighting fixtures is a pre-requisite for creating intelligent lighting control. Level 1 refers to the traditional lighting fixtures (e.g., incandescent, halogen, and CFL). Level 2 is LED lights that have higher overall lighting quality while consuming less electricity. Level 3 adds the dimmability and level 4 adds the color tunability requirements to the LED lighting fixtures.

4.2.2.7 Dynamic Building Envelope

This domain includes specifications of operable windows, shading, and other elements of an intelligent building envelope.

DBE-01 Shading System Control	
Level 0	None

Level 1	Manual operation
Level 2	Programmed operation
Level 3	IoT-based operation

Capability Intent: to examine the existence and quality of the shading system installed as part of the building envelop.

Indicator Description: a dynamic and intelligent building envelope (including shading and windows systems) may enhance many aspects of building performance such as thermal comfort (combining HVAC-based and natural ventilation), lighting comfort (combining artificial and natural lighting), and energy efficiency. This capability evaluates the method of controlling the shading system by defining level 1 as manual mechanical operation and control of system (a traditional approach). While level 2 is based on using a programmable shading system and digital control system that operate shadings by pre-determined setpoints. Then, level 3 is an IoT based operation that allows for automated operation of shadings based on real-time collected IEQ data.

DBE-02 Operable Windows Control	
Level 0	None
Level 1	Manual operation
Level 2	Programmed operation
Level 3	IoT-based operation

Capability Intent: to examine the existence and quality of the operable windows system installed as part of the building envelope.

Indicator Description: this capability is the same as the previous one except it evaluates the operable windows system in the building. Accordingly, level 1 refers to the manual mechanical operation and control of the system (a traditional approach). While level 2 is based on using a programmable shading system and digital control system that operate shadings by pre-determined setpoints. Then, level 3 is an IoT based operation that allows for automated operation of shadings based on real-time collected IEQ data.

DBE-03 Shading System Components	
Level 0	None
Level 1	Operable exterior shading system
Level 2	Level 1 + interior shading/blind system
Level 3	Level 2 + interior shading with adjustable spectral modes

Capability Intent: to evaluate the shading systems in terms of its components that contributes to better performance of the building.

Indicator Description: Level 1 simply requires that the exterior shading system be operable. Level 2 requires interior shading and blind system for windows. Additionally, level 3 adds the requirement that interior glass panels have a digital shading system with adjustable spectral modes for better control of lighting in the rooms.

4.2.2.8 Hydraulic Devices, Systems & Sensors

This domain contains technical requirements for the hydraulic system of an intelligent building to ensure water efficiency.

HDSS-01 Smart Flush Toilets/Urinals	
Level 0	None
Level 1	Automatic flushing based on proximity sensor
Level 2	Level 1 + low flow/ water efficient based on water sensors
Level 3	Level 2 + overflow protection
Level 4	Level 3 + built-in tank leak sensors with alert system

Capability Intent: to evaluate existence and quality of the toilets and urinals fixtures installed in the intelligent building.

Indicator Description: this capability describes different features of smart flush toilets and urinals that help with better water efficiency and management. Level 1 is toilets/urinals with automatic flushing. Level 2 requires low water flow devices with sensors to control water use. Also, level 3 requires devices with sensors to protect against water overflow. Level 4 adds the feature of using built-in sensors for detecting and alerting water leakage.

HDSS-02 Smart Faucets	
Level 0	None
Level 1	Automatic on/off based on proximity or touch sensor
Level 2	Level 1 + low flow/ water efficient use based on water sensors
Level 3	Level 2 + overflow protection
Level 4	Level 3 + built-in faucet and supply pipe leak sensors with alert system

Capability Intent: to evaluate existence and quality of the faucets installed in the intelligent building.

Indicator Description: this capability has indicators similar to the previous capability, but it evaluates smart faucet devices (e.g., basins and showers). In this case, level 1 is faucet with automatic water on and off. Level 2 requires low water flow fixtures with sensors to control water use. Also, level 3 requires devices with sensors to protect against water overflow. Level 4 adds the feature of using built-in sensors (installed on the fixtures and water supply pipes) for detecting and alerting water leakage.

HDSS-03 Smart Water Meters	
Level 0	None
Level 1	Traditional water metering
Level 2	Advanced and automated metering
Level 3	Level 2 + sub-metering network
Level 4	IoT-based real-time water metering

Capability Intent: to evaluate the extent and accuracy of the water metering network which is a pre-requisite for water consumption management in intelligent buildings.

Indicator Description: Level 1 is traditional water metering that mainly contains installing water meters (analog or digital devices) in main distribution pipes. Level 2 describes digital water meters that measure water consumption automatically and send data to the management system. Level 3 aims to increase the metering accuracy using a sub-metering network. Finally, level 4 is an IoT-based metering network that enables real time metering and reporting.

4.2.2.9 Vertical Transport

This domain provides specifications of smart lift, elevator and escalator systems and best practices for efficient use of them.

VT-01 Lift / Elevator Dispatching	
Level 0	None
Level 1	Conventional dispatching control
Level 2	Smart grouping system
Level 3	IoT-based dispatching
Level 4	Demand-based dispatching

Capability Intent: to evaluate the vertical transport dispatching control.

Indicator Description: dispatching control is the primary contributor to elevator intelligence because it significantly affects the elevators' performance (determined by factors like energy efficiency, waiting time, and user comfort). Level 1 describes the conventional control which means the lift/elevator is dispatched once a passenger uses its push button. As a more contemporary method, level 2 requires a smart grouping system which places passengers with similar destinations into a group and directs them to an elevator. For example, passengers may be directed to different evaluator(s) depending on whether they go to a floor with an even or odd number. Also, in high rise buildings, floors are divided into several groups and each group is covered by different elevator(s). This method can shorten the transport duration and reduce the waiting time. Level 3 requires an IoT network that collects passengers' number, location, waiting time, and congestion. The dispatching control uses the collected data for selecting the best dispatching model (among several programmed models) for the lifts/elevators. Finally, level 4 is demand-based dispatching that combines sensors' collected data with passengers' smartphones' data including calling elevators before arriving at the elevators lobby. This touchless system can also be used as an identity check for vertical transports' access control.

VT-02 Lift / Elevator power recovery

Level 0	None
Level 1	Power recovery with capacitor
Level 2	UPS-integrated power recovery
Level 3	Level 2 + smart grid integration

Capability Intent: to evaluate the vertical transport power recovery method in order to ensure their uninterrupted operation and the safety of passengers.

Indicator Description: power recovery mechanism is an essential capability of vertical transports. In this regard, level 1 is using built-in capacitors for power recovery. While level 2 needs lifts/elevators that can be integrated to the buildings UPS units. Level 3 adds the elevators' capability of feeding the stored/excessive power back to the building power grid.

VT-03 Lift / Elevator Energy Consumption	
Level 0	None
Level 1	Conventional vertical transport
Level 2	High-performance vertical transport
Level 3	Level 2 + demand-based operation

Capability Intent: to assess vertical transports in terms of energy efficiency.

Indicator Description: Level 1 refers to conventional lifts/elevators which won't lead to tangible energy savings. Level 2 is high-performance vertical transports. such higher performance is achieved through using equipment that minimizes energy consumption as well as using the energy recovered from an elevator counterweight. Also, level 3 leads to higher energy efficiency by requiring a program for design and operation of the vertical transport system in the building containing a combination of multi-capacity and multi-speed lifts/elevators that are dispatched based on the actual building demand and optimum energy efficiency.

4.2.3 *Controls, Monitoring, and Management*

This pillar contains the following seven domains:

4.2.3.1 Intelligent Asset Management Systems

This domain articulates specifications of virtual systems and workflows for long-term facility and asset management.

IAMS-01 Use of Data Analytics	
Level 0	None
Level 1	Statistical modeling and simulation methods supporting data analysis
Level 2	Level 1 + AI-based platform supporting building operation
Level 3	Level 2 + using ML for pattern detection and performance prediction
Level 4	Level 3 + knowledge-based capital planning and asset optimization

Capability Intent: to measure the technical requirements for leveraging data analytics in operation, management, and optimization of an intelligent building.

Indicator Description: data driven decision making is one of the key components of building intelligence. To leverage data during the project lifecycle, asset and facility managers need proper data analytics technology. This capability addresses different elements of advanced data analytics that are applicable to the intelligent buildings. In this regard, level 1 refers to having a technology solution that is capable of performing typical data analytics methods applied to asset/building databases including statistical data modeling (e.g., historical data of asset O&M and energy consumption) and building simulations. Level 2 is the use of AI for automating tasks and generating decision options related to operation of the building physical systems. Level 3 is the use of ML for enhancing facility management (e.g., energy management, space management, occupants management) specifically through detecting patterns of building usage and predicting the systems' performance. Finally, level 4 requires that the data analytics platform be used for capital planning (e.g., facility expansion and retrofit) and asset optimization (e.g., extending asset life span and improving its performance).

IAMS-02 Asset & Facility Management Technology Stack	
Level 0	None
Level 1	Single-purpose technology solutions

Level 2	Multi-purpose technology solutions
Level 3	Interoperable and integrated technology stack
Level 4	Enterprise technology solution

Capability Intent: to evaluate the strategy for adoption and implementation of technology solutions in an intelligent building.

Indicator Description: various technology solutions are available for intelligent buildings. Facility managers may purchase technologies organically based on an immediate need but ideally, they have a systematic plan for deploying a set of technologies to generate added values for their assets. This capability defines the level of maturity for strategic technology acquisition. Level 1 refers to the traditional approach of purchasing different technology solutions to address different issues in asset/facility management separately (e.g., using a CMMS software for managing O&M work orders and an EDMS tool for sharing and governing asset specifications). Level 2 is using technology solution(s) (e.g., some contemporary BMS/BAS applications) that has merged several single-purpose tools' features and functions and can be used for multiple related purposes to minimize technical challenges associated with the traditional approach. Level 3 requires the asset managers to develop a technology stack for their building containing a set of interoperable and integrated technology solutions that (in a combination) cover all building needs for virtual systems. Level 4 aims to promote using an enterprise technology solution (e.g., a digital twin solution) that serves as a virtual infrastructure allowing for creating, adding, and customizing needed functions and services.

IAMS-03 Integrated Workflows	
Level 0	None
Level 1	Emergency response and recovery
Level 2	Level 1 + fault detection and diagnostics
Level 3	Level 2 + safety and security management
Level 4	Level 3 + resource supply management

Capability Intent: to ensure that technological infrastructure is available for achieving integration between different building operation and management workflows.

Indicator Description: integrated workflows is defined as using virtual systems to integrate between two or more technical workflows of building operation and management which leads to higher synergy and added values for the building stakeholders. The given indicators articulate the most critical integrated workflows that an intelligent building should implement, and the accumulative capability aims to ensure that acquired technology solutions are capable of performing such workflows. Level 1 is emergency response and recovery. To meet this level requirement, a virtual system should be able to integrate between the following systems: fire prevention, natural disaster response, access control, occupant alarming and notification, as well as relevant physical systems (e.g., vertical transportation). Level 2 refers to fault detection and diagnostics which aims to identify and resolve physical system failures while minimizing the consequential impacts. To do this, the intended physical system should be connected to a BMS/BAS system as well as space/occupants management system and other impacted physical systems (depending on the types of system failure). Level 3 is called safety and security management and requires integration between several physical and virtual systems including safety, physical/cyber security system, access control, occupants' management, and alarming systems. Finally, level 4 refers to resource supply management which means enhancing management of resources (electricity, thermal energy, water, etc.) by integrating relevant physical systems (e.g., HVAC and building envelop) and virtual systems (e.g., EMS and BMS), and devices (e.g., IoT network and meters).

IAMS-04 Maintenance of Physical Systems	
Level 0	None
Level 1	Performance and efficiency monitoring
Level 2	Preventive O&M

Level 3	Life-Cycle asset optimization

Capability Intent: to measure the physical systems' monitoring and maintenance approach and to ensure its alignment with the facility strategic asset management plan.

Indicator Description: physical systems' required technical specifications and monitoring/control practices are addressed in other domains. This capability discusses overall strategy for physical systems' operation monitoring, maintenance, repair, and system improvements. Accordingly, level 1 requires monitoring the performance and efficiency of physical systems and reporting the results to facility managers. While level 2 is preventive O&M meaning that physical systems' O&M work orders are generated automatically using systems' condition assessments. Level 3 defines a life-cycle asset optimization that optimizes or replaces a physical system based on the analyzed performance of the building.

IAMS-05 Maintenance of Virtual Systems	
Level 0	None
Level 1	Sufficient technical features/functions
Level 2	Level 1 + integration and interoperability control
Level 3	Level 2 + performance tracking and optimization

Capability Intent: to measure the virtual systems' monitoring and maintenance approach and to ensure its alignment with the technology adoption roadmap.

Indicator Description: This capability discusses overall strategy for physical systems' operation monitoring, maintenance, repair, and system improvements. Accordingly, level 1 aims to perform periodic checking to make sure that available virtual systems provide all technical features and functions required to fulfill the goals asset/facility managers defined at the time of system acquisition. Level 2 adds the requirement of controlling integration and interoperability between the technology solutions added to the intelligent building technology stack over time. Any identified issue needs to be addressed to ensure smooth operation of the virtual systems. Moreover, level 3 requires tacking of virtual systems’ overall performance and plan for system optimization as needed.

4.2.3.2 Intelligent Energy Management

This domain provides strategies for systems needed for ensuring energy efficiency during the building operation and maintenance.

IEM-01 Energy Demand Prediction	
Level 0	None
Level 1	Historical data analysis
Level 2	Building energy simulation
Level 3	AI-based demand prediction

Capability Intent: To evaluate a building mechanism for predicting energy consumption as a basis for energy management.

Indicator Description: Level 1 refers to using building as-designed data and historical energy consumption data as a high-level benchmark for future energy usage. While level 2 requires the computer-aided building energy simulation. The simulation must be based on the as-built model as well as actual installed systems and occupancy information. Level 3 leverages AI-based data analytics that finds patterns in collected energy consumption data and uses them for prediction of energy demand.

IEM-02 Energy Efficiency Monitoring & Management	
Level 0	None
Level 1	Manual energy auditing
Level 2	Conventional energy management systems
Level 3	Integrated EMS
Level 4	DSO-based monitoring and management

Capability Intent: To evaluate implemented system for monitoring and management of building energy efficiency.

Indicator Description: Level 1 is periodic manual energy audit that targets certain building systems (usually HVAC) for auditing. The audit must be conducted by a third-party energy auditor. Level 2 on conventional energy management system (EMS) for more automated monitoring and management. Level 3 requires an integration between EMS and other virtual systems such as BMS as well as relevant physical systems to apply needed system configurations according to results of energy monitoring. Level 4 adds an external layer of monitoring and management based on inclusion of distributed system operator (DSO) in connected grid management and distributed energy resources facilitation.

IEM-03 Energy Performance Optimization	
Level 0	None
Level 1	Systems auditing and commissioning
Level 2	Level 1 + parametric performance optimization
Level 3	Level 2 + occupants training program
Level 4	Level 3 + system automation

Capability Intent: to evaluate implemented strategies to optimize the building energy performance.

Indicator Description: Level 1 refers to a conventional energy commissioning conducted by a third-party auditor. It consists of selecting critical physical systems for commissioning and providing recommendations for possible optimizations. Level 2 requires a parametric performance analysis that defines and examines energy performance parameters and produces optimization alternatives. Level 3 addresses the impacts of occupant behaviors on building energy performance and requires a training program to promote pro-environmental behaviors. Level 4 aims to achieve optimized performance of physical systems (e.g., lighting and HVAC) through automation of systems operations and set-points adjustments based on real-time building demand and system performance data analytics.

IEM-04 Energy Performance Evaluation & Visualization	
Level 0	None
Level 1	Energy consumption records

Level 2	Energy portfolio evaluation
Level 3	KPI-based evaluation

Capability Intent: To evaluate the approach for evaluating, visualizing, and reporting the building energy performance.

Indicator Description: Level 1 refers to using energy consumption records (e.g., electricity bills) to track changes in energy consumption and making an approximate performance evaluation based on previous records and available market benchmarks. Level 2 uses the building energy portfolio for better understanding of energy consumption sub-groups and a more detailed performance evaluation. Level 3 defines key performance indicators (KPI) related to energy use (e.g., energy cost, high-performance devices' life cycle cost, comfort level, etc.) to address different aspects of energy efficiency.

IEM-05 Demand Side Management	
Level 0	None
Level 1	Demand response program
Level 2	VPP Integration

Capability Intent: To evaluate the involvement of the building in demand side management (DSM) initiatives.

Indicator Description: Level 1 requires participation in a demand response program (operated by government agencies or eligible private companies). The goal of such programs is to make a balance between energy demand and supply in a region and better manage energy loads during peak times. The program may define rules for energy usage and provide time-based energy tariffs. Level 2 defines the use of Virtual Power Plant (VPP) for demand side management. In general, VPP is a network of decentralized, medium-scale power resources (e.g., wind turbines, solar panels, CHP units, biogas, hydropower, fossil steam, diesel engines) as well as consumers' distributed energy resources. In the context of demand response, VPP helps participants to trade their generated power on the energy market and get access to data analytics capabilities and real-time data for better demand prediction and management.

IEM-06 Building Energy Portfolio Development	
Level 0	None
Level 1	Basic energy portfolio
Level 2	Level 1 + on-site renewables inclusion
Level 3	Level 2 + DER inclusion

Capability Intent: to evaluate the comprehensiveness of the building portfolio developed for energy consumption.

Indicator Description: Level 1 is a basic energy portfolio that contains the main categories of energy end-users. This portfolio must determine the amount of energy use by the following categories: lighting, space heating, space cooling, refrigeration, water heating, ventilation, electronics, and kitchen. To qualify for Level 2, the portfolio should also report the amount of energy used from the energy resource(s) including onsite/offsite renewable energy sources. Level 3 requires the inclusion of Distributed Energy Resources (DER) in the portfolio as other sources of energy generation and consumption.

IEM-07 Grid Integration System	
Level 0	None
Level 1	Micro-grid off-line integration
Level 2	Grid on-line integration
Level 3	DSO-based grid integration

Capability Intent: To examine the building systems' ability of grid integration that allows for better demand side management in an individual building as well as the whole community.

Indicator Description: Level 1 refers to integration between building distributed energy resources (DER) to a local grid that is disconnected from the main power grid. A micro-grid integration controls and manages DERs and make balance between interconnected systems. Level 2 requires the connection between building energy resources and local controllers to the main power supply systems. It increases grid stability/resiliency and allows more consumers benefit from grid integration. Level 3 refers to grid integration managed by a distributed system operator (DSO). Grid integration enables two-way electricity transmission between power distributor and consumer energy resources. Distributed energy resources include generators, solar panels, power storage systems, electric vehicle chargers, heat pumps.

IEM-08 Energy Fault/Fraud Detection	
Level 0	None
Level 1	Conventional energy auditing
Level 2	FDD-based fault/fraud detection
Level 3	Level 2 + DSO-based fault/fraud detection

Capability Intent: to evaluate building strategies and solutions for detecting energy faults and frauds in the building.

Indicator Description: Level 1 refers to conventional energy audit that aims to identify discrepancies between expected and actual energy usage and track the potential energy faults (unexpected and unintentional energy uses in the form of energy leakage and waste) and frauds (unauthorized energy uses in the building) using the audit results. Level 2 refers to use of Faults Detection and Diagnostics (FDD) systems for more accurate and automated faults/fraud detection and resolutions. Level 3 requires the involvement of Distributed System Operator (DSO) as an external source for buildings energy consumption analysis and management.

IEM-09 Smart Appliances/Devices Control	
Level 0	None
Level 1	Device-specific control
Level 2	Device control by central hub

Capability Intent: to evaluate appliances and electric devices used in the intelligent building in terms of their connectivity and controllability.

Indicator Description: in general, the term “smart” is related to efficiency (in terms of energy consumption) and controllability of the electric appliances and devices (permanently used in the building). This capability measures the devices' controllability by two indicators. Level 1 refers to the embedded control features in a single device which is usually different from the other devices (from different brands). While level 2 requires using a central hub compatible with different devices for connecting and controlling them.

IEM-10 Carbon Footprint Reduction Program	
Level 0	None
Level 1	Carbon footprint data collection and monitoring
Level 2	Carbon footprint reduction initiatives
Level 3	Carbon footprint optimization

Capability Intent: to measure the existence and quality of program and action plan for reducing intelligent building carbon footprint.

Indicator Description: there are various tools and technologies that are implemented in a building to reduce its environmental impact, specifically carbon footprint. To achieve this goal, level 1 requires collecting and monitoring the data of the building carbon footprint which can be used to identify and potentially reduce the sources of greenhouse gas emissions in the buildings. Level 2 is engaging into a carbon footprint reduction initiative. To meet this requirement, the facility owners/managers may develop an internal initiative or participate in an existing public/private supervised program. Also, level 3 is carbon footprint optimization which employs a technology solution to analyze the building performance regarding carbon footprint and develop strategies for decreasing production of greenhouse gasses and minimizing the building environmental impacts (e.g., green roof with reused water irrigation system).

4.2.3.3 Building Occupants' Experience

This domain includes specifications of amenities and controls provided to intelligent building occupants to optimize the user experience.

BOE-01 Occupancy Data Analytics

Level 0	None
Level 1	Occupants' health and wellbeing
Level 2	Performance evaluation
Level 3	Demand Side Management
Level 4	Building systems controls

Capability Intent: To identify uses of building occupancy information in building performance analytics and decision making.

Indicator Description: collection and analysis of historical/real-time data of building occupancy and occupant information is an important part of performance evaluation and decision making in intelligent buildings. This capability identifies main use cases for occupancy data analytics: 1. Occupants' health and wellbeing that allows for connecting room occupancy information with indoor environmental quality data for facility management purposes as well as feeding data into personalized health and wellbeing tracking systems, 2. performance evaluation naming use of total number of occupants and their distributions for more accurate space, water, and energy consumption/efficiency analyses. Also, the detected pattern of occupancy is used for improving space planning and management, 3. Demand-side management including monitoring room/space occupancy for in-depth analysis of current/future building demands as well as HVAC and other related building systems' performances, and 4. access control based on connecting occupants' information and their location with access control databases to identify any unauthorized physical access.

BOE-02 Building Dashboards & Portals (Content)	
Level 0	None
Level 1	Single-purpose portal/app
Level 2	Multi-purpose portal/app

Capability Intent: To examine building intelligence regarding information sharing with building occupants.

Indicator Description: An important aspect of intelligent building is to provide occupants with reliable information about their workspace or common areas they occupy. For this purpose, different types of physical dashboards, internal web-based portals, or mobile apps may be used. This capability defines single-purpose and multi-purpose levels of maturity for dashboards/portals based on information they can share with occupants. The relevant information varies based on building types but generally includes indoor environmental quality (IEQ), Visitor management, parking and electric vehicles information and booking services, wayfinding and emergency notifications, building performance (e.g., energy and water consumption), space occupation schedules, and tenant directory.

BOE-03 Building Dashboards & Portals (Accessibility)	
Level 0	None
Level 1	Interactive building dashboard
Level 2	Room-designated interactive dashboard
Level 3	Level 2 + web-based portal and mobile application
Level 4	Level 3 + personalized portal and mobile application

Capability Intent: to examine building intelligence regarding information sharing with building occupants.

Indicator Description: besides evaluating content of occupants’ portals and dashboards, they should meet certain requirements in terms of accessibility and flexibility of options. In this regard, level 1 requires installation of interactive physical dashboards in building common areas. While level 2 requires dashboards designated for each room (although these smaller dashboards may be used for sharing occupancy data and booking services). level 3 refers to adding a web-based portal or mobile application that is accessible to occupants for receiving information and managing available building features and services). Finally, level 4 needs the portal/app to be connectable to occupants’ personal accounts such as email and calendar as well as room settings (related to building automation controls) for more convenience and data integration.

BOE-04 Safety & Emergency Alarms	
Level 0	None
Level 1	Safety notifications through physical signage/dashboards
Level 2	Safety notifications in personal devices
Level 3	Level 2 + generic wayfinding
Level 4	Level 3 + location-based wayfinding

Capability Intent: To evaluate buildings regarding safe/secure emergency response and disaster management.

Indicator Description: There are various ways for occupants' communication and guidance in the time of emergency and disaster. Level 1 refers to a more traditional way which is providing life safety notifications to occupants through physical signages and dashboards. Level 2 explains a more advanced approach that needs sending notifications to occupants' mobile devices. Level 3 adds the feature of wayfinding by showing a map of available routes and exit doors in the app. Level 4 requires an app that uses device GPS to help occupants with safe wayfinding based on their locations.

BOE-05 Space Occupation and Room Booking	
Level 0	None
Level 1	Manual room booking system
Level 2	In-place room booking devices
Level 3	Online room booking system
Level 4	Level 3 + Hot Desking

Capability Intent: to evaluate building efficiency and intelligence in terms of space management.

Indicator Description: level 1 refers to the conventional and manual room booking system in which a building operator needs to manage room booking requests that occupants submit. Level 2 defines leveraging in-place self-serving room booking devices (e.g., room dashboards) that are connected to real-time room schedules database. Level 3 is an online room booking system (e.g., occupants' internal portal) that allows for in-advance booking of public spaces and multiple rooms which leads to more efficient account management. Level 4 expands the level 3 capability to personal rooms/spaces which means a workspace can be shared between multiple occupants (hot-desking) by linking and managing the intended workspace and occupants' schedules.

BOE-06 Building Systems Controls	
Level 0	None
Level 1	Lighting fixtures
Level 2	Heating and cooling
Level 3	Room ventilation
Level 4	Internal and external shading

Capability Intent: to examine building capability of customizing services and functions based on occupants' needs

Indicator Description: an intelligent building should give occupants control over building certain functions, systems, and services. While different building systems are monitored and controlled by building management and automation systems, there should be flexibility in changing some default features based on occupants' needs and preferences. The main systems that should have this capability include 1. Lighting fixtures, 2. heating and cooling systems, 3. ventilation system (operable windows and HVAC system), and 4. Internal and external shading.

BEO-07 Digital Artwork	
Level 0	None
Level 1	Fixed digital artwork
Level 2	Interactive digital artwork
Level 3	Level 2 + information sharing

Capability Intent: To promote appealing and livable work environments.

Indicator Description: digital artworks can be used as a platform for improving social aspects of a building and a workspace performance. Accordingly, level 1 simply requires the existence of fixed digital artworks in the building common areas. Level 2 needs digital artwork to be interactive that gives some controllability to occupants. As addressed in level 3, a digital artwork can also be used to share information (social events, company news, etc.) with occupants.

4.2.3.4 Safety and Security Controls

This domain explains virtual systems and best practices required for safety, security, and well-being of an intelligent building occupants.

SSC-01 Emergency Communication and Alarm System	
Level 0	None
Level 1	Alarm and emergency lighting system
Level 2	Basic central alarming system
Level 3	Advanced central alarming system
Level 4	Integrated alarming system

Capability Intent: to ensure existence and quality of communication and alarming systems at the time of emergency.

Indicator Description: Emergency conditions may happen in buildings due to in-building life safety incidents (fire, hazardous materials leakage, etc.), natural disasters, and security threats (intrusion, burglary, etc.). Communication and alarm system is a critical part of a safety and security response program. The maturity of such a system is defined based on level 1 activation of the alarm and emergency lighting system at the time of incident without connection to a central management system. A more advanced approach is use of a central alarming system which is a safety/security alarming station outside the building facility. Such a system provides multiple services including 24/7 safety and security monitoring, occupants’ notification, path-finding system, and automatic fire/police departments notifications. Levels 2 and 3 are defined as basic and advanced central alarming systems based on the specific services provided. Finally, level 4 requires an integration between the alarming system and other building technical systems such as access control, fire/gas control systems, and vertical transport system.

SSC-02 Security Monitoring and Control	
Level 0	None
Level 1	Unauthorized access/occupancy detection
Level 2	Level 1 + real-time automated monitoring of security measures
Level 3	Level 2 + security incidents' response and recovery

Capability Intent: to evaluate the features and functions of the monitoring and control system used for security of building occupants.

Indicator Description: the indicators are defined in an accumulative manner to add the following features of a security monitoring and control system: 1. detection of unauthorized access or occupancy that may be associated with a physical security threat, 2. using an integrated management system for real time and automated monitoring of pre-determined security measures, and 3. Implementing an action plan for security incidents' response and recovery.

SSC-03 Physical Systems' Safety Monitoring and Control	
Level 0	None
Level 1	Building systems failure detection and reporting
Level 2	Level 1 + real-time automated monitoring of safety measures
Level 3	Level 2 + safety incidents' response and recovery

Capability Intent: to evaluate the features and functions of the monitoring and control system used for safety of building physical systems.

Indicator Description: this capability is the same as the previous capability while its focus is on ensuring the safety of buildings' systems (e.g., HVAC and hydraulic systems). The indicators are defined in an accumulative manner to add the following features of a monitoring and control system: 1. detection and reporting of building systems' failures that raise a safety threat, 2. using an integrated management system for real time and automated monitoring of pre-determined safety measures, and 3. Implementing an action plan for safety incidents' response and recovery.

SSC-04 Cyber Security Automation	
Level 0	None
Level 1	Manual systems' monitoring by security technicians
Level 2	Automated cyber security monitoring and alerting system
Level 3	Enterprise Security Management System

Capability Intent: to measure the level of automation of the in-use cyber security system.

Indicator Description: a cyber security system may consist of different basic to advanced functionalities. However, users often focus on the functionalities and neglect the level of automation the cyber security system provides for utilizing its functions. Therefore, this capability measures the automation of the cyber security system in an intelligent building by defining three indicators. Level 1 refers to the manual monitoring and management of building virtual systems performed by a cyber security technician. While level 2 requires the system to utilize some security monitoring and management functions automatically. Also, level 3 promotes higher levels of automation by using Enterprise Security Management (ESM) which standardizes the process of risk identification/mitigation and the framework for automated utilization of security policies.

Since the need for automating cyber security functions are determined depending on the building and occupants, this capability does not prescribe any specific security measures/functions to be automated as the minimum requirement for the indicators but to meet the capability requirements, the level of automation for the intended functions must be assessed and reported.

SSC-05 Cyber-Security Monitoring and Control	
Level 0	None
Level 1	Firewall and cyber-attack protection
Level 2	Level 1 + local and remote access control
Level 3	Level 2 + account/identity management
Level 4	Level 3 + secure information exchange

Capability Intent: to define the critical features and functions of an intelligent cyber security monitoring and control system.

Indicator Description: Level 1 is firewall and cyber-attack protection which is the basic requirement for safety of the virtual systems. Level 2 adds a system for monitoring and control of local (in-building) and remote accessibility to electronic devices and virtual systems in a building. Also, Level 3 adds another layer of protection by using a unified account and user identity management system to be used in all relevant applications and cloud environments. Level 4 requires secure methods for information access and exchange between different devices and users.

SSC-06 Cyber Security Coverage	
Level 0	None
Level 1	Basic coverage for cloud-based and local databases
Level 2	Level 1 + building technical systems
Level 3	Level 2 + occupants' electronic devices
Level 4	Level 3 + power grid networks

Capability Intent: to evaluate the level of coverage of the in-use cyber security system.

Indicator Description: another intelligence aspect of a cyber security system is to determine what electronic device, networks, and virtual systems it covers and protects. In this regard, this capability identified the following items as high priority for coverage by the cyber security system: 1. cloud-based and local proprietary databases, 2. building technical systems including both physical and virtual systems, 3. Electronic devices of the building permanent occupants, and 4. Building power grid networks including both power consumers and generators.

4.2.3.5 Heating/Cooling Monitoring and Control

This domain explains specifications of monitoring and control procedures required for heating and cooling system operation and maintenance.

HCMC-01 Heating/Cooling Emission Control	
Level 0	None
Level 1	Central control for all area
Level 2	Zone-based control
Level 3	BMS-enabled zone-based control
Level 4	Level 3 + real-time monitoring

Capability Intent: to evaluate the approach of HVAC heating and cooling emissions control in order to minimize environmental impacts and maximize energy efficiency.

Indicator Description: Level 1 refers to having a central system to control HVAC heating and cooling emissions throughout the building. Level 2 aims to increase the HVAC system performance by defining a certain control configuration for each zone of the building. Level 3 requires using a BMS that allows for leveraging data analytics and adjusts the HVAC control setpoints accordingly. Level 4 adds real-time monitoring of related building conditions and the HVAC performance (through an IoT system) for achieving the most accurate system controlling and optimization.

HCMC-02 Chilled Water Distribution Control	
Level 0	None
Level 1	Manual control (fixed setpoint)
Level 2	Schedule-based control
Level 3	Demand-based control

Capability Intent: to evaluate the approach of HVAC chilled water distribution control to ensure water and energy efficiency.

Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC chilled water distribution. Level 2 means having scheduled setpoints defined for automatically adjusting the distribution control (based on times of the day, historical data of chilled water usage, etc.). Level 3 refers to controlling the water distribution based on the actual measured demand of the building.

HCMC-03 Distribution Pumps Control	
Level 0	None
Level 1	Manual control
Level 2	Variable capacity control
Level 3	Load-based control

Capability Intent: to evaluate the approach of HVAC distribution pumps control to ensure energy efficiency and optimum performance of the equipment.

Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC chilled water distribution. Level 2 means having a distribution pump system with variable capacities (idle pump is activated in the distribution network only when needed) to increase the HVAC equipment life span. Level 3 refers to controlling the water distribution based on the actual measured demand of the building.

HCMC-04 Heating/Cooling Distribution Control	
Level 0	None
Level 1	Manual control
Level 2	Schedule-based control
Level 3	Load-based control

Capability Intent: to evaluate the approach of HVAC heating/cooling distribution control to ensure energy efficiency and enhanced thermal comfort.

Indicator Description: Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC heating/cooling distribution. Level 2 means having scheduled setpoints defined for automatically adjusting the distribution control (based on times of the day, historical data of heating/cooling needs, etc.). Level 3 refers to controlling the heating/cooling distribution based on the actual measured demand of the building.

HCMC-05 Thermal Energy Storage (TES) Operation Control	
Level 0	None
Level 1	Fixed-rate storage control
Level 2	Schedule-based storage control
Level 3	Demand-based storage control

Capability Intent: to evaluate the existence of thermal energy storage connected to the HVAC system and the approach of its operation control.

Indicator Description: Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the TES system. Level 2 means having scheduled setpoints defined for automatically adjusting the operation of the TES (based on times of the day, historical data of thermal energy usage, etc.). Level 3 refers to controlling the TES operation based on the actual measured demand of the building (based on the combined thermal and electrical energy consumption). This capability is only applicable if the intelligent building uses a TES system connected to the HVAC system.

HCMC-06 Heating/Cooling Generator control	
Level 0	None
Level 1	Manual control (fixed setpoint)
Level 2	Schedule -based control
Level 3	Demand-based control

Capability Intent: to evaluate the approach of HVAC heating/cooling generator control to ensure energy efficiency and enhanced thermal comfort.

Indicator Description: Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC heating and cooling generator. Level 2 means having scheduled setpoints defined for automatically adjusting the generator control (based on times of the day, historical data of heating/cooling generation needs, etc.). Level 3 refers to controlling the generator based on the actual measured demand of the building.

4.2.3.6 Ventilation Monitoring and Control

This domain provides specifications of monitoring and control procedures required for ventilation system operation and maintenance.

VMC-01 Supply Air Flow Monitoring/Control	
Level 0	None
Level 1	Manual control (fixed setpoint)
Level 2	Time-based control
Level 3	Occupancy-based control
Level 4	Demand-based control

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC supply air flow. Level 2 means having predetermined setpoints defined for automatically adjusting the supply air flow (based on times of the day, historical data of air flow rate needs, etc.). Level 3 refers to controlling the supply air flow based on the occupancy of the building (configuring HVAC system for vacant and occupied areas). Level 4 aims for higher efficiency through applying a demand analysis that considers more factors (e.g., real time IAQ data) to calculate the actual building demand.

VMC-02 Exhaust Air Flow Monitoring/Control	
Level 0	None
Level 1	Manual control (fixed setpoint)
Level 2	Time-based control
Level 3	Occupancy-based control
Level 4	Demand-based control

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: this capability is like the previous one except that it is related to the HVAC exhaust air flow. Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC exhaust air flow. Level 2 means having predetermined setpoints defined for automatically adjusting the exhaust air flow rate (based on times of the day, historical data of exhaust air flow rate needs, etc.). Level 3 refers to controlling the exhaust air flow based on the occupancy of the building (configuring HVAC system for vacant and occupied areas). Level 4 aims for higher efficiency through applying a demand analysis that considers more factors (e.g., real time IAQ data) to calculate the actual building demand.

VMC-03 Indoor Air Temperature Monitoring/Control	
Level 0	None
Level 1	Variable-capacity control
Level 2	Time-based control
Level 3	Demand-based control

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: this capability is like the previous one except that it is related to controlling indoor air temperature. Level 1 is manual control meaning that a fixed setpoint is used to turn on/off the HVAC heating/cooling ventilator. Level 2 means having predetermined setpoints defined for automatically adjusting the air temperature (based on times of the day, historical data of indoor air temperature needs, etc.). Level 3 refers to controlling the air temperature based on the occupancy of the building (configuring HVAC system for vacant and occupied areas). Level 4 aims for higher efficiency through applying a demand analysis that considers more factors (e.g., real time IAQ data) to calculate the actual building demand.

VMC-04 Indoor Temperature Adjustments	
Level 0	None
Level 1	Manual adjustment
Level 2	IoT-based automated adjustments
Level 3	Level 2 + occupants’ control

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: an important factor of an intelligent HVAC system is its capability for adjusting the system default load/performance in order to make a balance between system automation and user controllability. In this regard, level 1 is manual adjustment which means that the system operator can re-adjust the HVAC setpoints (mostly air temperature setpoints). Level 2 refers to the approach of maximizing the system automation through a BMS/BAS that adjusts HVAC systems automatically using an IoT-based IAQ data collection and analysis. Level 3 requires the same capability while providing occupants with the ability to control the indoor temperature by overriding the HVAC setpoints.

VMC-05 Supply Air Controlling Approach	
Level 0	None
Level 1	All-area fixed setpoint
Level 2	Zone-based variable setpoints

Level 3	Room-based variable setpoints

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: a way of improving the HVAC system efficiency is to use variable setpoints for operating the HVAC system in different building areas so that the system load can be configured based on the actual building demand. For this purpose, the indicators are defined as follows: level 1 refers to using fixed setpoint for all building areas, level 2 is using variable setpoints for different building zones, and level 3 provides more system flexibility by using variable setpoint for different building rooms.

VMC-06 Heat Recovery Control	
Level 0	None
Level 1	Manual heat exchanger control
Level 2	IoT-based automated heat exchanger control

Capability Intent: to measure monitoring and controlling capabilities of the HVAC system needed to achieve optimum efficiency, indoor air quality, and thermal comfort.

Indicator Description: this capability assumes that an intelligent HVAC equipment has a heat recovery system. Accordingly, the level of maturity is defined in two levels including level 1 controlling the heat recovery using a manual heat exchanger and level 2 using an IoT-based system that allows for leveraging data analytics and automated control.

VMC-07 Building Free Cooling System	
Level 0	None
Level 1	Manual configuration
Level 2	Scheduled free cooling
Level 3	IAQ-based free cooling

Capability Intent: to improve system performance and energy consumption by combining natural and HVAC-based space cooling.

Indicator Description: an intelligent HVAC device should be used as a support for the building natural cooling system (including operable windows, louvers, heat sinks, etc.). In this case, the indicators are defined based on the approach for combining the two natural and artificial cooling systems. Level 1 is manually overriding the HVAC configuration at time that natural cooling is being used. Level 2 is adjusting the HVAC cooling based on a time schedule (mostly night cooling). Finally, level 3 is using the real-time collected IAQ data to decide on combining artificial/natural systems.

VMC-08 IAQ Performance Evaluation & Visualization	
Level 0	None
Level 1	Basic IAQ performance visualization
Level 2	Advanced IAQ performance visualization
Level 3	Level 2 + analysis & optimization

Capability Intent: to increase transparency about the actual HVAC system performance and to plan for its optimization.

Indicator Description: the evaluation and visualization of the IAQ data are generally used to increase awareness among the facility managers and occupants. In this regard, level 1 refers to a basic IAQ performance visualization including thermal comfort and air quality report created for the facility operators and managers. Level 2 requires an advanced performance visualization that includes more IAQ elements (e.g., acoustic performance) and also as well as reporting to the occupants. Level 3 adds the layer of IAQ data analysis (impacts of HVAC system operation and user behaviors on the building IAQ performance) and provides actionable recommendations for performance optimization. The developed recommendations must include initiatives for both HVAC system management and user intervention.

4.2.3.7 Hydraulics Monitoring and Control

This domain provides specifications of monitoring and control procedures required for the hydraulic system operation and maintenance.

HMC-01 Hot Water Storage Charging Control	
Level 0	None
Level 1	Manual control
Level 2	Time-based Control
Level 3	Occupancy-based Control
Level 4	Demand-based Control

Capability Intent: to measure monitoring and controlling capabilities of the hydraulic system needed to achieve optimum water efficiency and management.

Indicator Description: Level 1 is manual control meaning that the water heater is controlled through an on/off switch. Level 2 means having scheduled setpoints defined for automatically storage charging (based on times of the day, historical data of hot water needs, etc.). Level 3 refers to controlling the hot water storage based on the occupancy of the building (configuring the system using multi-sensors installed on water fixtures). Level 4 aims for higher efficiency through applying a demand analysis that considers more factors (e.g., real time water consumption data) to calculate the current and predict future building demand.

This capability is applicable to a hot water storage unit regardless of the water heating system (hot water generator, steam boiler, direct tankless electric heater, etc.) since each system has advantages/disadvantages and selecting the right system depends on the project.

HMC-02 Control of Hot Water Storage Temperature	
Level 0	None
Level 1	Manual control
Level 2	Time-based Control
Level 3	Demand-based Control

Capability Intent: to examine different approaches to control supplied hot water temperature that leads to higher energy efficiency and supplying water with comfortable temperature.

Indicator Description: Level 1 is manual control of water temperature using an on/off switch on the heat pump. Level 2 means having scheduled setpoints defined for heating water automatically (based on the season, times of the day, historical data of hot water needs, etc.). Level 3 refers to controlling the hot water temperature using integrated electronic heating and based on analysis of the actual demand.

HMC-03 Control of Hot Water Circulation Pump	
Level 0	None
Level 1	Time-based Control
Level 2	Demand-based Control

Capability Intent: to measure monitoring and controlling capabilities of the hydraulic system needed to achieve optimum water efficiency and management.

Indicator Description: Level 1 refers to using a schedule for automated water circulation which may cause energy waste. While level 2 requires a system (e.g., multi-sensors and analytics platform) that determines the building actual demand and controls the circulation pump accordingly.

HMC-04 Water Efficiency Evaluation & Visualization	
Level 0	None
Level 1	Basic Water Efficiency Visualization
Level 2	Advanced Water Efficiency Visualization
Level 3	Level 2 + Analysis & Optimization

Capability Intent: to increase transparency about the actual hydraulic system performance and to plan for its optimization.

Indicator Description: the evaluation and visualization of the hydraulic system performance are generally used to increase awareness among the facility managers and occupants. In this regard, level 1 refers to a basic performance visualization including water consumption and water temperature/flow assessment report created for the facility operators and managers. Level 2 requires an advanced performance visualization that includes more performance visualization elements (e.g., benchmarking and comparison between the current and historical data) and also as well as reporting to the occupants. Level 3 adds the layer of water use data analysis (impacts of hydraulic system operation and user behaviors on the building water efficiency) and providing actionable recommendations for performance optimization. The developed recommendations must include initiatives for both hydraulic system management and user intervention.

Chapter 5. CONCLUSION

5.1 RESEARCH SUMMARY

This research aimed to develop an intelligent building evaluation system in response to the identified gaps in knowledge and practice related to intelligent buildings capabilities (technologies, services, processes and workflows, and best practices) on one hand, and high demands for leveraging opportunities provided by this emerging industry, on the other hand. For this purpose, I conducted an initial literature review (Chapter 2) synthesizing the existing knowledge regarding the concepts of intelligent buildings and evaluation systems and finding potential gaps in research. During the literature review, I conceptualized the term intelligent buildings through classifying different definitions provided for the term (technology-based, performance-based, and system-based definitions) and reviewed the term in multiple contexts. Also, I made a distinction between the concepts of intelligent building and sustainable building in order to determine their applicability and examine the possibility of using the well-established sustainable building criteria best practices for developing the domain of intelligent buildings. Another reason for performing a comparative analysis between the two terms was that the current challenges with the intelligent building conceptualization echoes and extends from the problem the industry faced in articulating and measuring sustainable buildings as the concept was evolving during the past decades. In the second part of the literature review, I studied the uses of evaluation systems in the AECO industry which contained discussions on the purposes of using evaluation systems for different stakeholders, the potentials of using an evaluation system as a decision-making tool, structure of evaluation systems and their key elements, and a review of existing evaluation systems for intelligent buildings. The literature review revealed three specific gaps in the research which led to setting three objectives including identifying components of building intelligence, developing a standard system for intelligent buildings evaluation, and creating a framework to connect intended impacts of building intelligence on building performance.

To address the research objectives, I created a methodology (articulated in Chapter 3) containing the research process, overall approaches of developing the evaluation system (bottom-up vs. top-down), and the theories and methods used in the research. The final product of this research (an evaluation system called the IB Index) was created in multiple phases and revised through multiple version creation. The first versions were created mainly based on the bottom-up approach as the focus was on collecting as many building intelligence metrics and criteria as possible. While the creation of later versions was more aligned with the top-down approach (with the focus on standardization). As explained in the research methodology, Actor-network theory served as the basis for identifying building intelligence components and organizing the evaluation criteria. Based upon it, the main research methods namely systematic literature review and case studies with focus group interviews were used through an iterative process (established by the grounded theory) to achieve the research outcomes.

I presented the findings of this research in the forms of IB Index framework and content (Chapter 4). The IB Index framework comprises the elements and activities needed for creating a standard evaluation system. As a pre-requisite for developing the IB Index capabilities, the building intelligence components were identified using a comparative ontological analysis. Next, I explained the typology (the boundaries for the applicability and usability of the evaluation system) and the structure of the IB Index. The context comparison is another activity in this framework that is required for creating either a market-independent or market-aware evaluation system since it reveals the differences between prospective markets for an intelligent building evaluation system. In addition, I introduced the layers of analysis' model which is used to demonstrate the building intelligence capabilities in relation to an intelligent building mission-critical topics. Technological artifacts model was another key element that I created to position specifically emerging digital technologies in the IB Index capabilities. Moreover, I discussed the IB index weighting system and its two parts including the relative importance of the developed evaluation capabilities, and the impacts of building intelligence on the building performance. Although the first part of the weighting system is common in many evaluation systems the second part is relatively unique in the IB Index since it distinguishes between the building intelligence and performance and provides a framework to determine the impacts of building intelligence capabilities/indicators on the overall building performance (articulated by 15 criteria based on the triple bottom line concept). Additionally, I introduced the idea of neural network ontology as the IB Index dynamic and interactive ontology which facilitates the evaluation process by sorting and organizing the IB Index capabilities based on the users’ goals and expertise. As the last element of the IB Index framework, I explained the process of revision and validation of the IB Index evaluation system. A main outcome of the research is the content of IB Index presented as the IB Index catalogue and guidance which consists of the capabilities for evaluating all aspects of the building intelligence. In the Catalogue, the capabilities were organized using the project lifecycle hierarchy (three pillars and 18 domains) and each capability was explained based on the Capability Intent and its Indicator Description.

To make the process and the logic underlying the methodology of this research even clearer, I created the following conceptual visualization of the IB Index development workflow. The visualization (Figure 5.1) contains the main keywords used in the dissertations and illustrates the relationships between the theories and methods used in the process of IB Index development.

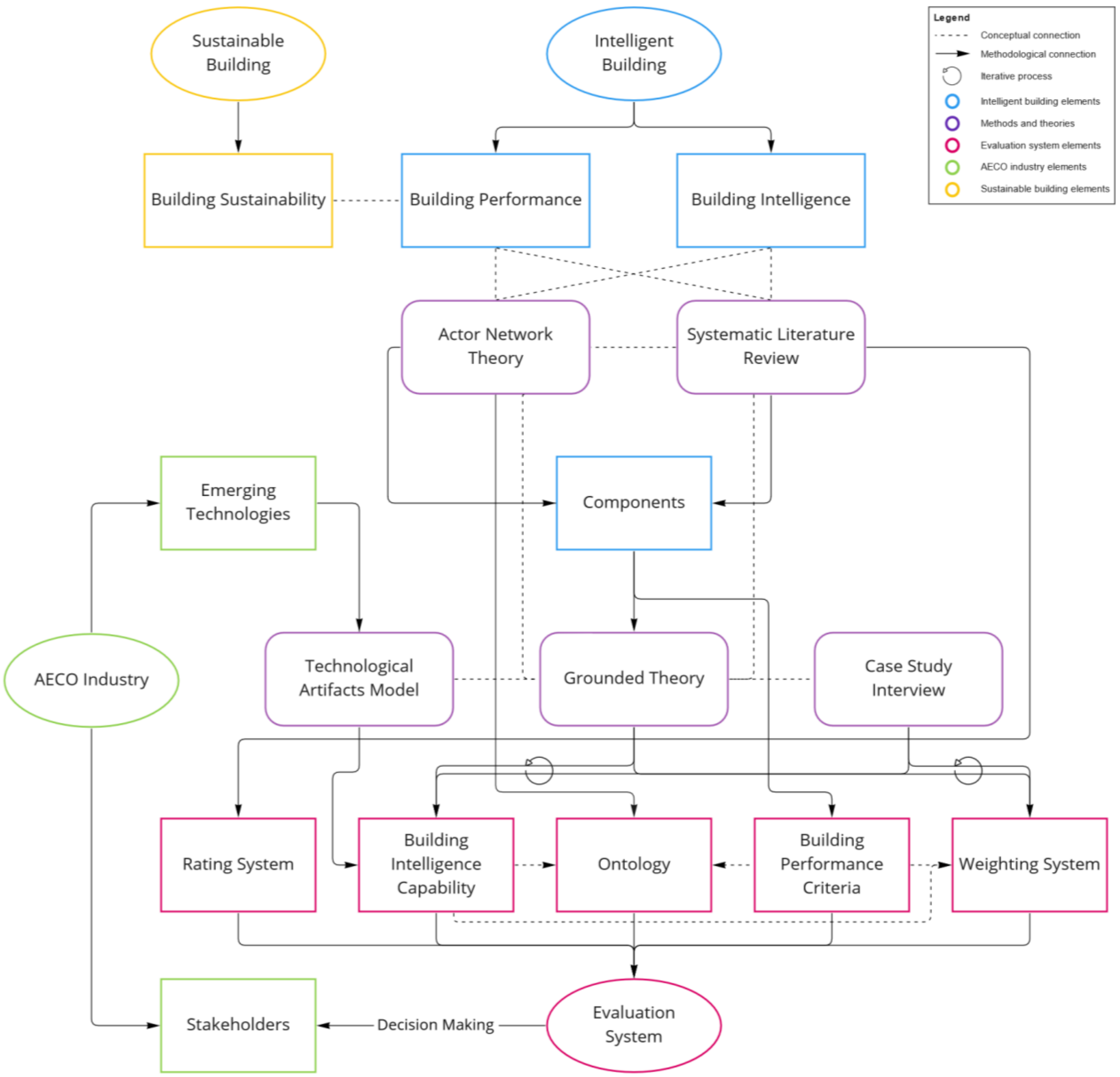


Figure 5.1. Visualization of the logical workflow of the IB Index development

Accordingly, I investigated the concept of intelligent building in accordance with the existing term sustainable building and identified the components of building intelligence/sustainability which served as a basis for creating the critical elements of the standard evaluation system namely the IB Index. Also, I showed the bidirectional relation between the AECO industry and the evaluation system that includes having the AECO emerging technologies in the core of the IB Index and investigating them as the main contributors to the creation of the building intelligence capabilities as well as having the developed evaluation system as an effective decision-making tool to be used by the AECO industry stakeholders.

5.2 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

This research contributes to the body of knowledge mainly by providing an intelligent building evaluation system. Based on the gaps and the issues found in existing evaluation systems (discussed in Section 2.3.1), the research team made an effort to develop a standardized and consistent whole-building evaluation system with quantifiable, clear, and non-binary capabilities and indicators. Intelligent building stakeholders may implement the IB Index throughout the life cycle of their project to

- evaluate their building intelligence specifically during the design phase to select building physical and virtual systems based on their desired level of intelligence, and later during the building occupancy phase to measure the actual intelligence of the building and identify any discrepancies between the expected and actual outcomes.
- prove their building intelligence compared to the industry benchmark using the evaluation system that demonstrates the building advantages in detail. Beyond using IB Index as a marketing tool, building owners may leverage IB Index technical documentation to estimate the building appraisal value more accurately.
- improve their building intelligence through reviewing the IB Index Catalogue to find realistic opportunities for enhancing and standardizing the building operation and management workflows, adopting more advanced building technologies, and optimizing building systems.

In addition, several scholars (e.g., Wong 2005, Clements-Croome 2014) have developed a list of intelligent building components in the past. This research is considered as an extension and expansion of their works in terms of identifying the components through a comparative ontological analysis. For this purpose, the research team examined relevant academic literature, industry publications, and formal evaluation systems and found 79 components of building intelligence classified in 18 clusters. Implementation of emerging technologies and use of data analytics capabilities were found as the significant underlying themes in these components. During the analysis, the research team recognized two types of components including “desired outcomes” related to building intelligence/performance and “required actions” for realizing such outcomes. Most of the current literature uses both types of components without acknowledging this semantic difference between them. So, the result of this research provides a more consistent way to articulate building intelligence through its identified components. Furthermore, unlike many existing literatures, this research made a clear distinction between the terms building intelligence and building sustainability in accordance with their components. Based on the results of the research, it was concluded that the building sustainability aims to answer the question of what the desired/required characteristics of a building are (in terms of environmental, economic, and social performance) while the building intelligence aims to answer the question of how to achieve them (through utilizing and improving intelligent technologies, processes, and occupants’ interactions).

The findings of this research facilitate more informed decision making by elaborating on the sociotechnical connections between the emerging technologies, building intelligence, and building performance. For instance, to adopt a new building management system, a building stakeholders may use the relevant IB Index capabilities to choose the technical features and functions of the system (e.g., the IAQ controllability it gives to the facility managers and occupants) based on the desired level of building intelligence and the potential impacts the intended technology has on the building social performance (e.g., enhanced occupants convenience and productivity). Consequently, the IB Index shows building owners and managers how specifically a technology solution can make their building more intelligent. It provides the specifications and requirements they need to consider when deciding about obtaining a technology solution or developing a technology stack for their building. In addition, IB Index makes a connection between building intelligence and performance which is especially important for long-term decision-making regarding asset/facility management and capital planning and enables the stakeholders to select intelligent building initiatives with highest ROI based on their project goals and needs.

Beside the research final product, the process documentation of the IB Index is a contribution to knowledge as well. As discussed in section 4.1, the IB Index framework introduced the key elements required for creating a standard and rule-based evaluation system for intelligent buildings. These elements include

- Building intelligence components: to provide a better understanding of the concept building intelligence and to be used as a basis for developing the evaluation capabilities.
- Typology and structure: to distinguish between different evaluation systems using consistent factors (e.g., target audience, scale, and building types) and to understand the overall structure of the evaluation system.
- Context comparison: to create a globally usable evaluation system that addresses the potential discrepancies (e.g., terminology and technology attainability) between regional intelligent building industries.
- Layers of analysis: to address various aspects of building intelligence (e.g., dependency on the occupants’ behaviors) beyond the specific evaluation capabilities.

- Technological artifact model: to use a methodical approach for translating emerging technologies functionalities into measurable capabilities in the evaluation system.
- Weighting system: to provide a framework for capturing the impacts of building intelligence on the building performance and to address the relative importance of the developed capabilities.
- Neural network ontology: to create a dynamic ontology for the evaluation system containing multiple user interfaces (e.g., building managements and building systems) that allows for sorting the evaluation capabilities based on the end-users' goals and expertise.
- Validation: to provide a workflow for revision and validation of the developing evaluation system in terms of comprehensiveness, independence, and clarity of the evaluation capabilities, accuracy of the weighting system, and effectiveness of the ontology.

In summary, the IB Index framework provides academic researchers and industry practitioners with a generalizable and reproducible process that articulates all elements, activities, and considerations needed for developing a standard evaluation system for intelligent buildings.

5.3 FUTURE WORK

In general, several tasks may be defined as the next steps in the IB Index project to facilitate the adoption and implementation of this evaluation system. For example, the research team should develop a comprehensive user guideline containing capabilities' references (e.g., national/international building standards and regulations) and the building evaluation workflow (e.g., required documentation and evidence submittals as well as the audit procedures). Also, the research team completed the development of a web-based tool based on the IB Index capabilities and framework for buildings' evaluation and certification.

Regarding future research implications, the following topics seem to be of higher priority:

- Create a dynamic weighting system that reflects the difference in the relative importance of the capabilities based on multiple factors including the building types and regions. Additionally, extensive research and collection of empirical data would be required to quantify the actual impacts of the building intelligence indicators on the building performance (based on the identified criteria). This study should entail a cost-benefit analysis addressing all tangible and intangible factors associated with creating an intelligent building specifically the emerging technologies.
- In the case that IB Index is used as a formal certification system, more research is needed to identify the requirements and process of building rating and certification including a comparison between self-evaluation and third-party evaluation. This research is important because each evaluation approach has advantages and disadvantages. For instance, the third-party certification provides the users with a consistent and independent evaluation process that creates a benchmark for comparing between the buildings and the market average. On the other hand, most of the current third-party certifications rely on a score-based rating that may encourage the building stakeholders to seek low-cost criteria to pass a certain rating level instead of developing a long-term roadmap to enhance the building intelligence based on their actual needs and objectives.
- Develop an in-depth guideline to articulate the meaning of the IB Index capability indicators to different building stakeholders and the ways they can take full advantage of the indicators to prioritize their intelligent building initiatives. In general, the indicators provide a descriptive explanation for a capability (e.g., the level of advancement of an intelligent building process/best practice or the level of maturity for an intelligent building technology solution). Different stakeholders may use the IB Index for different purposes.

For example, an architect can use the indicators to develop various design alternative related to a building system while a technology vendor may use them to justify deploying a specific technology solution. Therefore, developing a guideline to situate the indicators in different contexts is invaluable. In addition, such effort creates new opportunities for collaboration between the stakeholders. For instance, facility owners and managers may benefit from an independent assessment of the existing technology solutions using the IB Index indicators to choose from the solution options that meet a certain level of indicators.

Overall, this research is a step in a longer process of understanding the concept of building intelligence and advancing the intelligent building industry. Implementing the IB Index in intelligent building projects will lead to adopting new visions for utilizing the building evaluation systems including for value-based technology acquisition, continuous asset improvement, and data-driven decision making.

BIBLIOGRAPHY

[1] Abdun-Nur, E. A. (1970). “Control of quality—A system.” J. Constr. Div.,96(2), 119–136.

[2] Ade, Rochelle, and Michael Rehm. 2020. “The Unwritten History of Green Building Rating Tools: A Personal View from Some of the ‘Founding Fathers.’” Building Research & Information 48(1):1–17. doi: 10.1080/09613218.2019.1627179.

[3] Ahmadi-Karvigh, S., Becerik-Gerber, B., Soibelman, L. 2019. “Intelligent adaptive automation: A framework for an activity-driven and user-centered building automation,” *Energy and Buildings*, 188–189, 184–199. https://doi.org/10.1016/j.enbuild.2019.02.007

[4] Ahmed, Henni Sid, Belbachir Mohamed Faouzi, Jean Caelen. 2013. “Detection and Classification of the Behavior of People in an Intelligent Building by Camera.” International Journal on Smart Sensing and Intelligent Systems 6(4):1317–42. doi: 10.21307/ijssis-2017-592.

[5] Al Dakheel, Joud, Claudio Del Pero, Niccolò Aste, and Fabrizio Leonforte. 2020. “Smart Buildings Features and Key Performance Indicators: A Review.” Sustainable Cities and Society 61:102328. doi: 10.1016/j.scs.2020.102328.

[6] Al Waer and Kirk. 2012. “Building Sustainability Assessment Methods.” Proceedings of the Institution of Civil Engineers - Engineering Sustainability 165(4):241–53. doi: 10.1680/ensu.10.00058.

[7] Al Waer, H., Clements-Croome, D. J. 2010. “Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings.” Building and Environment, 45(4), 799–807. (https://doi.org/10.1016/j.buildenv.2009.08.019, accessed 08/11/2020)

[8] Anritsu. 2015. “Understanding IBW Solutions In-Building Wireless: DAS to Small Cells.” PartNo11410-00885A.

[9] AON. 2017. “Smart Building Technologies: Balancing Value and Risk.” The One Brief. Retrieved June 7, 2020 (https://theonebrief.com/smart-building-technologies-balancing-value-risk/).

[10] Arkin H, Paciuk M. 1997. “Evaluating Intelligent Buildings According to Level of Service System Integration”, *Automation in Construction*. 6(5–6): 471-9.

[11] Arup. 2003. www.arup.com/communications/knowledge/intelligent.htm.

[12] Bašić, S., Vezilić Strmo, N., Sladoljev, M. 2019. “Smart Cities and Buildings.” Journal of the Croatian Association of Civil Engineers 71(10):943–64. doi: 10.14256/JCE.2733.2019.

[13] Batov, Eugeny I. 2015. “The Distinctive Features of mart’ Buildings.” Procedia Engineering 111:103–7. doi: 10.1016/j.proeng.2015.07.061.

[14] Bean, F., De Groote, M., Volt, J. 2017. "Opening the Door to Smart Buildings. Driving the Transition with EU Directives". the Buildings Performance Institute Europe (BPIE).

[15] Blanco, J. L., Fuchs, S., Parsons, M., Ribeirinho, M. J. 2019. "Artificial intelligence: Construction technology next frontier," McKinsey. (accessed 06/15/2020) https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/artificial-intelligence-construction-technologys-next-frontier

[16] Blanco, J. L., Mullin, A., Pandya, K., et al. 2018. "Seizing Opportunity In Today Construction Technology Ecosystem," McKinsey & Company, Construction innovation and the technology ecosystem, (https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/seizing-opportunity-in-todays-construction-technology-ecosystem, accessed 06/20/2020)

[17] Borhani, Alireza, Atieh Borhani, Carrie Sturts Dossick, and Julie Jupp. 2022. "Smart Building Conceptualization: A Comparative Analysis of Literature and Standards." Pp. 310–18 in Construction Research Congress 2022. Arlington, Virginia: ASCE.

[18] Brad, B S, Murar, M M. 2014. "Smart Buildings Using IoT Technologies," Construction of Unique Buildings and Structures, 5(20). p.15-27.

[19] Brown, S., Kurt Karnatz, Rob Knight 2016. "A Comprehensive Look at the Intelligent Building." Consulting - Specifying Engineer. Retrieved March 24, 2020 (https://www.csemag.com/articles/a-comprehensive-look-at-the-intelligent-building/).

[20] Buckman, A.H., Mayfield, M., Beck, S.B.M. 2014. "What is a Smart Building?", Smart and Sustainable Built Environment, vol. 3, no. 2.

[21] CABA. 2015. "Intelligent Buildings and Big Data". Navigant Research (https://www.caba.org/wp-content/uploads/2020/07/2015-CABA-Intelligent-Buildings-and-Big-Data-Full-Report.pdf, accessed 07/15/22)

[22] Cempel, W. A., Mikulik, J. 2013. "Intelligent Building Reengineering: Adjusting Life and Work Environment to Occupant Optimal Routine Processes." Intelligent Buildings International; London 5 (1): 51–64.

[23] Cheng, J., Kunz, T. 2009. "A Survey on Smart Home Networking," Carleton University, Systems and Computer Engineering,, Tech. Rep. (http://kunz-pc:sce:carleton:ca/Thesis/SmartHomeNetworking.pdf, accessed 08/05/2020)

[24] Chow, L. K H, Leung A. Y T. 2005. "New Intelligent Building Index For Buildings Around The World – A Quantitative Approach In Building Assessment Experience With Hong Kong Tallest Building, Two International Finance Centre", The 2005 World Sustainable Building Conference, Tokyo, 27-29.

[25] Clements-Croome, Derek, ed. 2014. Intelligent Buildings: An Introduction. New York: Routledge.

[26] Clements-Croome, Derek. 2011. “Sustainable Intelligent Buildings for People: A Review.” Intelligent Buildings International; London 3(2):67–86.

[27] Clements-Croome, T.D.J. 1997. “What do we mean by intelligent buildings?” Automation in Construction 6 395– 399.

[28] CommScope. 2018. “Smart Building Connectivity; Shaping The Always-on Businesses of Tomorrow”, CO-109520.3-EN (03/18)

[29] CommScope. 2018. “Universal connectivity grid design guide”. SYSTIMAX® Solutions from CommScope, BR-108900.1-EN (10/18)

[30] Costanzo, G. T., Zhu, G., Anjos, M. F., Savard, G. 2012. “A system architecture for autonomous demand side load management in smart buildings”. IEEE Transactions on Smart Grid, 3(4), 2157–2165.

[31] Daissaoui, A., Boulmakoul, A., Karim, L., & Lbath, A. 2020. “IoT and Big Data Analytics for Smart Buildings: A Survey”. Procedia Computer Science, 170, 161–168. (https://doi.org/10.1016/j.procs.2020.03.021, accessed 05/11/2020).

[32] De Freitas Melo, Danilo, Epaminondas De Souza Lage, et al. 2017. “Improving the Consumption and Water Heating Efficiency in Smart Buildings.” Pp. 1–6 in 2017 13th International Conference and Expo on Emerging Technologies for a Smarter World.

[33] De Groote, M., Volt, J., Bean, F., 2017. “Smart Buildings Decoded. The Concept Beyond the Buzzword”, the Buildings Performance Institute Europe (BPIE), (https://www.bpie.eu/wp-content/uploads/2017/06/PAPER-Smart-buildings-decoded_05.pdf, accessed 01/05/2021).

[34] DEGW and Technibank. 1992. “The Intelligent Building in Europe”.

[35] Demiris, G., Hensel, B., 2009, mart homes for patients at the end of life’, Journal of Housing for the Elderly 23(1), 106–115

[36] Ding, Grace K. C. 2008. “Sustainable Construction—The Role of Environmental Assessment Tools.” Journal of Environmental Management 86(3):451–64. doi: 10.1016/j.jenvman.2006.12.025.

[37] DoD. 2020. “Cybersecurity Maturity Model Certification (CMMC)”.

[38] Dusek, V. 2006. “Philosophy of Technology: An Introduction.” 258. (http://aleteya.cs.buap.mx/~jlavalle/filMetInvComp/Philosophy_of_Technology__An_Introduction.pdf, access date: 8/12/2019)

[39] EESI. n.d. “Grid, Transmission & Utilities.” Retrieved June 6, 2020 (https://www.eesi.org/topics/grid/description).

[40] Ehrlich, C. 2007. “Intelligent Building Dictionary: Terminology for Smart, Integrated, Green Building, Design, Construction, and Management”. San Francisco: Hands-on-Guide.

[41] Engelsgaard, Sebastian, Emil Kjøller Alexandersen, Jonathan Dallaire, and Muhyiddine Jradi. 2020. “IBACSA: An Interactive Tool for Building Automation and Control Systems Auditing and Smartness Evaluation.” Building and Environment 184:107240. doi: 10.1016/j.buildenv.2020.107240.

[42] EPA. 2008. “Green Building Strategy”. US EPA Archived Document. (https://archive.epa.gov/greenbuilding/web/pdf/greenbuilding_strategy_nov08.pdf, accessed 07.20.22)

[43] Everett, R. 2008. “The ‘building colleges for the future’ program. Delivering a green and intelligent building agenda”, New Review of Information Networking, Vol. 14 No. 1, pp. 3-20.

[44] Flax, B. M. 1991. “Intelligent buildings,” IEEE Communications Magazine, vol. 29, no. 4, pp. 24–27.

[45] Fletcher. R., Santhanam, N., Varanasi, S. 2018. “Laying a Foundation for Success in the Era of the Connected Building” , McKinsey & Co. Retrieved June 7, 2020 (https://www.mckinsey.com/industries/advanced-electronics/our-insights/laying-the-foundation-for-success-in-the-connected-building-era).

[46] Flyvbjerg, B. 2001. “Making Social Science Matter, Why Social Inquiry Fails and How It Can Succeed Again.” Cambridge University Press. Cambridge. UK. pp. 10-24, 60-79

[47] Frank, Eva Weise, Hanaa Dahy, and Kasper Sánchez Vibæk. 2022. “Challenges in Creating a Sustainable Building Certificate for Single-Family Housing in Denmark through an Actor-Network Theory (ANT) Lens.” Current Research in Environmental Sustainability 4:100144. doi: 10.1016/j.crsust.2022.100144.

[48] Froufe, M.M., Chinelli, C. K., Guedes, A.L.A., Haddad, A.N., Hammad, A.W.A., Soares, C.A.P. 2020. “Smart Buildings: Systems and Drivers.” Buildings 10 (9): 153. (https://doi.org/10.3390/buildings10090153, accessed 03/11/2021).

[49] Gabe, J., Christensen, P. H. 2019. “Information or marketing? lessons from the history of private-sector green building labelling”. Sustainable real estate (pp. 115–163). Springer.

[50] Gad, Christopher, and Casper Bruun Jensen. 2010. “On the Consequences of Post-ANT.” Science, Technology, & Human Values 35(1):55–80.

[51] Gerber, D., Nguyen, B., Gaetani, I. 2019. “Digital Twin Towards a Meaningful Framework”. Arup (www.arup.com/digitaltwinreport, accessed 03/20/21).

[52] Ghaffarianhoseini, A., Berardi, U., et al. 2016. “What is an intelligent building? Analysis of recent interpretations from an international perspective”, Architectural Science Review, 59:5,

338-357, DOI: 10.1080/00038628.2015.1079164, (https://doi.org/10.1080/00038628.2015.1079164, accessed 06/12/2020)

[53] GhaffarianHoseini, AmirHosein. 2012. “Ecologically Sustainable Design (ESD): Theories, Implementations and Challenges towards Intelligent Building Design Development.” Intelligent Buildings International; London 4(1):34–48.

[54] Gill, P., Stewart, K., Treasure, E., & Chadwick, B. 2008. “Methods of data collection in qualitative research: Interviews and focus groups”. British Dental Journal, 204(6), 291–295. https://doi.org/10.1038/bdj.2008.192

[55] Griffor, Edward R., Chris Greer, David A. Wollman, and Martin J. Burns. 2017. “Framework for Cyber-Physical Systems: Volume 2, Working Group Reports”. NIST SP 1500-202. Gaithersburg, MD: National Institute of Standards and Technology. doi: 10.6028/NIST.SP.1500-202.

[56] Hajj, Claudette El, Dima Jawad, and German Martinez Montes. 2021. “Analysis of a Construction Innovative Solution from the Perspective of an Information System Theory.” Journal of Construction Engineering and Management 147(9):03121003. doi: 10.1061/(ASCE)CO.1943-7862.0002120.

[57] Hartkopf V, Loftness V, Mahdavi A, Lee S, Shankavaram J. 1997. “An integrated approach to design and engineering of intelligent buildings—The Intelligent Workplace at the Carnegie Mellon University”. Automation in Construction, 6:401–15.

[58] Harty, C. 2008. “Implementing innovation in construction: Contexts, relative boundedness and actor-network theory”. Construction Management and Economics, 26(10), 1029–1041. https://doi.org/10.1080/01446190802298413

[59] Hatefi, S M. 2019. “Intelligent Building Assessment based on an Integrated Model of Fuzzy Analytic Hierarchy Process and Fuzzy Preference Degree Approach (FAHP-FPDA),” 14. Int. J. Optim. Civil Eng., 2019; 9(1):79-92.

[60] Healey, G. 2011. “Intelligent Buildings: Integrated Systems and Controls.” Melbourne: International Specialised Skills Institute.

[61] Hicks, Glenn. 2019. “Do You Know Your Smart Building Score?” Retrieved June 7, 2020 (https://www.iofficecorp.com/blog/your-smart-building-score).

[62] Himanen, M. 2003. “The Intelligence of Intelligent Buildings; The Feasibility of the Intelligent Building Concept in Office Buildings”. Technical Research Center of Finland. VTT.

[63] Howell, K. E. 2013. “An Introduction to the Philosophy of Methodology”, Sage Publication

[64] Hudson, F.D. 2010. “IBM Smarter Planet Strategy”. IBM Corporation (https://researcher.watson.ibm.com/files/us-egaioni/FlorenceHudson-IBMworkshop.ppt, accessed 05/12/2020).

[65] Hui, S.C.M. 2016. “Intelligent Buildings”, GEE5303 Green and Intelligent Building. (http://ibse.hk/GEE5303/GEE5303_1617-09.pdf, accessed 08/11/2020)

[66] Inkoom, Ebo E., and Roine Leiringer. 2016. “Exploring the Dynamic Nature of the Evolution of Building Environmental Assessment Methods (BEAMs): A Call for a Diachronic Analysis of BEAMs.” Engineering Project Organization Journal 6(2–4):104–14. doi: 10.1080/21573727.2016.1270204.

[67] International Institute of Sustainable Development (IISD). 2009. “BellagioSTAMP: Sustainability Assessment and Measurement Principles”. International Institute for Sustainable Development, Manitoba, Canada. (www.iisd.org/pdf/2009/brochure_bellagiostamp.pdf, accessed 08/15/2022).

[68] IRENA. 2019. “Innovation landscape brief: Future Role of Distribution System Operators.” International Renewable Energy Agency, Abu Dhabi.

[69] ISO International Standard. 2011. “Sustainability in Building Construction- Sustainability Indicators”. ISO 21929-1 (https://gpp.golocal-ukraine.com/wp-content/uploads/ISO_21929-1_2011E-Character_PDF_document.pdf, accessed 01/12/21)

[70] Katz, David, and Jiri Skopek. 2009. “The CABA Building Intelligence Quotient Programme.” Intelligent Buildings International 1(4):277–95. doi: 10.3763/inbi.2009.SI05.

[71] Kaya, İhsan, and Cengiz Kahraman. 2014. “A Comparison of Fuzzy Multicriteria Decision Making Methods for Intelligent Building Assessment.” Journal of Civil Engineering & Management 20 (1): 59–69. (https://doi.org/10.3846/13923730.2013.801906, accessed 06/09/2020)

[72] Kibert, C. J. 2012. “Sustainable construction: green building design and delivery”. Hoboken: Wiley

[73] Kiliccote, S., Piette, M.A., Ghatikar, G., Hafemeister, D., Kammen, D., Levi, B.G., Schwartz, P. 2011. “Smart buildings and demand response,” AIP Conference Proceedings, Vol. 1401, Berkeley.

[74] King, J., Perry, C. 2017. “Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings”. SMART BUILDINGS, 55. American Council for an Energy-Efficient Economy (ACEEE), Washington DC.

[75] Kolokotsa, D., G. Sutherland, G. Stavrakakis, S. Karatassou, and M. Santamouris. 2007. “A Matrix Tool for Assessing the Performance of Intelligent Buildings.” Management of Environmental Quality: An International Journal 18(1):36–49. doi: 10.1108/14777830710717703.

[76] Kressin, Jill. 2020. “Breaking Down the Identity and Access Management Capability Maturity Model, Part Two.” Retrieved September 29, 2020 (https://blog.identityautomation.com/breaking-down-the-identity-and-access-management-capability-maturity-model-part-two).

[77] Kroner, W.M. 1997. "An intelligent and responsive architecture", Automation in Construction 6, 381–393.

[78] Kua, H. W., & Lee, S. E. 2002. "Demonstration Intelligent Building-A Methodology for The Promotion Of Total Sustainability In The Built Environment", Building and Environment, 37(3), 231–240. https://doi.org/10.1016/S0360-1323(01)00002-6

[79] Kushal Jain. 2019. "Development of a Smart Building Evaluation System for Office Buildings." doi: 10.13140/RG.2.2.32122.24000.

[80] Langhammer, M. 2019. "The growth of proptech," https://www.pitcher.com.au/news/growth-proptech (accessed 06/15/2020)

[81] Latour, B. 1996. "On actor-network theory: A few clarifications." Soziale Welt 47 (4): 369–381.

[82] Latour, B. 2005. "Reassembling the social: An introduction to actor-network-theory". Oxford University Press. https://www-fulcrumorg.offcampus.lib.washington.edu/concern/monographs/rv042t698

[83] Lawrence, Thomas M., Marie-Claude Boudreau, Lieve Helsen, et al. 2016. "Ten Questions Concerning Integrating Smart Buildings into the Smart Grid." Building and Environment 108:273–83. doi: 10.1016/j.buildenv.2016.08.022.

[84] Leavitt, Austin. 2020. "Access Control Guide: Which Models and Methods Are Right for You?" Safe and Sound Security. Retrieved September 29, 2020 (https://getsafeandsound.com/2020/01/access-control-models/).

[85] Leiringer, Roine. 2020. "Sustainable Construction through Industry Self-Regulation: The Development and Role of Building Environmental Assessment Methods in Achieving Green Building." Sustainability 12(21):8853. doi: 10.3390/su12218853.

[86] London, Kerry, and Zelinna Pablo. 2017. "An Actor–Network Theory Approach to Developing an Expanded Conceptualization of Collaboration in Industrialized Building Housing Construction." Construction Management & Economics 35(8/9):553–77. doi: 10.1080/01446193.2017.1339361.

[87] Mahmoud, S., M., Tarek Zayed, and M. Fahmy. 2022. "Multiobjective Optimization Model for the Life Cycle Cost-Sustainability Trade-Off Problem of Building Upgrading Using a Generic Sustainability Assessment Tool." Journal of Construction Engineering and Management 148(7):04022050. doi: 10.1061/(ASCE)CO.1943-7862.0002281.

[88] Manic, M., Amarasinghe, K., Juan J. R., Rieger C. 2016. "Intelligent Buildings of the Future: Cyberaware, Deep Learning Powered, and Human Interacting." IEEE Industrial Electronics Magazine 10(4):32–49. doi: 10.1109/MIE.2016.2615575.

[89] Medineckiene, M., E. K. Zavadskas, F. Björk, and Z. Turskis. 2015. “Multi-Criteria Decision-Making System for Sustainable Building Assessment/Certification.” Archives of Civil and Mechanical Engineering 15(1):11–18. doi: 10.1016/j.acme.2014.09.001.

[90] Missonier, Stephanie, and Sabrina Loufrani-Fedida. 2014. “Stakeholder Analysis and Engagement in Projects: From Stakeholder Relational Perspective to Stakeholder Relational Ontology.” International Journal of Project Management 32(7):1108–22. doi: 10.1016/j.ijproman.2014.02.010.

[91] Moné, Lesa. 2018. “Internet of Things: Middleware.” Retrieved July 14, 2020 (https://www.leanix.net/en/blog/internet-of-things-middleware).

[92] Neb, A., Remling, D. 2019. “Quantification and Evaluation of Automation Concepts based on a Multi-Criteria Decision Analysis.” Procedia CIRP, 84, 624–629. https://doi.org/10.1016/j.procir.2019.04.321

[93] Nik Bakht, M., El-Diraby, T. E. 2015. “Synthesis of Decision-Making Research in Construction”. J. Constr. Eng. Manage., 141(9): 04015027

[94] Oltean-Dumbrava, C., Watts, G. R., Miah, A. H. S. 2014. “Top-Down-Bottom-Up Methodology as a Common Approach to Defining Bespoke Sets of Sustainability Assessment Criteria for the Built Environment,” Journal of Management in Engineering, 30(1), 19–31. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000169

[95] Omar, O. 2018. “Intelligent Building, Definitions, Factors and Evaluation Criteria of Selection.” Alexandria Engineering Journal 57 (4): 2903–10. https://doi.org/10.1016/j.aej.2018.07.004.

[96] Ottinger, E., Minglani, H., Gibson, M. 2020. “Technological Advancements Disrupting the Global construction Industry”, Ernst & Young LLP. Retrieved July 27, 2020 (https://www.documentcloud.org/documents/6838866-Ottinger-Minglani-and-Gibson-Technological.html).

[97] Papajohn D., Brinker C., Asmar M. 2016. “Uncovering Key Criteria to Assess Sustainability Rating Systems for the Built Environment,” Construction Research Congress 2016, 1303–1312. https://doi.org/10.1061/9780784479827.131

[98] Pekericli, Mehmet Koray, Burcu Akinci, and Itir Karaesmen. 2012. “Modeling Information Dependencies in Construction Project Network Organizations.” 1–13. doi: 10.1061/40704(2003)45.

[99] Pennell, N. 2013. “Opportunities and Challenges for Intelligent Buildings.” In Intelligent Buildings: Design, Management and Operation. 2nd ed., edited by D. J. Clements-Croome, 305–312. London: ICE Publishing.

[100] Perumal, T., Ramli, A. R., Leong, C. Y., Samsudin, K., Mansor, S. 2010. “Middleware for Heterogeneous Subsystems Interoperability in Intelligent Buildings.” Automation in Construction 19(2):160–68. doi: 10.1016/j.autcon.2009.11.014.

[101] Petit, J., Putnam, T., Busch, W. 2014. “Intelligent Buildings & Enterprise,” Johnson Controls, Navitas Capital.

[102] Potter, Jennifer, Elizabeth Stuart, and Peter Cappers. 2018. “Barriers and Opportunities to Broader Adoption of Integrated Demand Side Management at Electric Utilities: A Scoping Study”. 1425437. doi: 10.2172/1425437.

[103] Potter, Jennifer, Elizabeth Stuart, and Peter Cappers. 2018. “Barriers and Opportunities to Broader Adoption of Integrated Demand Side Management at Electric Utilities: A Scoping Study”. doi: 10.2172/1425437.

[104] Pulla, V. 2014. “Grounded Theory Approach in Social Research. Space and Culture”, India, 2(3), 14–23. https://doi.org/10.20896/saci.v2i3.93

[105] Qolomany, B., Ala Al-Fuqaha, Ajay Gupta, Driss Benhaddou, Safaa Alwajidi, Junaid Qadir, and Alvis C. Fong. 2019. “Leveraging Machine Learning and Big Data for Smart Buildings: A Comprehensive Survey.” IEEE Access 7:90316–56. doi: 10.1109/ACCESS.2019.2926642.

[106] Rasmussen, Neil. 2011. “The Different Types of UPS Systems.” 10. Schneider Electric – Data Center Science Center

[107] Rodríguez López, Fernando, and Fernández Sánchez, Gonzalo. 2011. “Challenges for Sustainability Assessment by Indicators.” Leadership and Management in Engineering 11(4):321–25. doi: 10.1061/(ASCE)LM.1943-5630.0000142.

[108] Rosenberg, P. 2000. “The Basics of Structured Cabling.” EC&M. Retrieved September 27, 2020 (https://www.ecmweb.com/basics/article/20897067/the-basics-of-structured-cabling).

[109] Roulston, K., Choi, M. 2018. “The SAGE Handbook of Qualitative Data Collection”, edited by: Flick, U. pp. 2-24.

[110] Rwelamila PD, Talukhaba AA, Ngowi AB. 2000. “Project procurement systems in the attainment of sustainable construction”. Sustainable Development 8(1): 39–50

[111] Rydin, Yvonne. 2013. “Using Actor–Network Theory to Understand Planning Practice: Exploring Relationships between Actants in Regulating Low-Carbon Commercial Development.” Planning Theory 12(1):23–45. doi: 10.1177/1473095212455494.

[112] Sackey, E., M. Tuuli, and A. Dainty. 2015. “Sociotechnical Systems Approach to BIM Implementation in a Multidisciplinary Construction Context.” Journal of Management in Engineering 31(1):A4014005. doi: 10.1061/(ASCE)ME.1943-5479.0000303.

[113] Schoemaker, P. J. H., Russo, J. E. (1993), “A Pyramid of Decision Approaches,” California Management Review, 36(1), 9–31. https://doi.org/10.2307/41165732

[114] Sinopoli, James. 2010. “Smart Building Systems for Architects, Owners, and Builders”. Knovel. ISBN 978-1-85617-653-8.

[115] Sinopoli, James. 2010. “Smart Building Systems for Architects, Owners, and Builders.” Elsevier Inc., ISBN: 978-1-85617-653-8

[116] Smart Buildings, LLC. 2011. “What is a Smart Building?”.

[117] So, A. T. P. et al. 2001, “The Intelligent Building Index Manual Version 2.0”. Asian Institute of Intelligent Buildings (AIIB). City University of Hong Kong

[118] Solanki, A., Nayyar, A. 2020. “Green Building Management and Smart Automation” IGI Global, DOI: 10.4018/978-1-5225-9754-4.

[119] Soncodi, M. 2021. “Assessing Smart Buildings in the Digital Era.” Smart Buildings Technology. (https://www.smartbuildingstech.com/communications-systems/article/21158739/assessing-smart-buildings-in-the-digital-era, accessed 07/15/22).

[120] Star, S. L. 1991. Power, technologies and the phenomenology of conventions: On being allergic to onions. In A sociology of monsters: Essays on power, technology and domination, ed. J. Law, 26-56. London: Routledge.

[121] Stubbings, M. 1988. “Intelligent Buildings: An IFS Executive Briefing”, Springer-Verlag, Berlin.

[122] Suzer, O., 2015. “A comparative review of environmental concern prioritization: LEED vs other major certification systems,” *Journal of Environmental Management*, 154, 266–283. https://doi.org/10.1016/j.jenvman.2015.02.029

[123] Taylor, J. E., Dossick, C. S., & Garvin, M. 2011. “Meeting the Burden of Proof with Case-Study Research”. Journal of Construction Engineering and Management, 137(4), 303–311. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000283

[124] The Institution of Engineering & Technology (IET), 2012. “Intelligent Buildings: Understanding and managing the security risks”. (https://doi.org/10.1049/etr.2012.9001, accessed 05/11/2020).

[125] TIA, 2017. “Smart Buildings.” TIA Online. (https://tiaonline.org/what-we-do/technology/programs/smart-buildings/, accessed 06/07/2020).

[126] Trivedi, Dipti, and Venkataramana Badarla. 2019. “Occupancy Detection Systems for Indoor Environments: A Survey of Approaches and Methods.” Indoor and Built Environment. doi: 10.1177/1420326X19875621.

[127] US EPA, OAR. 2015. “What Is CHP?” US EPA. Retrieved June 6, 2020 (https://www.epa.gov/chp/what-chp).

[128] Van Rooijen, T., Nesterova, N. (2013). “Applied framework for evaluation in CIVITAS PLUS II”.

[129] Verbeke, S., Waide, P., Bettgenhäuser, K., Uslar, M., Bogaert, S., et al. 2018. "Support for setting up a Smart Readiness Indicator for buildings and related impact assessment," Flemish Institute for Technological Research NV ("VITO"), Executive Summary of Final Report, the European Commission DG Energy, (https://www.buildup.eu/sites/default/files/content/sri_1st_technical_study_-_executive_summary.pdf, accessed 06/20/2020)

[130] VillarinhoRosa, Lúcio, and Assed Naked Haddad. 2013. "Building Sustainability Assessment throughout Multicriteria Decision Making." Journal of Construction Engineering 2013:1–9. doi: 10.1155/2013/578671.

[131] Wang, S. 2010. "Intelligent Buildings and Building Automation". London and New York: Spon Press. ISBN10: 0- 203- 89081- 7 (ebk).

[132] WBDG. 2018. "Enhance Indoor Environmental Quality (IEQ) | WBDG - Whole Building Design Guide." Retrieved June 7, 2020 (https://www.wbdg.org/design-objectives/sustainable/enhance-indoor-environmental-quality).

[133] Weiss, R.S. 1994. "Learning from Strangers: The Art and Method of Qualitative Interview Studies". The Free Press. Maxwell Macmillan International. New York. pp. 1, 65-76.

[134] Wigginton, M., Harris, J. 2002. "Intelligent Skin", Architectural Press, Oxford, UK

[135] Willow. 2020. "An Introduction to Digital Twin Definition Language." (https://www.willowinc.com/posts/an-introduction-to-digital-twin-definition-language/, accessed 2/5/21).

[136] WiredScore. 2021. "Smart buildings. Our future is smart". SmartScore white paper. (https://wiredscore.com/wp-content/uploads/2021/04/2021-Smart-Building-Whitepaper.pdf, accessed 07/15/2022)

[137] Wong, J., Li, H. 2006. "Development of A Conceptual Model For The Selection Of Intelligent Building Systems," Building and Environment, 41(8), 1106–1123. https://doi.org/10.1016/j.buildenv.2005.04.021

[138] Wong, J.K.W., Li, H., Wang, S.W. 2005. "Intelligent building research: a review.", Automation in Construction, 14 (1), 143–159.

[139] Wong, Kwok Wai Johnny. 2007. "Development of selection evaluation and system intelligence analytic models for the intelligent building control systems". PhD thesis, The Hong Kong Polytechnic University.

[140] WRI Ross Center for Sustainable Cities. 2011. "What Is a Smart Building? | Building Efficiency Initiative" Retrieved June 7, 2020 (https://buildingefficiencyinitiative.org/articles/what-smart-building).

[141] Yang, J., Peng, H. 2001. “Decision support to the application of intelligent building technologies”, Renewable Energy 22, 67–77.

[142] Yilmaz, K. 2013. Comparison of Quantitative and Qualitative Research Traditions: Epistemological, theoretical, and methodological differences. European Journal of Education, 48(2), 311–325. https://doi.org/10.1111/ejed.12014

[143] Yin, R. K. 1984. “Case study research: design and methods”, Sage, Thousand Oaks, CA.

Bibliography of the Reviewed Evaluation Systems

[144] BCA Green Mark. 2015. “GM NRB: Green Mark for Non-Residential Buildings”. Singapore. (https://www1.bca.gov.sg/docs/default-source/docs-corp-buildsg/sustainability/green_mark_nrb_2015_criteria.pdf)

[145] BRE. 2018. “BREEAM UK New Construction”. Technical Manual SD5078 (https://bregroup.com/products/breeam/)

[146] Cerway. 2011. “HQE Non-residential building” (https://www.behqe.com/offers/non-residential-building)

[147] DGNB GmbH. 2020. “DGNB System New Construction”. (https://www.dgnb-system.de/en/system/)

[148] EnergyStar. “How the 1-100 ENERGY STAR Score Is Calculated.” (https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/how-1-100).

[149] Fitwel. 2021. “Fitwel V. 2.1 Multi-tenant Whole Building “. (https://www.fitwel.org/resources)

[150] GBCA. 2020. “Green Star Design & As Built Guidance for industrial projects”. (https://www.nzgbc.org.nz/Attachment?Action=Download&Attachment_id=3699)

[151] GBCI. 2020. “GRESB for Real Estate Assessment” (https://www.gresb.com/nl-en/products/real-estate-assessments/)

[152] GBI. 2016. “Guiding Principles Compliance for New Construction & Modernization V.2”(https://thegbi.org/content/misc/Guiding_Principles_Compliance_New_Construction_Technical_Reference_Manual.pdf)

[153] HKGBC. 2021. “BEAM Plus New Buildings”. BEAM Society Limited, V.2.0. (https://www.beamsociety.org.hk/files/download/NBv2_0_2021_FinalVersion.pdf)

[154] IFC. 2019. “EDGE Certification V.2.1” (https://edgebuildings.com/certify/certification/)

[155] iiSBE. 2012. “SBTool 2012-2020” (https://www.iisbe.org/node/140)

[156] ILFI. 2019. “Living Building Challenge 4.0” (https://living-future.org/lbc/)

[157] IWBI. 2020. “WELL V.2 Rating” (https://v2.wellcertified.com/en/wellv2/overview)

[158] JaGBC. 2014. ”CASBEE for Building (New Construction)”, (https://www.ibec.or.jp/CASBEE/english/download.htm)

[159] NABERS. 2019. “NABERS Office Building Rating” (https://www.nabers.gov.au/ratings)

[160] PCA. 2017. “PCA for industrial/commercial buildings” (https://www.pcaservices.com.au/)

[161] USGBC. 2014. “LEED V.4 New Construction” (https://www.usgbc.org/)

APPENDIX A: Focus Group Interview Tool

Topic	Related IB Index Domains	Questions
Asset Management (CMMS) & Data Governance	PD01, PD02, PD03, CMM02	Explain your lift/elevator management plan Do you have any life/elevator energy recovery system? Do you have any lift/elevator drive and control system? Is your lift/elevator connected to IoT and BMS? What CMMS system would be more technologically advanced? Do you have any data governance system (related to the asset)? Do you use any common data environment? Explain your standards for asset data QA/QC, asset data verification (as-built), condition assessment. What documents do you use to perform your daily tasks (asset inventory, O&M manuals, BIM models, etc.) What technologies do you use to perform your daily tasks?
Asset Management (VFA) & Document Maintenance	PD01, PD02, PD03, CMM02	What is your asset & operation data management framework? Do you have any asset management plan standard? Do you have any asset capital planning? Explain the VFA system. What features? (life-cycle asset tracking and forecast) What VFA system would be more technologically advanced? Explain your standards for asset data QA/QC, asset data verification (as-built), condition assessment. What documents do you use to perform your daily tasks (asset inventory, O&M manuals, BIM models, etc.) What technologies do you use to perform your daily tasks?
Cybersecurity Program	PD01, CMM07, IDA01	Explain your cybersecurity program What are your information accessibility/exchange/storage protocols? What are your cybersecurity requirements (for facility managers/ for tenants)?

Procurement System, Project Management & Capital Planning	PD01, PD02, PD03, PD05	What are the Microsoft smart building initiatives? Explain your procurement system (bidding, competency assessment) What are your project delivery requirements? Explain your data governance system (roles & responsibilities). What are your information requirements? (Organizational information for projects) Do you have a data validation & verification standard?
BIM Deliveries	PD04	Do you have any BIM BEP? Explain your BIM delivery requirements (design, construction, as-built). What are your BIM uses? Do you integrate BIM deliveries into other systems (AMS, BMS, IoT, DT). Explain the digital building lifecycle. What technologies do you use to perform your daily tasks? What non-BIM documents do you use to perform your daily tasks?
Sustainability Certification	PD06	Do you have any sustainability masterplan? Do you require any sustainability certification for Microsofts buildings? (LEED, LBC, WELL) Do you have any program regarding occupants health & well being, productivity, satisfaction? Do you have any office/building quality assessment (e.g., IEQ) Do you have any energy/water efficiency program? Do you have any carbon footprint tracking program? Do you have any POE program?
Cyber-infrastructure	IDA01	Explain your cyber-infrastructure regarding network cable infrastructure, Ethernet, wireless coverage, mobile coverage, and cabling. What are the digital infrastructure requirements for IoT, DT, and data governance services? Explain your lighting network infrastructure.
IoT Network	IDA01, IDA06, IDA08, IDA09, IDA13, CMM06	How does Microsoft define IoT and its different levels of integration?

		How IoT is being adopted and implemented at Microsoft? (IoT initiatives) Explain your IoT sensors and connectivity Explain the IoT data analytics. What other systems/platforms are connected to your IoT system? What information is being shared with tenants? How?
Building Management System	IDA01, IDA09, IDA11, IDA12, CMM01, CMM04, CMM06, CMM08, CMM09, CMM10, CMM11	Explain Microsoft BMS. What features? What building systems are connected to the BMS? What other systems/platforms are connected to your BMS system?
Building Access, Safety & Security	IDA03, IDA08	What is your building accessibility protocol? What technologies do you use for building access management & monitoring? What access control devices do you use? Explain your standards regarding tenants' life safety, building security and disaster planning/management Do you use any occupancy detection and occupants counting devices? Do you use any surveillance system (CCTV)?
Energy Generation	IDA02	Do you have any renewable energy generation initiative? Explain your energy storage/distribution system. Do you have any energy efficiency optimization program? Do you purchase green energy?
Parking Facilities	IDA04, IDA05, CMM11	Explain your parking maintenance/management program Do you have any smart car park management system? Do you have any car/parking spot detection technology (cameras, license plate recognition) Do you have any EV charging spot? Explain the technologies.
Building Controls & Information Services (for Tenants)	IDA06, IDA07, IDA11, IDA12, CMM08, CMM09	What digital information services are available to tenants (e.g., room booking, building performance dashboard, lockers booking, visitor arrival) What building controls are available to tenants (e.g., heating/cooling, lighting, ventilation, smart envelop)

		Other available services? (Digital art, tenants' platform, etc.)
Vertical Transport	CMM05	Explain your lift/elevator management plan Do you have any life/elevator energy recovery system? Do you have any lift/elevator drive and control system? Is your lift/elevator connected to IoT and BMS?
Building Systems Controls	IDA09, IDA13, CMM04, CMM08, CMM09, CMM10, CMM11	Explain the HVAC system regarding demand control ventilation, variable speed fan, refrigerant flow system. Explain the hydraulic (water supply) system regarding appliances and efficiency system. What building systems are integrated to BMS, AI, and IoT? How? Explain your demand side management plan (system integrations, efficiency KPIs, demand prediction, reporting system, etc.) Explain the control devices/systems for HVAC, water supply, and energy supply systems.
Power Supply	IDA10	Explain the power supply regarding diversity of primary electrical feeds and uninterruptible power supply Do you use any smart electricity meters?
AI/ML/DT Integration	PD04, CMM01, CMM04	Explain the DT in Microsoft. What features? What are the data requirements for deploying DT? What building systems are connected to the DT system? What other systems/platforms are connected to the DT system? Do you have a standard digital twin management plan or guideline? How the information is being shared with facility owners/tenants? What are the levels of maturity for DT deployment?

APPENDIX B: Case Study 1

This section presents the results of evaluating the case study 1 buildings using the IB Index capabilities. A detailed breakdown of the overall assessed building intelligence is provided according to the three pillars of the IB Index – Project Delivery, Infrastructure, Devices and Applications, and Controls Monitoring and Management.

Figure 1. Project Delivery Pillar Evaluation of Case Study 1

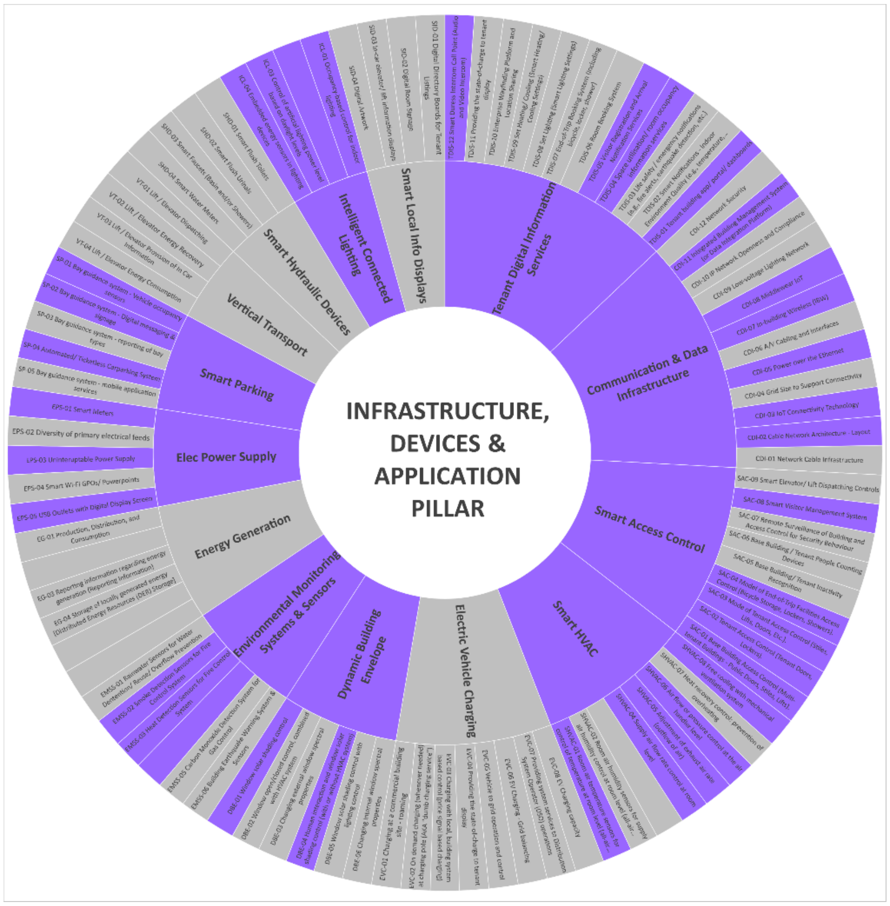


Figure 2. Infrastructure, Devices, and Application Pillar Evaluation of Case Study 1

Figure 3. Controls Monitoring and Management Pillar Evaluation of Case Study 1

Case Analysis – Outcomes

This section presents the results of case analysis regarding the impacts of the building intelligence (based on the intended capabilities) on the performance of buildings on the organization 1 building. The outcomes of the evaluated buildings' performance were categorized based on environmental, economic & fiscal, and social & behavioral impacts.

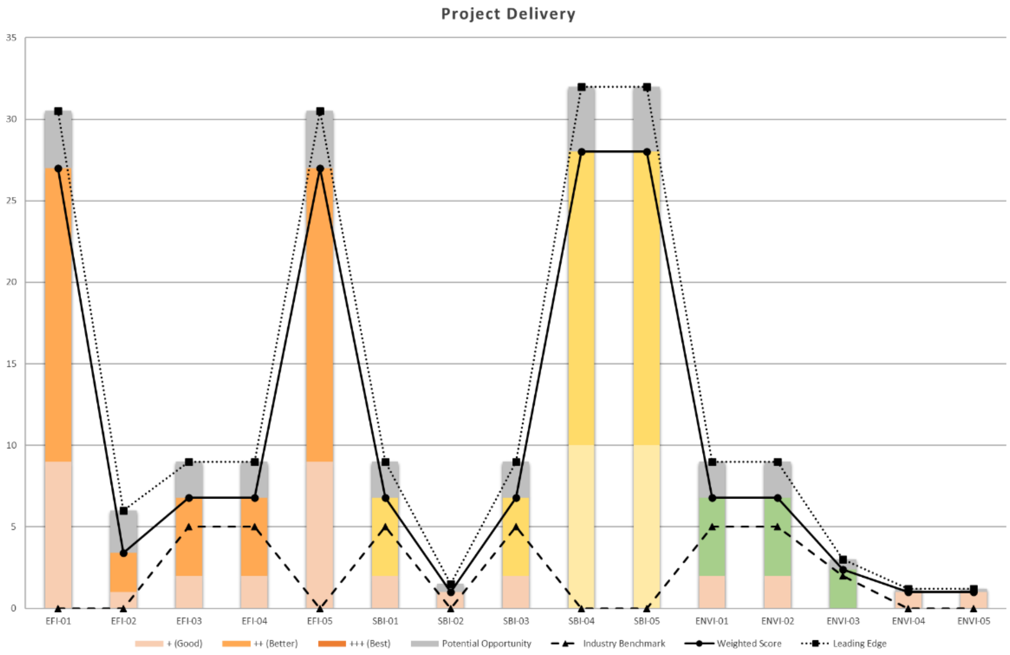


Figure 4. Outcomes identified across Project Delivery Pillar

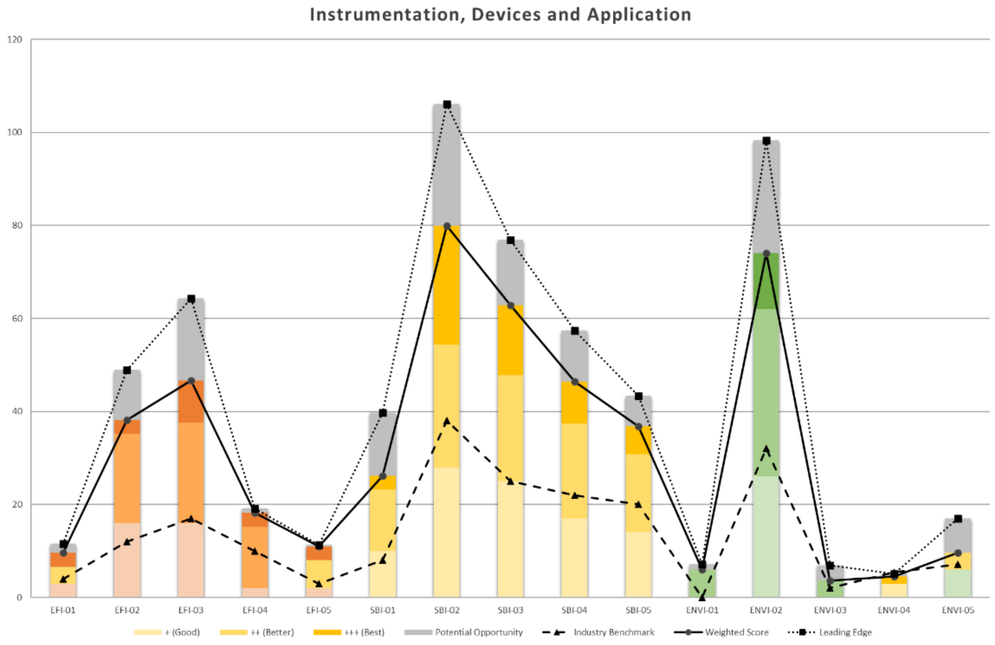


Figure 5. Outcomes identified across Infrastructure, Devices & Applications Pillar

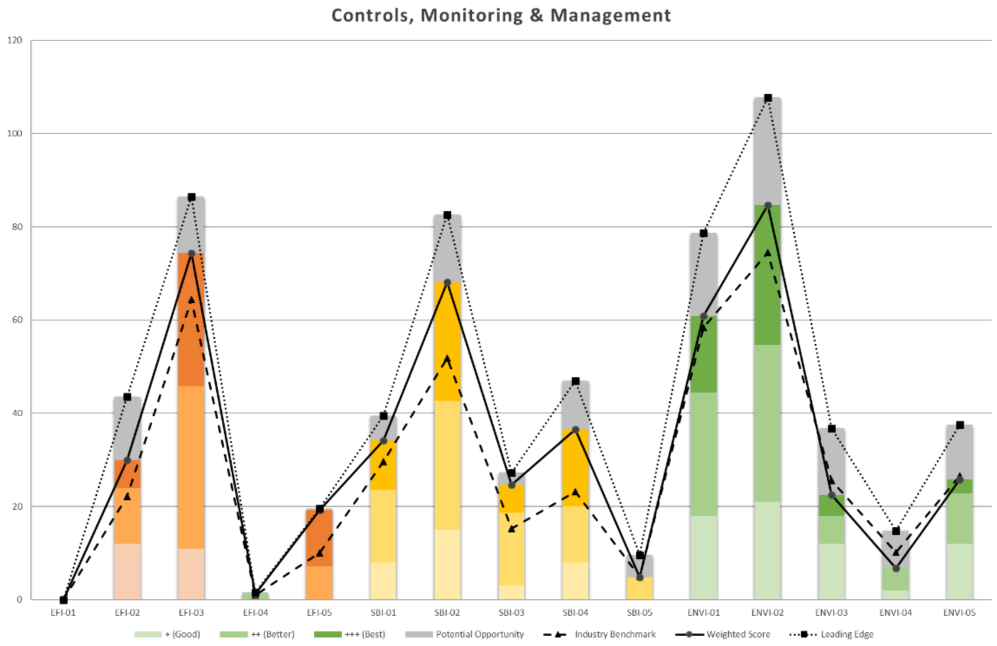


Figure 6. Outcomes identified across Controls Monitoring & Management Pillar

APPENDIX C: Case Study 2

This section presents the results of evaluating the case study 2 buildings using the IB Index capabilities. A detailed breakdown of the overall assessed building intelligence is provided according to the three pillars of the IB Index – Project Delivery, Infrastructure, Devices and Applications, and Controls Monitoring and Management. Also, the organization 2 has recently developed multiple initiatives related to intelligent buildings that it aims to apply in its campus expansion project. Thus, this analysis contains a comparison of evaluated buildings' current score and potential scores (for the project delivery pillar assuming that the initiatives were implemented) in order to provide the effectiveness of the examined initiatives on the building intelligence.

Project Delivery

Overall, the evaluated buildings' intelligence regarding project delivery planning and specification is consistent with the current industry. Organization 2 has developed various standards and protocols for using data. For example, in terms of data governance, it defined data warehousing strategy. it also uses multiple data lakes that serve different purposes with a data Catalogue over the top of them that determines data location and access rules. Moreover, regarding information requirements, organization 2 has facility system business rules process. In addition, it has standard documents for information delivery such as naming conventions and communication protocols.

Figure 1. Project Delivery Pillar Evaluation of Case Study 2

Figure 1 above shows the Project Delivery domains and capabilities that were applicable for scoring. Below is a list of the selected capabilities:

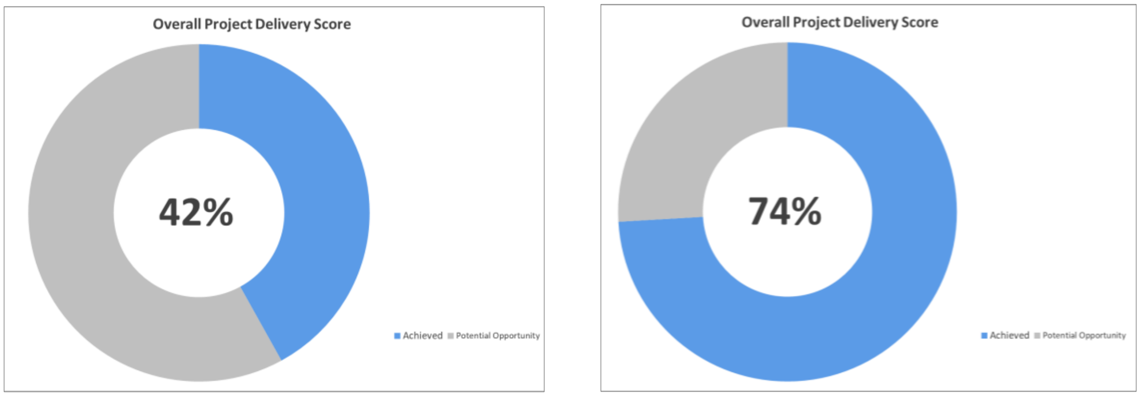
(1) SBS - Smart Building Specification:
    a. SBS-01 Smart Building Brief
    b. SBS-02 Smart Building Blueprint
    c. SBS-03 Integrated Communications Network
    d. SBS-04 Integration platform specification
    e. SBS-05 Asset & operations data management framework
    f. SBS-06 Cyber security requirements
(2) DG - Data Governance:
    a. DG-01 Agreed data/ information management roles and responsibilities
    b. DG-02 Agreed data/ model and progression deliverables
    c. DG-03 Specification & use of common data environment
    d. DG-04 Data quality assurance framework
(3) IR - Information Requirements:

  a. IR-01 Employer/ Exchange information requirements
  b. IR-03 Asset information requirements/ asset information model
  c. IR-05 Asset classification scheme & naming conventions

(4) BIM Delivery Framework:
  a. BDF-01 BIM requirements for projects
  b. BDF-02 Design BIM management plan
  c. BDF-03 Construction BIM management plan
  d. BDF-04 Organisational / asset management plan
  e. BDF-05 Digital Twin strategy/ management plan

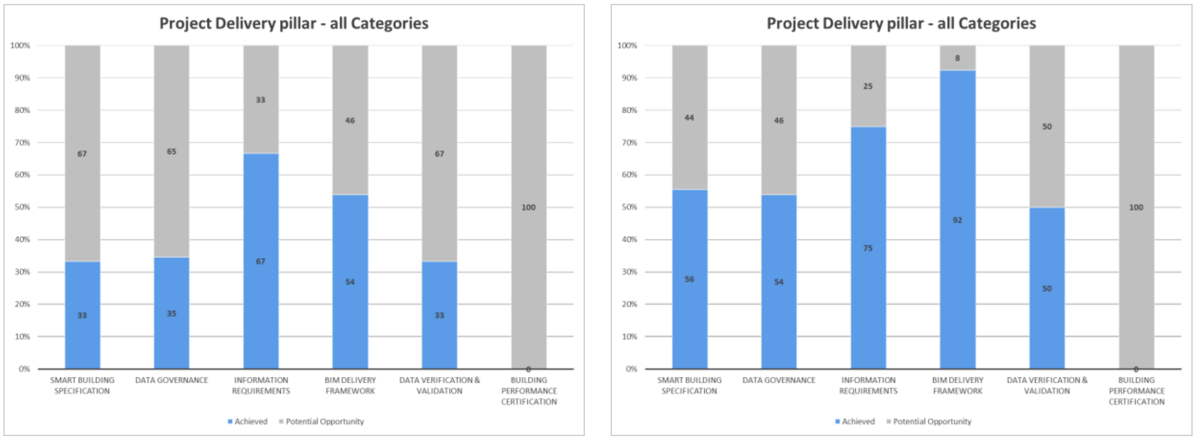
(5) DVV Data Verification and Validation:
  a. DVV-01 Data verification/ validation of digital O&M manuals
  b. DVV-02 Design / construction verification & validation of as-built data/ models
  c. DVV-03 Verification and validation of digital asset data (e.g.,, asset registry data)

The Building Performance Certification (BPC) domain was not applicable to the case study 2 Campus and was also not applicable to the two buildings as there are no LEED Certifications on the campus. Consequently, the overall Project Delivery Pillar for the two buildings scored a total of 42%. When the case study two smart building initiatives are considered, the score increases to 74%, see Figure 2, achieving a mid-level ranking on the preliminary IB Index evaluation system. level ranking on the preliminary IB Index evaluation system.



(a) (b)

Figure 2. Project Delivery Pillar – evaluation of the selected buildings (a) without the initiatives (b) with the initiatives

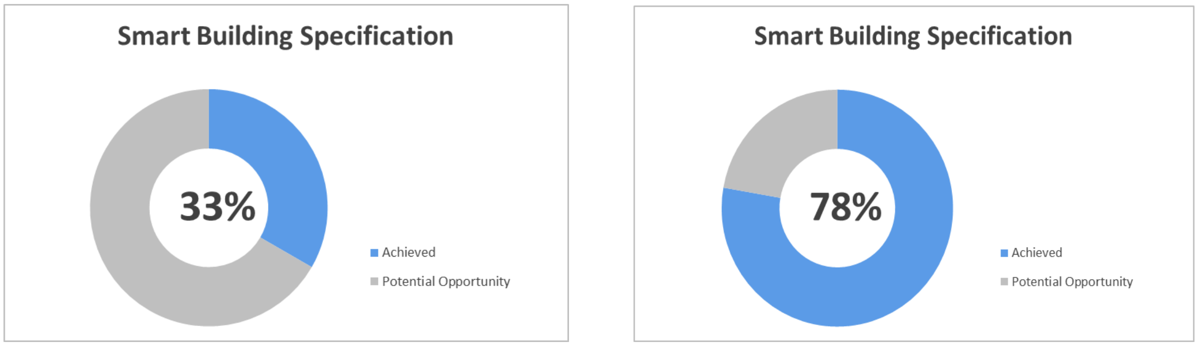


(a) (b)

Figure 3. Project Delivery Pillar – (breakdown of the evaluation based on the domains

The overall Project Delivery score is illustrated in the pie charts below relative to the pillar six Domains.

SBS - Smart Building Specification

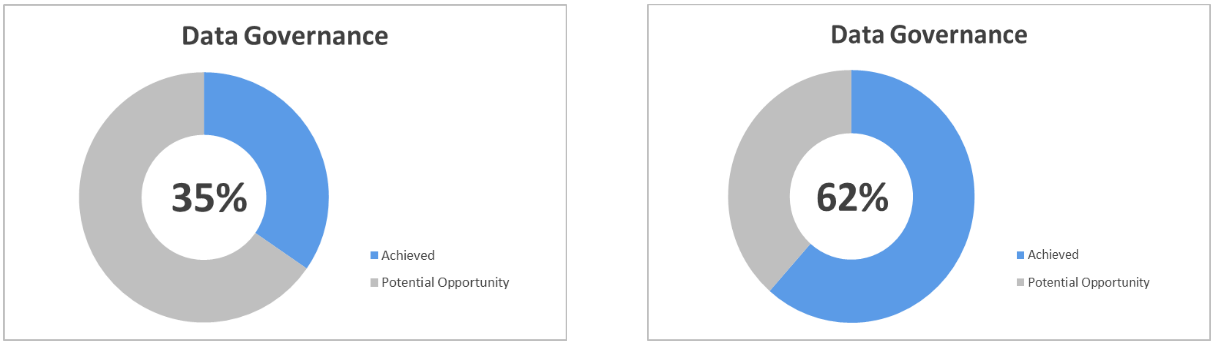


(a) (b)

Figure 4. Smart Building Specification domain – evaluation of the selected buildings (a) without the initiatives (b) with the initiatives

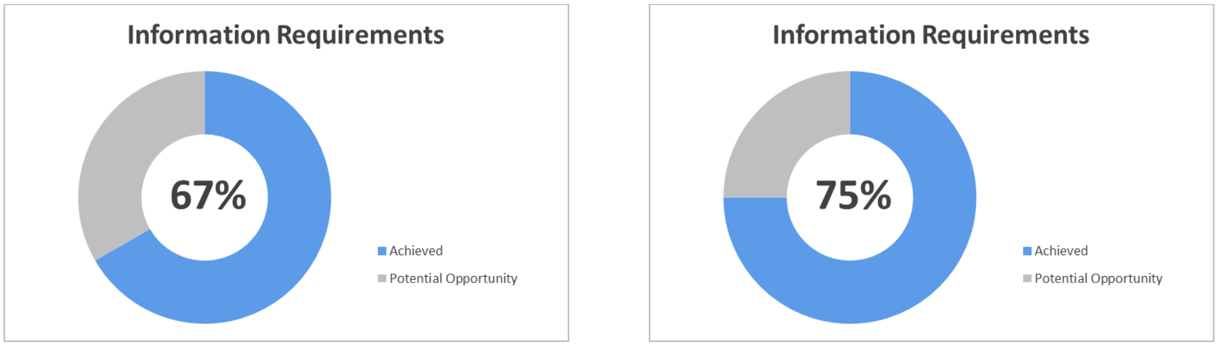
Building Lifecycle Approach

The deployment of the organizations 2 initiative related to information lifecycle management may reduce the need for traditional requirements specification to support data governance, information requirements, and data validation and verification and improve stakeholder collaboration and information sharing. However, the details of the initiative were not provided in sufficient detail in order to create an alignment with IB Index capability indicators and satisfy the requirements of the evaluation criteria. It was evident from the interviews that the organization 2 approach aims to standardize the delivery and use of BIM models which is currently not occurring nor optimal. Further details on the data governance and information requirements specifications are therefore required in order to benchmark this capability conclusively.



(a) (b)

Figure 5. Data Governance domain – evaluation of the selected buildings (a) without the initiatives (b) with the initiatives



(a) (b)

Figure 6. Data Governance domain – evaluation of the selected buildings (a) without the initiatives (b) with the initiatives

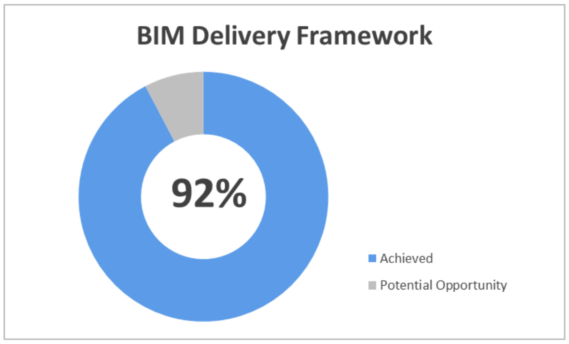


Figure 7. BIM Delivery Framework domain – evaluation of the selected buildings with the initiatives This domain could not be applied to the two selected buildings as they were delivered using traditional methods and were not BIM-based projects.

As for asset management and facility O&M, organization 2 has comprehensive standards for asset information requirements as well as procedures for organizational asset management while there are rooms for improvement regarding process automation and integration between technologies (e.g., BMS, CMMS, and IoT) and O&M practices. For example, the current condition assessment process is manual and technicians on the field do not use any tool. Furthermore, there are interoperability issues between CMMS, VFA, and project management platforms.

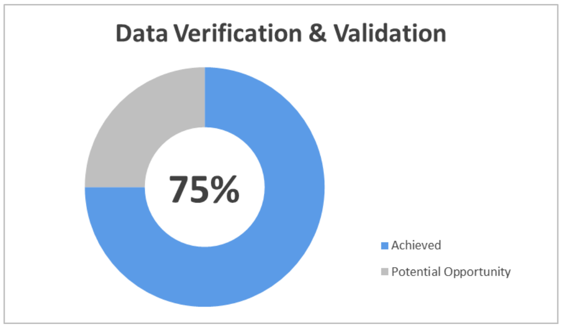


Figure 8. Data Verification & Validation domain – evaluation of the selected buildings with the initiatives This domain could not be applied to the two selected buildings as they were delivered using traditional methods and were not BIM-based projects.

Organization 2 develops and implements various digital technologies that are applicable in intelligent buildings (digital twin, IoT, connectivity protocols, etc.). Thus, creating workflows for adopting and implementing these technologies in the context of buildings lifecycle can significantly improve organization 2 building intelligence in this pillar.

Infrastructure, Devices, and Applications

The results of the case study show that the evaluated building intelligence is aligned with or better than the industry benchmark.

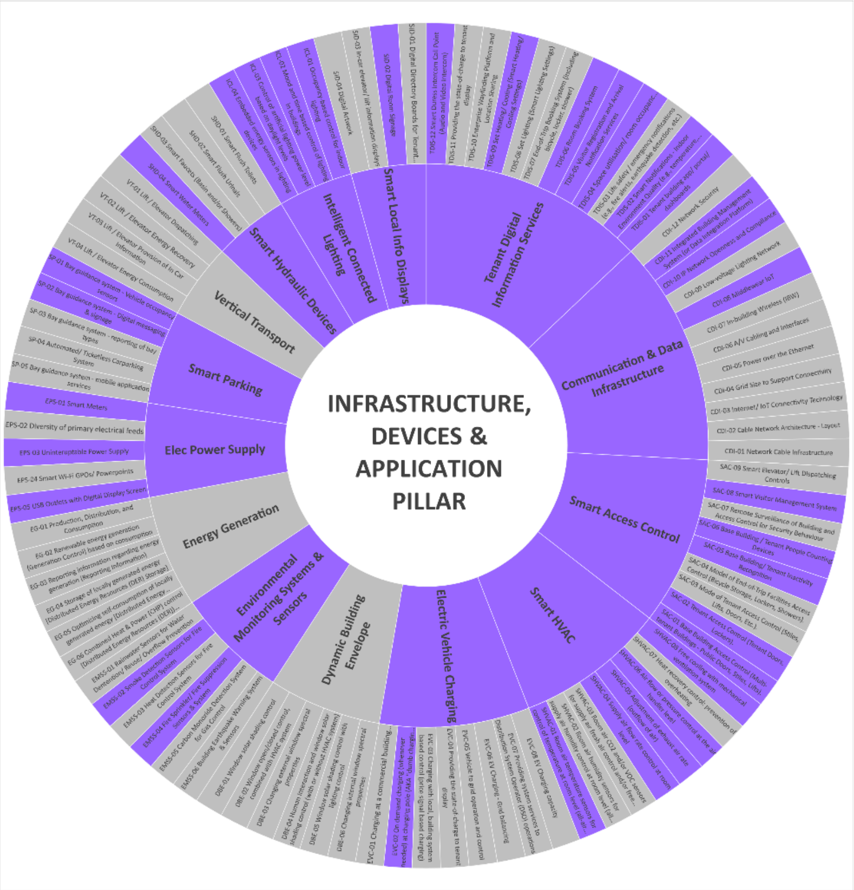


Figure 9 Infrastructure, Devices, and Application Pillar Evaluation of Case Study 2

Figures 9 above shows the IDA pillar and the domains and capabilities that were possible and/ or applicable to the assessment process including:

(1) CDI - Communication and Data Infrastructure:
    a. CDI-08 Middleware IoT
    b. CDI-10 Network Openness and Compliance
    c. CDI-11 Integrated Building Management System
(2) EG - Energy Generation:
    a. No data was collected
(3) SAC - Smart Access Controls:
    a. SAC-01 Base Building Access Control (Multi-tenant Buildings - Public Doors, Stiles, Lifts)
    b. SAC-02 Tenant Access Control (Tenant Doors, Lockers)
    c. SAC-03 Mode of Tenant Access Control (Stiles, Lifts, Doors, Etc.)
    d. SAC-04 Model of End-of-Trip Facilities Access Control (Bicycle Storage, Lockers, Showers)
    e. SAC-05 Base Building/ Tenant Inactivity Recognition
    f. SAC-06 Base Building / Tenant People Counting Devices

  - g. SAC-07 Remote Surveillance of Building and Access Control for Security Behaviour
  - h. SAC-08 Smart Visitor Management System
  - i. SAC-09 Smart Elevator/ Lift Dispatching Controls

(4) SP – Smart Parking:

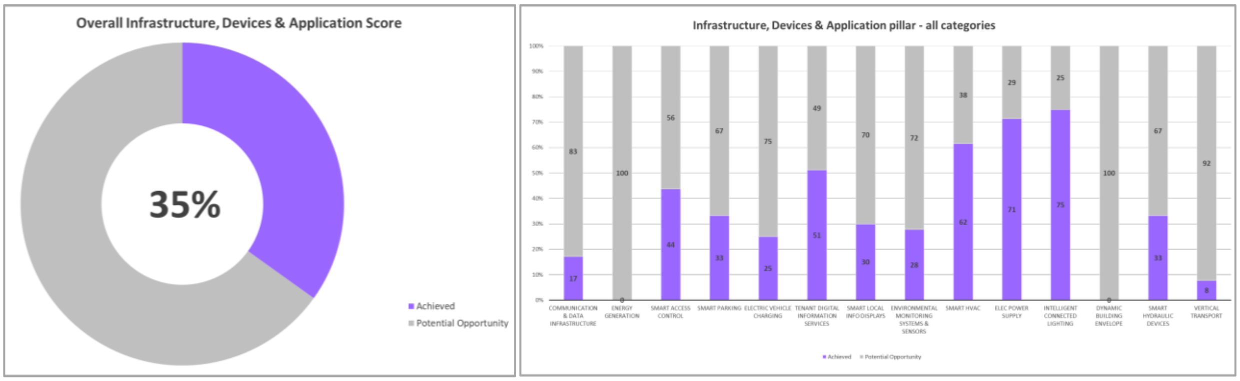
  - a. SP-01 Bay guidance system - Vehicle occupancy sensors
  - b. SP-02 Bay guidance system - Digital messaging & signage
  - c. SP-03 Bay guidance system - reporting of bay types
  - d. SP-04 Automated/ Ticketless Carparking System

(5) EVC - Electric Vehicle Charging:

  - a. EVC-01 Charging at a commercial building site – roaming
  - b. EVC-02 On demand charging (whenever needed) at charging pole (AKA "dumb charging service")
  - c. EVC-03 Charging with local, building system-based control (price signal-based charging)
  - d. EVC-04 Providing the state-of-charge to tenant display

(6) TDIS - Tenant Digital Information Services:

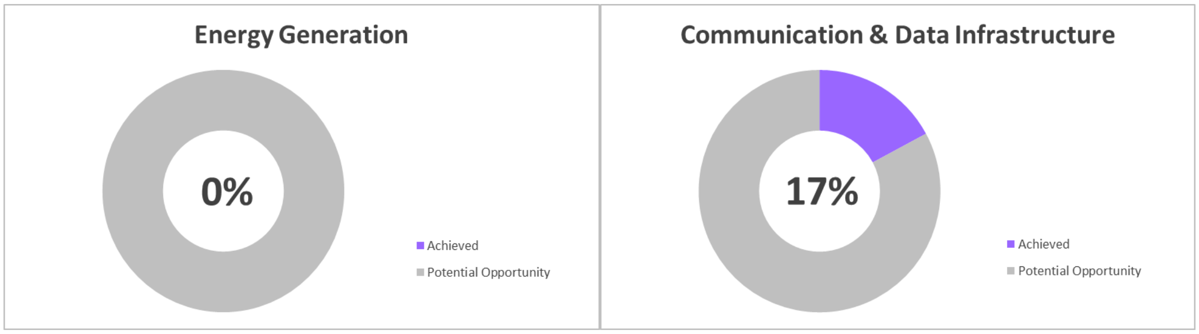
  - a. TDIS-01 Tenant building app/ portal/ dashboards
  - b. TDIS-02 Smart Notifications - Indoor Environment Quality (e.g.,, temperature, humidity, CO2, carbon monoxide, etc.)
  - c. TDIS-03 Life safety / emergency notifications (e.g.,, fire alerts, earthquake detection, etc.)
  - d. TDIS-04 Space utilisation/ room occupancy information services
  - e. TDIS-05 Visitor Registration and Arrival Notification Services
  - f. TDIS-06 Room Booking System
  - g. TDIS-07 End-of-Trip Booking System (including bicycle, locker, shower)
  - h. TDIS-08 Set Lighting (Smart Lighting Settings)
  - i. TDIS-09 Set Heating/ Cooling (Smart Heating/ Cooling Settings)
  - j. TDIS-10 Enterprise Wayfinding Platform and Location Sharing
  - k. TDIS-11 Providing the state-of-charge to tenant display
  - l. TDIS-12 Smart Duress Intercom Call Point (Audio and Video Intercom)



(a) (b)

Figure 10 Overall Score of IDA Pillar and its Breakdown into Domains

As shown in Figure 10, the current overall score of the Infrastructure, Devices, and Applications is 35%. Lighting System and Electrical Power Supply domains received highest scores. Although Energy Generation (due to lack of on-site renewable sources) and Vertical Transport (due to lack of integration with other building systems) received lowest scores both domains are expected to be tangibly improved after deploying the initiatives. Most reviewed buildings on the organization 2 campus meet the basic intelligent buildings requirements in terms of access control, parking facilities, power supply, and hydraulic devices. For smart access control, most buildings are equipped with badge readers for people to scan. They also have cameras to identify who is entering the building. However, there is currently no real-time occupancy sensors or people counters installed in buildings. Regarding power supply, Microsoft has advanced systems for energy metering and power usage report while there is no internal mechanism for integrated power storage and distribution.



(a) (b)

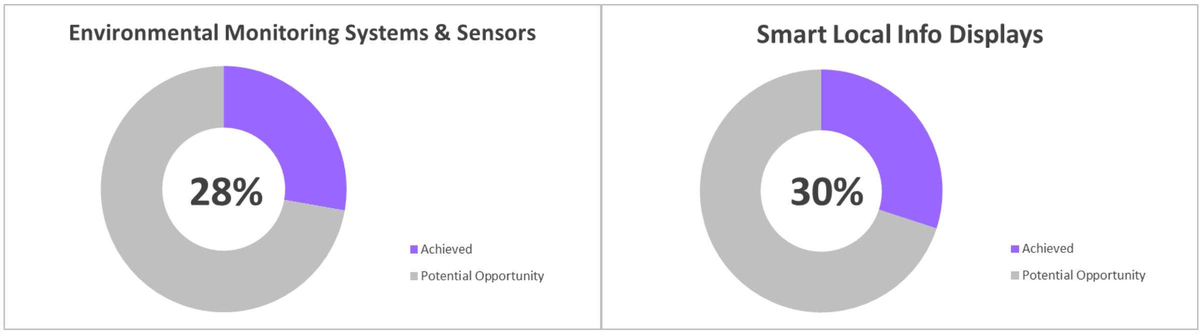
Figure 11. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Communications and Data Infrastructure (b) Energy Generation

(a) (b)

Figure 12. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Smart Access Control (b) Smart Parking

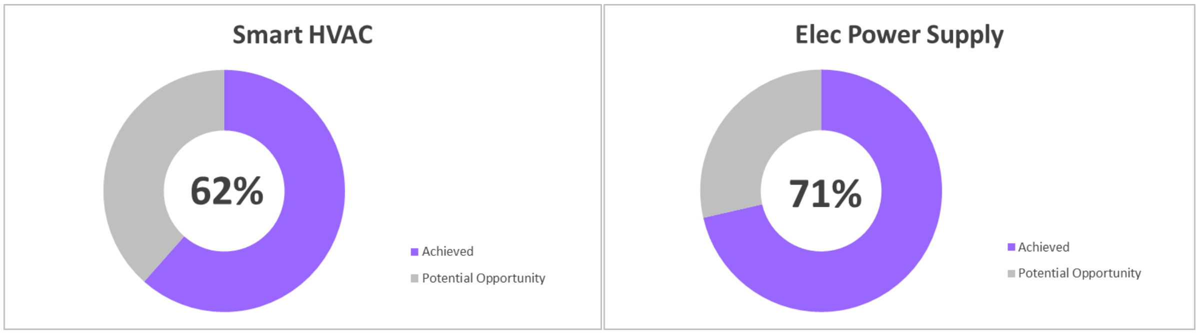
(a) (b)

Figure 13. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Tenant Digital Information Services (b) Electric Vehicle Charging



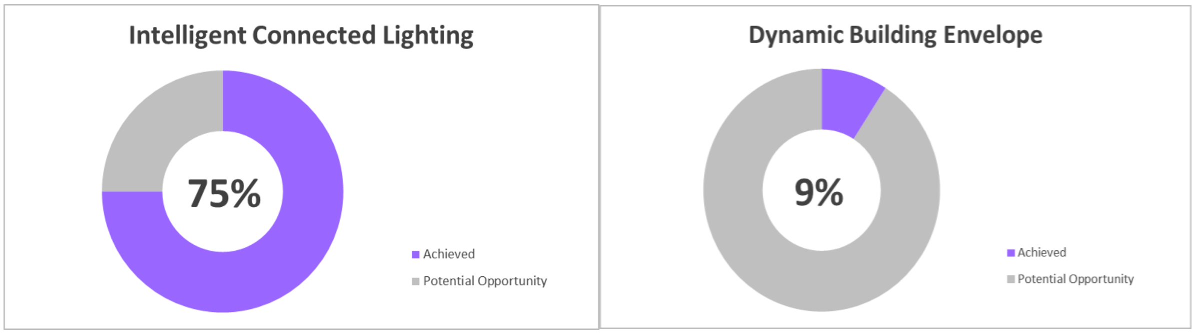
(a) (b)

Figure 14. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Environmental Monitoring Systems & Sensors (b) Smart Information Displays



(a) (b)

Figure 15. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Smart HVAC (b) Electric Power Supply



(a) (b)

Figure 16. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Intelligent & Connected Lighting (b) Dynamic Building Envelope

(a) (b)

Figure 17. Infrastructure, Devices and Applications pillar for the selected buildings – (a) Smart Hydraulic Devices (b) Vertical Transport

In some domains such as smart HVAC and intelligent connected lighting, the building performance is substantially higher than the benchmark due to using advanced technologies that enables data-driven systems’ utilization and management. For instance, most spaces in the evaluated buildings have motion sensors for lighting control. Also, some buildings have additional sensors for ambient sunlight so the lightings in the building change gradually over time to accommodate for changes in sunlight.

In some other areas like energy generation and environmental monitoring systems & sensors, organization 2 did not aim for using advanced technologies or higher levels of building intelligence due to the lack of internal and external demands for them. For example, among different IEQ factors, temperature was mostly measured and considered for system operation because other factors (e.g., humidity) do not have much priority in the Pacific Northwest region.

Controls, Monitoring, and Management

The organization 2 building intelligence in this pillar is also close to the industry benchmark.

Figure 18 Controls Monitoring and Management Pillar Evaluation of Case Study 2

Figure 18 above shows the Controls Monitoring and Management domains, where those that are highlighted in red represent those domains and capabilities that were possible to evaluate (as listed below):

(1) IBMS - Intelligent BMS:
  a. IBMS-01 Intelligent building management system
  b. IBMS-02 Use of AI / ML analytics for asset maintenance and performance optimisation
  c. IBMS-03 Fault detection and diagnostics (FDD)
  d. IBMS-04 Monitoring & control of lighting
  e. IBMS-05 Monitoring & control of HVAC/ temperature
  f. IBMS-09 Monitoring & control of environmental sensors (e.g.,, IAQ)
  g. IBMS-11 Remote surveillance of building behaviour & performance

(2) VC – Ventilation Controls:
  a. VC-01 Room based supply air flow control
  b. VC-02 Adjustment based on outdoor air flow or exhaust air rate
  c. VC-05 Room based air temperature control – Combined air-water systems
  d. VC-06 Supply air temperature control
  e. VC-07 Heat recovery control: Prevention of overheating
  f. VC-09 Free cooling with mechanical ventilation system

(3) DSM – Demand Side Management:
  a. DSM-05 Demand-side energy management and communication (reporting)
  b. DSM-06 Power flows measurement and communications (reporting)
  c. DSM-13 Energy cost allocation for heating, cooling and water*
  d. DSM-18 Demand side management control of equipment
  e. DSM-23 Override of DSM control

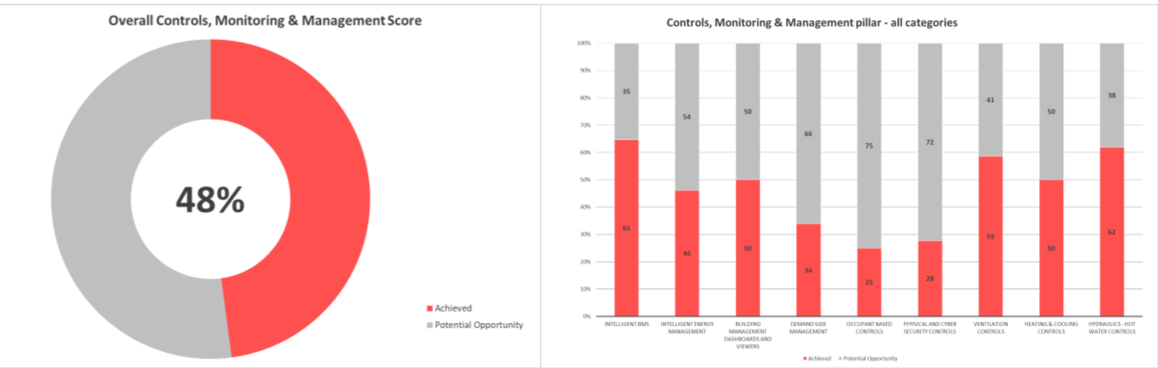
(4) HCC – Heating & Cooling Controls:
  a. HCC-01 Cooling emission control
  b. HCC-03 Control of distributed network chilled water temperature (supply or return)
  c. HCC-04 Control of distributed pumps in network
  d. HCC-05 Intermittent control of emissions and/or distribution
  e. HCC-08 Generator control for cooling
  f. HCC-09 Sequencing of different cooling generators
  g. HCC-10 Heating and cooling set point management
  h. HCC-13 Reporting of information regarding cooling system performance
  i. HCC-14 Heat emission control
  j. HCC-18 Intermittent control of emissions and/or distribution (heating)

(5) IEM - Intelligent Energy Management:

   a. IEM-02 Monitoring & control of Technical Building Systems (TBS) energy performance
   b. IEM-03 Monitoring & control of energy generation & consumption

(6) PCSC – Physical & Cyber Security Controls:
   a. PCSC-03 Smart testing of emergency lighting

(7) HHWC - Hydraulics- Hot Water Controls:
   a. HHWC-01 Control of HW storage charging (with direct electronic heating or integrated electronic heat pump)
   b. HHWC-02 Control of HW storage charging (using hot water generation)
   c. HHWC-03 Control of HW storage temperature, varying seasonally: with heat generation or integrated electronic heating
   d. HHWC-05 Control of HW circulation pump/s
   e. HHWC-06 Reporting of information regarding tenant hot water usage performance
   f. HHWC-07 Monitoring & control of smart meters

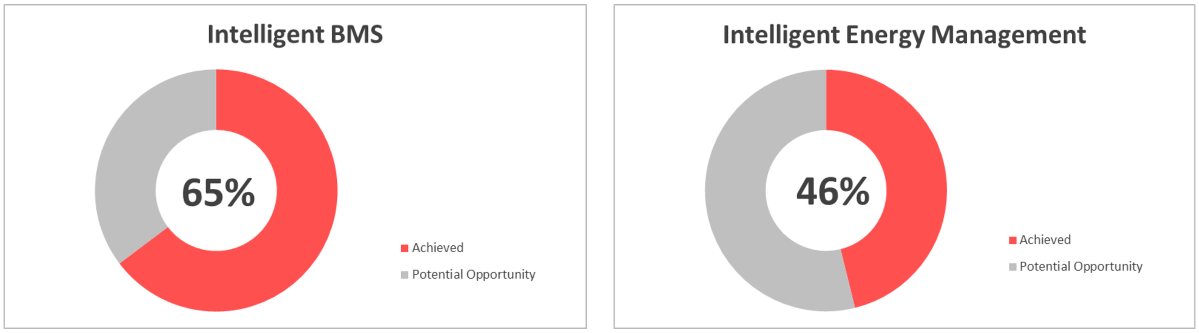


(a) (b)

Figure 19 Overall Score of CMM Pillar and its Breakdown into Domains

According to Figure 19, the Control, Monitoring, and Management pillar overall score is 48%. Building Management System and HVAC controls (heating, cooling, and ventilation) scored high in this pillar. The analysis revealed opportunities for more initiatives and technology leverage in occupants' services and controls. Also, for some domains (e.g., physical and cyber security), the research team was not able to collect all information required for an accurate assessment.

Organization 2 uses various building and energy management systems (Siemens Desigo, ETS system Compass, Johnson Controls Metasys, etc.) within the buildings on its campus. Although they provide advanced features for HVAC system control and energy portfolio management there are rooms for improvements regarding the interoperability between these systems as well as levels of integration with building systems.



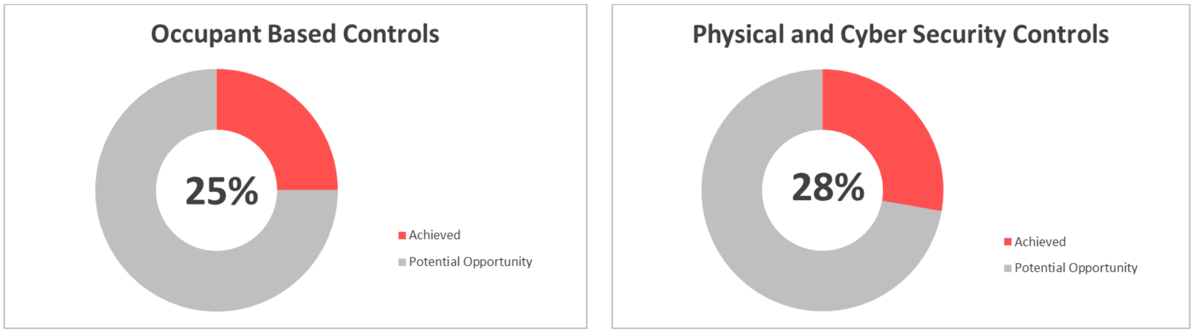
(a) (b)

Figure 20. Controls, Monitoring & Management pillar for the selected buildings – (a) Intelligent BMS (b) Intelligent Energy Management

(a) (b)

Figure 21. Controls, Monitoring & Management pillar for the selected buildings – (a) Building Management Dashboards & Viewers (b) Demand Side Management

As for demand side management, the buildings are highly intelligent regarding equipment control and energy demand prediction/management while the main opportunity for improvements is for micro-grid integration. Another significant opportunity that has been addressed in the organization 2 workflows is the use of AI and ML for control and monitoring.



(a) (b)

Figure 22. Controls, Monitoring & Management pillar for the selected buildings – (a) Occupant Based Controls (b) Physical & Cyber Security Controls

(a) (b)

Figure 23. Controls, Monitoring & Management pillar for the selected buildings – (a) Ventilation Controls (b) Heating & Cooling Controls

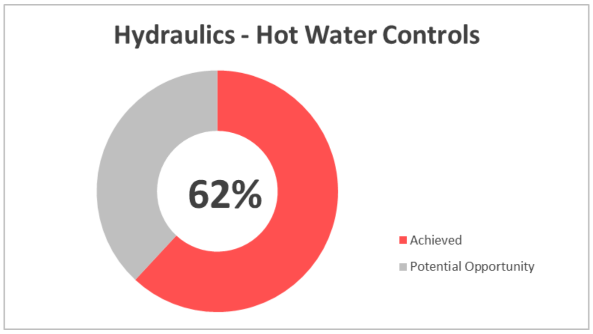


Figure 24. Controls, Monitoring & Management pillar for the selected buildings – (a) Hydraulic Controls

Currently organization 2 uses AI/ML for identifying faults with high priority that should be automatically turned into work orders and dispatched. It is also used for HVAC performance assessment and demand prediction based on occupancy and system feedback. In both cases, further developments are needed to achieve consistent level of connectivity and accuracy/reliability in AI/ML based analytics.

Case Analysis – Outcomes

This section presents the results of case analysis regarding the impacts of the building intelligence (based on the intended capabilities) on the performance of buildings on the organization 2 Campus. The outcomes of the evaluated buildings' performance were categorized based on environmental, economic & fiscal, and social & behavioural impacts.

Project Delivery Outcomes

Figure 25 shows details of the impact criteria and the scores of the organization 2 Campus in the Project Delivery pillar. Also, it shows the received scores in relation to industry benchmark and leading-edge ranges. Based on Figure 25, the evaluated buildings' performance stand above the medium range in reduced delivery cost, predictable financial planning and savings from CAPEX, as well as increased safety/security and information sharing among occupants. Also, the identified outcomes in environmental impacts seem to be related to the lack of data collected in the area campus sustainability and energy efficiency planning.

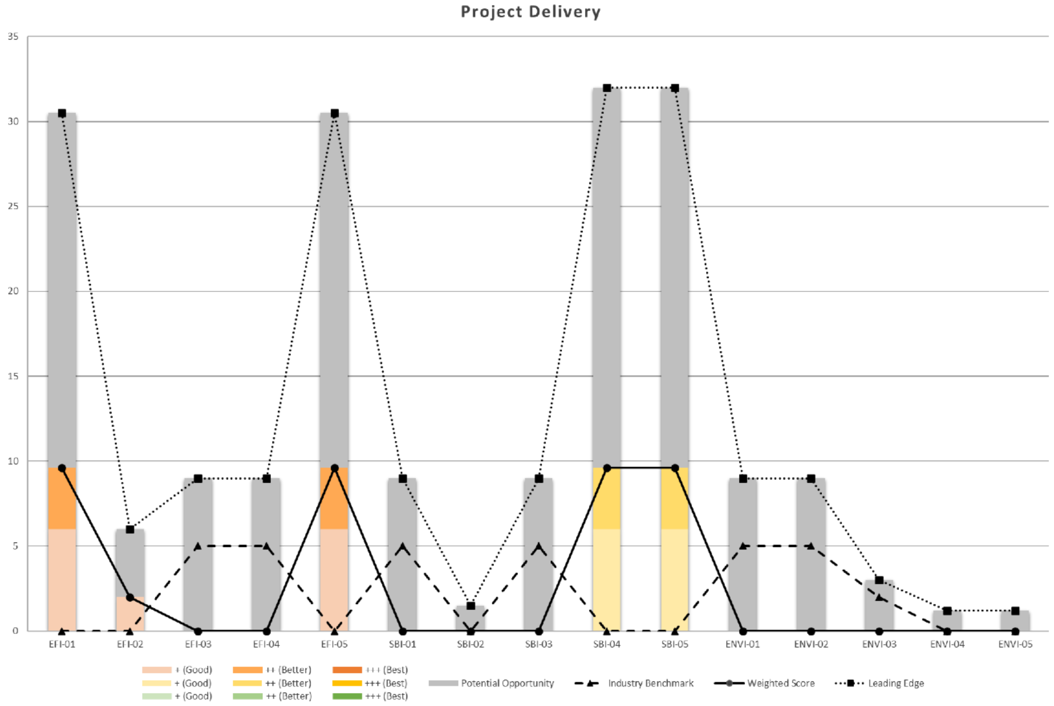


Figure 25. Outcomes identified across Project Delivery Pillar

Infrastructure, Devices & Applications Outcomes

The outcomes of analysis regarding Infrastructure, Devices and Applications pillar are shown in Figures 26. Overall, the performance of evaluated buildings aligns with industry benchmarks. Figure 26 depicts relatively high scores regarding the building systems including installation of high-performance systems (water- and energy-efficient), increased convenience for occupants, and enhanced utilization/optimization of building systems. Also, there are room for improvements in self-energy generation and grid optimization.

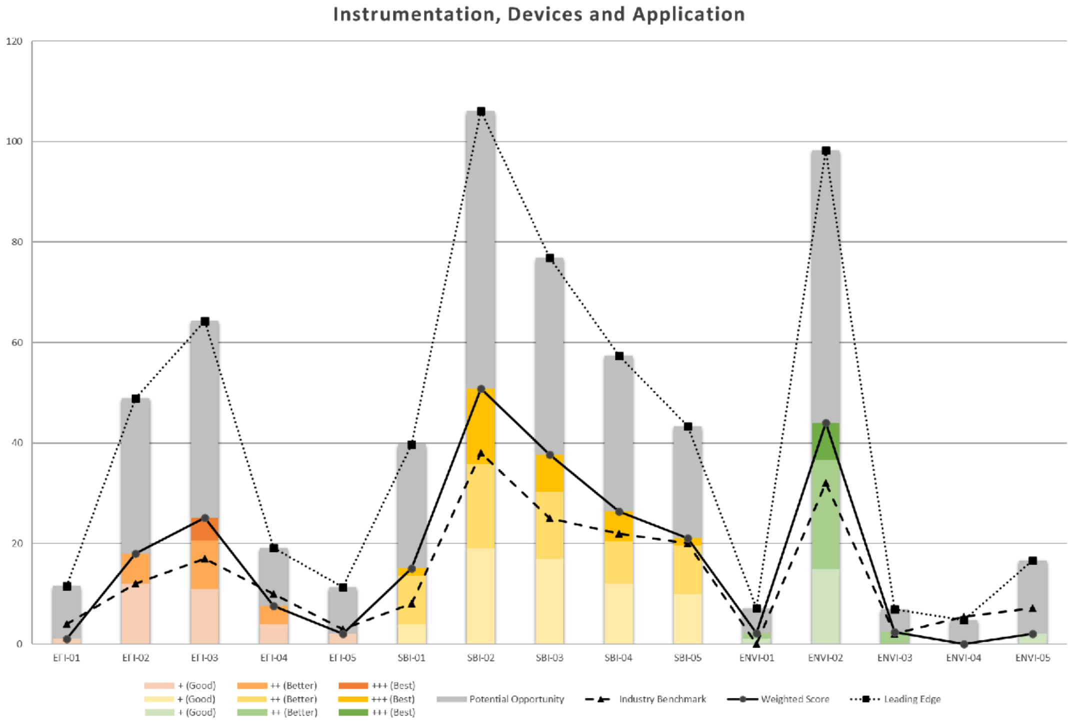


Figure 26. Outcomes identified across Infrastructure, Devices & Applications Pillar

Controls, Monitoring & Management Outcomes

Figure 27 presents the analysis outcomes for the Controls, Monitoring, and Management pillar. Accordingly, there is more fluctuations in identified scores for this pillar although it still aligned with the industry benchmark. The evaluated buildings' performance is slightly above the medium range regarding social impacts and slightly below the medium range regarding environmental impacts.

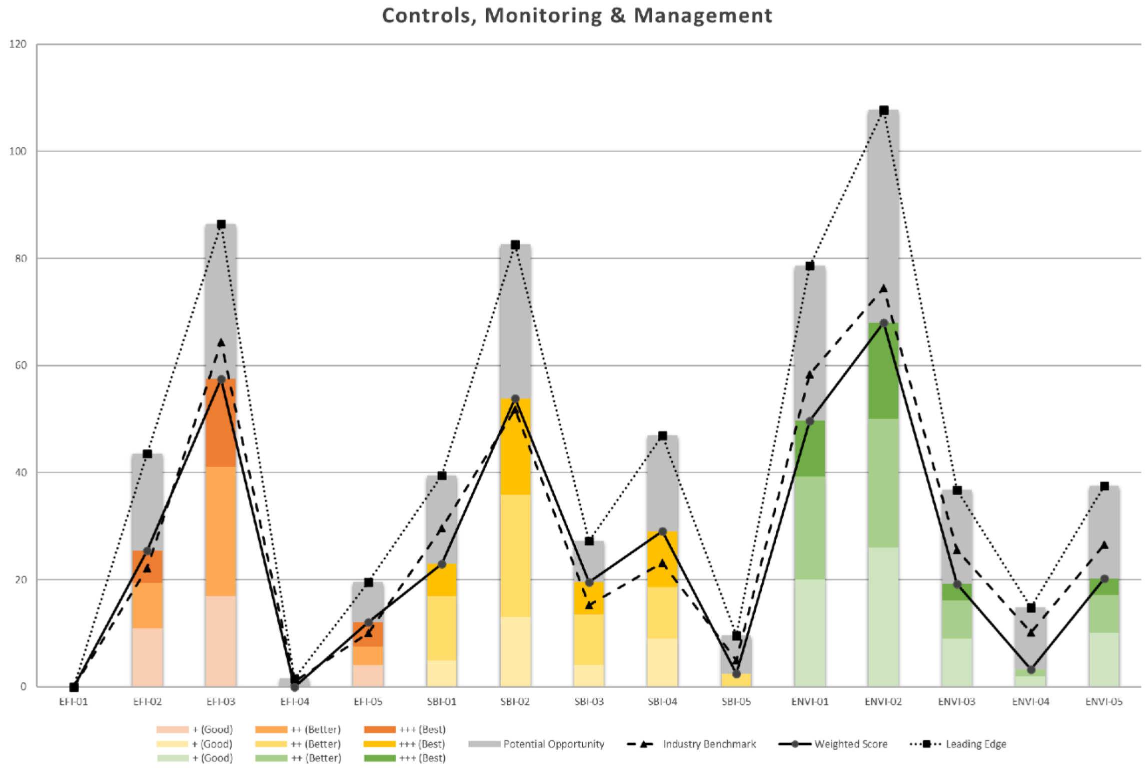


Figure 27. Outcomes identified across Controls Monitoring & Management Pillar

APPENDIX D: Existing Evaluation Systems

Table below introduces the main existing sustainability evaluation and certification systems.

System Name	Organization	Country of Origin	Year	Project Type	Accreditation	Rating Levels	Metrics Type
BCA Green Mark Scheme	The Building and Construction Authority (BCA)	Singapore	2005	Green Mark SLE certification, Green Mark certification covers new and existing buildings (residential and non-residential), as well as public parks, office interiors and infrastructure/ There is specific scoring framework for each project type	Green Mark Accredited Professional, Green Mark Accredited Professional (Facilities Management), Green Mark Advanced Accredited Professional, Green Mark Advanced Accredited Professional (Facilities Management), Energy auditor	Green Mark Certified, Gold, Gold Plus and Platinum	Multi-attribute
BEAM Plus	BEAM Society Limited (BSL), Hong Kong Green Building Council	China	2010	Certification: BEAM Plus New Buildings, BEAM Plus Existing Building, BEAM Plus Interiors, BEAM Plus Neighborhood/BEAM Plus Assessment Tools: BEAM Plus New Buildings & Existing Buildings, BEAM Plus Interiors, BEAM Plus Neighborhood, BEAM Plus Data Centres, BEAM Plus Bespoke	BEAM Professionals (BEAM Pro), BEAM Affiliate, BEAM Assessors (BASs), Green Building Faculty (GBF)	BEAM Plus Existing Buildings V2.0: assessment under Comprehensive Scheme: Platinum, Gold, Silver, Bronze/ assessment under the Selective Scheme:	Multi-attribute

						Excellent, Very Good, Good, Satisfactory	
BOMA 360	Building Owners and Managers Association (BOMA) International	USA	2009	BOMA 360 designation: All occupied commercial and industrial buildings (office and industrial buildings)	BOMA 360 Ambassador	BOMA 360 label	Multi-attribute (get points above the minimum in 6 criteria)
BREEAM	Building Research Establishment (BRE)	United Kingdom	1990	Communities (Master planning), Infrastructure (Civil Engineering and Public Realm), New Construction (Homes and Commercial Buildings), In-Use (Homes and Commercial Buildings), Refurbishment and Fit-Out (Homes and Commercial Buildings)	BREEAM Associate, BREEAM AP (Advisory Professional), BREEAM Assessor	Unclassified, Pass, Good, Very Good, Excellent, Outstanding	Multi-attribute
CASBEE	Japan Sustainable Building Consortium (JSBC)	Japan	2001	Two authorization systems (certification system, and the local governments' reporting system)/ Certification system: Certification for Buildings, Certification for Housing, Certification for CASBEE for Real Estate	CASBEE Accredited Professional (CASBEE-AP) (assessor): CASBEE Accredited Professional for Housing, CASBEE Accredited Professional for Buildings, CASBEE Accredited Professional for Real Estate	overall environmental performance assessment rating: S (Excellent: 5 star), A (Very Good: 4 star), B+ (Good: 3 star), B- (Fairy	Multi-attribute

						Poor: 2 star), C (Poor: 1 star)	
DGNB	no profit association DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) (German Green Building Council)	Germany	2009	DGNB precertification for new construction, districts (planning/Development), existing buildings, renovated buildings, interiors, buildings in use, new constructions, dismantling/ buildings, districts and interiors	DGNB Registered Professional, DGNB Consultant, DGNB Auditor	platinum, gold, silver, bronze	-
EDGE (Excellence in Design for Greater Efficiencies)	International Finance Corporation (IFC)	USA	2014	new construction, existing and renovations/ Existing Building Projects, Core and Shell Projects, Partial Building Projects, Social Housing Projects	EDGE Auditors, EDGE Experts	EDGE Certified, EDGE Advanced, Zero Carbon	Single-attribute
Energy Star	Environmental Protection Agency (EPA), Department of Energy (DOE)	USA	2011	Products, New Construction, Existing homes, Commercial Buildings, Industrial plants	–	The ENERGY STAR score, expressed as a number on a simple 1 - 100 scale, rates performance on a percentile basis: buildings with a score of 50 perform better than 50% of their peers;	

						buildings earning a score of 75 or higher are in the top quartile of energy performance	
Fitwel	U.S. Centers for Disease Control (CDC). The Center for Active Design (CfAD) was selected as the licensed operator of Fitwel	USA	2016	Certifications: Design Certification (new construction and major renovation projects), Built Certification (existing or recently completed projects that are occupied and in use)/ Scorecards: Sites, Buildings	Champions (companies), Ambassadors	Fitwel Star Ratings: 1 star, 2 stars, 3 stars	Multi-attribute
Green Star	Green Building Council of Australia (GBCA)	Australia	2003	Green Star Buildings and Green Star - Design & As Built, Green Star – Interiors, Green Star – Performance (operational performance of existing buildings), Green Star – Communities	Green Star Associate (GSA), Green Star Accredited Professional (GSAP)	6 Star (World leadership), 5 Star (Australian excellence), 4 Star (Best practice), 3 Star (Good practice), 2 Star (Average practice), 1 Star (Minimum practice)	Multi-attribute
GreenGlobes	Green Building Initiative, Inc. (GBI)	United States and Canada	2000	Green Globes® For New Construction (NC), Sustainable Interiors (SI), Existing Buildings (EB),	Green Globes Emerging Professional (GGEP), Green Globes Professional (GGP),	Four Green Globes, Three Green Globes, Two Green	Multi-attribute

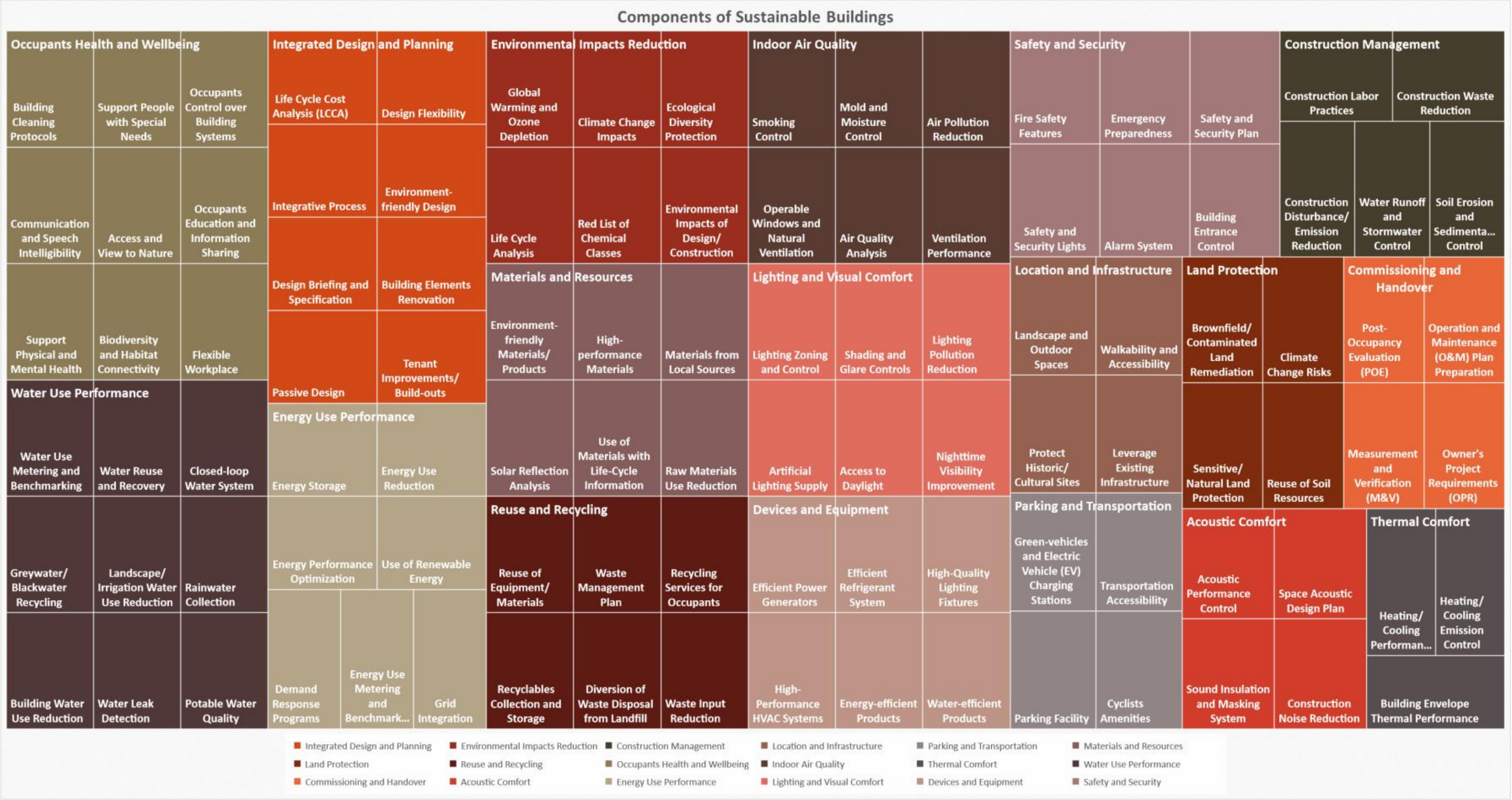
				Core & Shell (C&S) Protocol, Multifamily for New Construction Protocol, Multifamily for Existing Buildings Protocol	Green Globes Assessor (GGA), Federal Guiding Principles Compliance Professional (GPCP), Green Globes Fellow & Guiding Principles Compliance Fellow (GGF & GPCF)	Globes, One Green Globe	
HQE (Haute Qualité Environnementale or High-Quality Environmental standard)	HQE Association, Cerway	France	2011	HQE™ Certification for Construction, Buildings in Operation, Urban Planning and Development/ Certification Schemes: Residential Building, Non-Residential Building, Non-Residential Buildings In Operation, Sustainable Urban Planning	HQE™ Certification Référents (HQE™ CR)	HQE Excellent, HQE Very Good, HQE Good, HQE Pass	Multi-attribute
LBC	International Living Future Institute	USA	2006	Living Certification, Petal Certification, Core Green Building Certification, Zero Energy Certification, Zero Carbon Certification/New Building, Existing Building, Interior, Landscape or Infrastructure	LIVING FUTURE ACCREDITATION (LFA)	Living Certification, Petal Certification, Core Green Building Certification, Zero Energy Certification, Zero Carbon Certification	Single-attribute
LEED	U.S. Green Building	USA	1998	LEED For Building Design and Construction, Interior Design and Construction,	LEED Green Associate, LEED Accredited Professional (AP)	Certified, Silver, Gold, Platinum	Multi-attribute

	Council (USGBC)			Building Operations and Maintenance, Neighborhood Development, Homes			
NABERS	Government initiative	Australia	2000	NABERS Energy, NABERS Water, NABERS Indoor Environment, NABERS Waste, Carbon Neutral Certification /Office Buildings and Tenancies, Shopping Centres, Apartment Buildings, Hospitals (Public), Hotels, Data Centers	Accredited Assessor	6 - Market leading, 5 - Excellent, 4- Good, 3 - Average, 2 - Below average, 1 - Poor performance, 0 Stars - Very poor performance	
NGBS (National Green Building Standard)	ASHRAE, the International Code Council (ICC), and the National Association of Home Builders (NAHB)	USA	2008	Multifamily or Mixed-Use NGBS Green Certification, Single-Family NGBS Green Certification, Remodeling NGBS Green Certification, Land Development NGBS Green Certification, NGBS Green+ Badges, NGBS Green Certified Products	NGBS Green Verifier	Buildings: Bronze, Silver, Gold, or Emerald/ Land development: 1-Star, 2-Star, 3-Star, 4-Star	Multi-attribute
NZEB (Net Zero Energy Building Certification)	The International Living Future Institute (ILFI)	USA	?	zero energy certification (Buildings)	–	If the auditor determines the project performs at zero energy and meets ILFI requirements, it will be certified	Single-attribute
PCA	Property Council of Australia	Australia	?	Office buildings and office spaces (new and existing buildings)	–	New office buildings: Premium, Grade	Single-attribute

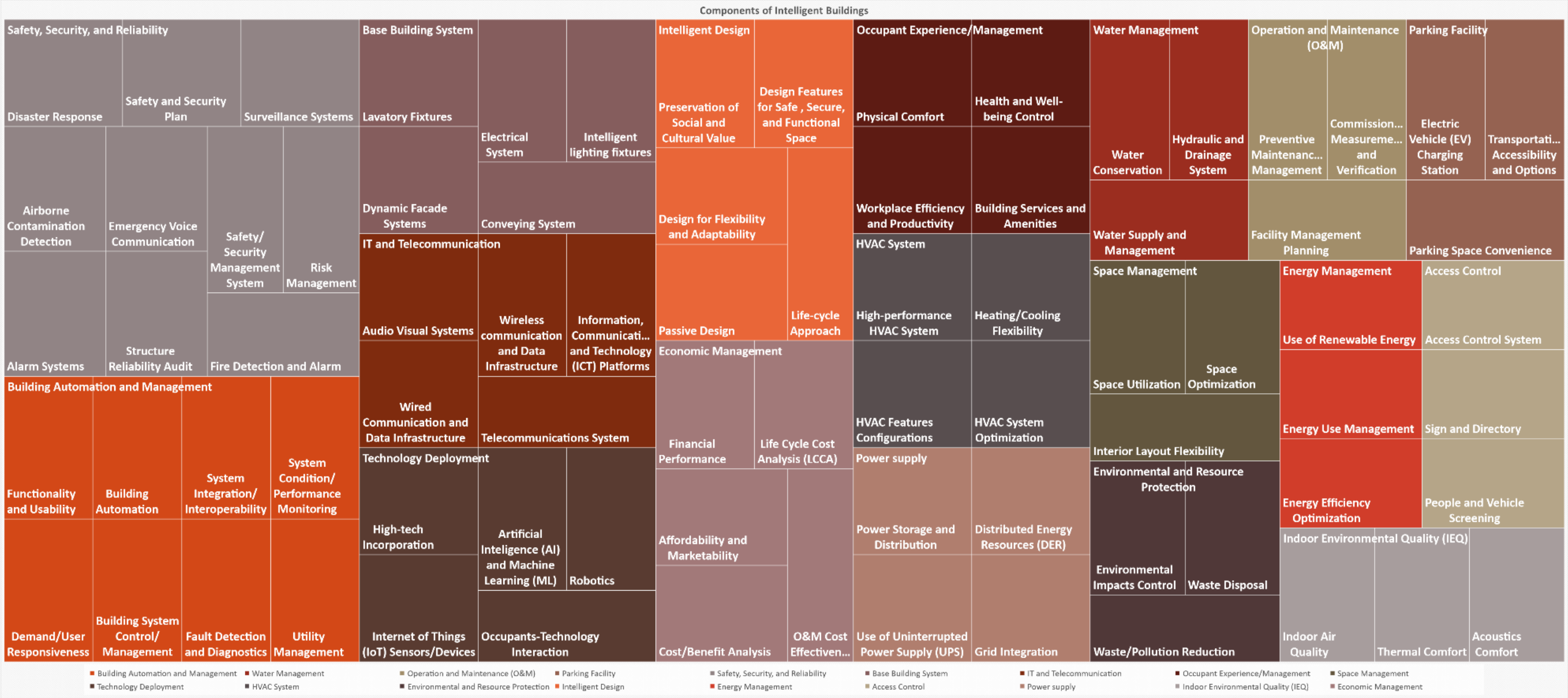
						A, Grade B/ Existing office buildings: Premium, Grade A, Grade B, Grade C and Grade D	
SBTool	International Initiative for a Sustainable Built Environment (iiSBE)	international non-profit organization	?	-	-	-	-
WELL	International WELL Building Institute (IWBI), Green Business Certification Incorporation (GBCI)	USA	2014	Well Certification, Well Core Certification/ Buildings (New and Existing Buildings), Interiors (New and Existing Interiors), Core and Shell	WELL Accredited Professional (WELL AP)	Bronze, Silver, Gold or Platinum	Multi-attribute (points-based system)

APPENDIX E: Sustainable and Intelligent Buildings' Components

The figure below shows the sustainable building components including 18 cluster and 103 components.



The figure below shows the intelligent building components including 18 cluster and 79 components.



APPENDIX F: IB Index Context Analysis

The context analysis was conducted to examine the IB Index capabilities through a comparison between Australia and United States contexts.

Pillar	Domain	Major Diff.	Type of Difference
01 Project delivery	01 Smart building specification	X	Terminology
	02 Data Governance Framework		Framework
	03 Information Requirements	X	Terminology Framework
	04 BIM Delivery Framework		Terminology Framework
	05 Data Verification & Validation	X	Evaluation
	06 Building Performance Certification		Framework
02 Infrastructure, Devices & Applications	01 Communication and Data Infrastructure	X	Terminology Framework
	02 Energy Generation	X	Technology
	03 Smart Access Controls		Evaluation
	04 Smart Parking		Evaluation
	05 Electric Vehicle Charging		Technology
	06 Tenant Digital Information Services	X	Framework Evaluation
	07 Smart Information Displays		Evaluation
	08 Environmental Monitoring Systems & Sensors		Evaluation
	09 Smart HVAC - Systems & Sensors	X	Evaluation
	10 Electrical Power Supply	X	Framework
	11 Intelligent and Connected Lighting		Evaluation
	12 Dynamic Building Envelop		Framework
	13 Smart Hydraulic Devices - Systems & Sensors	X	Framework
	14 Vertical Transport		Evaluation
03 Controls, Monitoring & Management	01 Intelligent BMS	X	Evaluation
	02 Intelligent Energy Management	X	Framework
	03 Building Management Dashboards and Viewers		Framework
	04 Demand Side Management		Framework Evaluation Technology
	05 Vertical Transport Controls		Technology
	06 Occupant Based Controls	X	Framework Evaluation
	07 Physical & Cyber Security Controls		Framework

	08 Ventilation Controls		Framework Technology
	09 Heating & Cooling Controls		Framework Technology
	10 Hydraulics – Hot Water Controls		Framework

Pillar 1: Project Delivery

PD-01-SBS: A difference between the two contexts is regarding used terms and terminologies. In the US context, different domain-related terminologies are used by different project stakeholders in different project phases. Specifically, the “design program” and “design specification” (in US context) is the equivalent terminology for “building brief” (in AU context). Another relevant terminology is “design offering memorandum” which is mostly used by real estate developers. Also, “proposal” as a response to the RFP (during the bidding phase) and building “drawings and specifications” (during the construction phase) are other terminologies that specify building systems and elements.

Levels of technology attainability		
	AU	US
SBS01		All kinds of initiative plans (including technological) may be added to the typical program/proposal document.
SBS03	Levels are defined based on the integration to diff. building systems	The specification requires technical information about physical network system and application platform that supports systems integration
SBS04	Levels are defined based on the level of integration (to FM and IBMS)	Levels are defined based on the planning for connectivity with physical assets, visualization capabilities, and DT platform provided services (a distinction between IoT, DT, and BMS services is required)
SBS05	Levels are defined based on traditional, digital, and intelligent data management frameworks	Asset management framework has various aspects including AMS specification & requirements, capital planning, O&M planning, etc.

PD-02-DG: there are some minor differences between the two contexts in terms of processes and the structure of capabilities in this domain. Also, the use of ISO standards depends on the agreement between project stakeholders entirely and is not necessarily considered as a capability for building intelligence. Moreover, the use of open data standards is not a preference or an indicator of advanced data governance in all projects/for all owners (e.g., army facility owners).

Levels of technology attainability		
	AU	US
DG02		Levels are defined based on the specification of project deliverables: 1) not specifically, 2) as joint project-based agreements, and 3) as a standard contractual requirement.
DG03		Levels are defined based on the required protocols (data accessibility, file naming convention, file format, security, etc.) and level of CDE adoption (none, mix of CDE and traditional methods for file sharing, and fully CDE-based file sharing)
DG08		For projects containing major tech-based initiatives, levels are defined as 1) tech-related qualification criteria not specified, 2) qualitative/descriptive criteria, and level 2 + business proforma for the intended initiatives

PD-03-IR: The main difference between the two context is related to terminologies and frameworks for data specification. The terms of Asset Information Model (AIM), Project Information Management (PIM), and Built Asset Security Information Requirements (BASIR) originated from the British standards (PAS 1192) and does not have specific equivalent in the US context. Also, “information exchange requirements” or “interoperability requirements” comprises of technical- and data requirements.

Levels of technology attainability		
	AU	US
IR01		The EIR and AIR can be specified in project and organizational levels.
IR03		AIR is specified based on the asset information uses (similar to BIM uses) and existence of a standard asset classification

		(the AIR taxonomy is determined according to the asset classification & taxonomy)
IR05		see IR03 explanation.

PD-04-BDF: Overall, there is not much difference between the two contexts. There are some minor differences in terminologies and frameworks for BIM implementation planning. Also, the asset management and digital twin management plans are not necessarily part of the BIM processes & plans and are specified independently.

Levels of technology attainability		
	AU	US
BDF01		The levels for BIM implementation include 1) project-based BIM utilization plan (including service outsourcing), 2) organization-level standard BIM maturity model, and 3) level 2 + BIM implementation roadmap (capability name could be changed to BIM implementation planning, BIM requirements is addressed in BDF02)
BDF02	Levels are defined based on the comprehensiveness of the project BIM brief	BIM execution plan (BEP) can be adopted as 1) project based, organization-level standard BEP template, and 3) standard BEP integration to other tech. adoption (e.g., AR/VR, reality capture, DT)
BDF03		BIM delivery standard may be specified for 1) only general and design phase requirements, 2) level 1 + construction phase, and 3) life-cycle BIM delivery standard
BDF04		See BDF03 explanation

PD-05-DVV: the current domain (based on the AU context) identifies capabilities for verification and validation of model & data, as-built models, digital asset information, and digital O&M manuals. In the US context, the verification and validation workflows are implemented for almost all physical and virtual project deliveries. For example, owners have design review and code validation (during design phase), BIM deliverables QC plan (during design and construction phases), construction site QA/QC plans (for materials delivered by suppliers, and work-packages delivered by (sub-)contractors), building inspection and measurement & verification (M&V) plans (during project close-out), and assets verification including asset information QC and physical asset condition assessment plans (during O&M phase).

Levels of technology attainability		
	AU	US
DVV01	Levels are defined based on the automation of the V&V methods	The V&V plan has different components including 1) technology used, 2) manual vs. rule-based automated methods, 3) V&V system (e.g., descriptive, quantitative rating, etc.), 4) V&V results visualization and reporting

PD-06-BPC: Building sustainability and performance assessment contains various initiatives that may or may not be enabled by technologies. In the US context, main technology-based initiatives and planning for sustainability include energy efficiency & optimization, water efficiency & optimization, lighting efficiency & optimization, occupants' experience & satisfaction (using POE), occupants' health, well-being & productivity, waste management (tracking, optimization, and education), and carbon footprint management (tracking, optimization, and education)

Pillar 2: Infrastructure, Devices, and Applications

IDA-01-CDI: There is a difference between the two contexts in terms of terminologies that articulate this domain. The telecommunication, information and communication technology (ICT), and cyber-infrastructure are well-known terminologies in the US context. Also, the concept of Internet of Things (IoT) addresses two different areas in intelligent buildings: 1) Providing connectivity between occupants and devices on a shared internet platform, and 2) a physical network of sensors for real-time building information collection and a cloud-based platform for the collected information governance. Other technological capabilities in the US market include smart office equipment such as smart workstations, A/V devices, and cyber-infrastructure management systems (e.g., fault detection systems).

Levels of technology attainability		
	AU	US
CDI02	Levels are defined based on the user accessibility.	Levels are defined based on the system architecture (e.g., subsystems, zoning) specified by ANSI/TIA-862-B.
CDI03	Levels are defined based on the short and long-term internet connectivity.	Levels are defined based on the 1) internet coverage (range and data speed), 2) # of sensors and types of data collected.

IDA-02-EG: While energy generation in the Australian context is mostly focused on installation of PV panels in buildings it has a broader definition (including other renewable energy sources such as biofuels and wind power) in the US context. Purchasing green power (from local sources) is another well-known option in the US IB industry. Also, there is a growing market in the US for on-site energy storage, distribution and sharing (with adjacent buildings) technologies.

Levels of technology attainability		
	AU	US
EG02	Levels are defined based on the percentage of the average daily needs that is generated as renewable energy.	Levels are defined based the cost of generated renewable energy divided by the total annual energy cost.
EG03		There is a distinction between items reported to tenants/occupants vs. facility owners/managers.
EG05	Levels are defined by short- and long-term optimization.	Levels are defined based on the short term, long-term (manual performance analysis), and long-term (simulation-based performance analysis) optimizations.

IDA-03-SAC: Overall, there is not much difference between the two contexts. Access control and security systems in the US market are evaluated based on 1) access control hardware and software, 2) communication options (for access request processing), and 3) occupants/visitors managements systems. There are different protocols for US federal and non-federal buildings.

Levels of technology attainability		
	AU	US
SAC01		Levels are defined based on the integration into access control system

SAC03		There is no difference between tags and cards. Biometric technology is not commonly used for commercial buildings
SAC06	Levels are defined based on the occupancy detection accuracy	Levels are defined based on occupancy data (e.g., pattern recognition, BMS integration)

IDA-04-SP: in the US context, the smart parking intelligence is generally evaluated based on the 1) parking lot occupancy recognition/reporting, 2) parking lot permit/reservation, and 3) unauthorized vehicles detection.

Levels of technology attainability		
	AU	US
SP03	Different bay types are identified for reporting.	Most of parking facilities does not have this capability.

IDA-05-EVC: Intelligence of EV charging technologies mostly depends on EV charging types (plugs, connectors, capacity, etc.) and charging infrastructure (accessibility to charging stations and available charging options).

Levels of technology attainability		
	AU	US
EVC01		Levels defined based on the availability of different charging types and plug options.
EVC03	Levels are defined based on the tariffs structure.	There is no single mechanism and the structure depends on private service providers.

IDA-06-TDIS: Tenant digital information services have a broad range of available technologies and functions in the US market. The services are often part of the space and tenant management systems and since there is no specific standard to require features' specifications private service providers developed different platforms and features. However, two major evaluation criteria include 1) data overload that determines ideal amount of data (IEQ, occupancy, etc.) collection and 2) levels of building automation that determines to what extent tenants can directly/manually work with the platforms.

Levels of technology attainability

	AU	US
TDIS04	Levels are defined by integration into space management and building management systems.	Levels defined based on the accuracy of data (e.g., space utilization data entered to BMS vs. actual real-time space utilization)
TDIS05		Additional features include visitor tracking within the building and building/individual visiting analysis (pattern recognition, etc.)
TDIS08		No difference found between physical and virtual (smartphone) control. Levels include set status by tenant, set preference by tenant, and set preference by AI systems.
TDIS09		No difference found between physical and virtual (smartphone) control. Levels include set status by tenant, set preference by tenant, and set preference by AI systems.

IDA-07-SID: Similar to the previous domain, there is no standard for the digital information displays in the US market and specific platform interface and features depend on the tools developed by private service providers.

IDA-08-EMSS: Overall, there is not much difference between the two contexts. The intelligence of relevant technologies is evaluated based on the integration into different systems generally from 1) not-integrated systems, 2) basic integration (e.g., connection between heat/smoke fire detection sensors and fire protection system, emergency alarming system, and vertical lifts), to 3) fully integrated system (connection between sensors and BMS systems for HVAC controls, tenant information platforms, access controls, etc.).

Levels of technology attainability		
	AU	US
EMSS01		Although rainwater collection systems are commonly used, the use of rainwater sensors is limited for commercial buildings.
EMSS06		Additional features include occupants tracking and emergency pathfinding systems.

IDA-09-SHVAC: the key IB sensors (temperature, humidity, air quality, etc.) evaluation criteria include 1) data collection intervals and storage, 2) supporting cloud-based data analytics platform, and 3) integration to building management/automation systems. In addition, the HVAC system intelligence is accessed by system automation and AI utilization (e.g., controlling heating/cooling/ventilating based on scheduled time, user-defined custom program (for different times and zones), and AI-aided actual building performance).

Levels of technology attainability		
	AU	US
SHVAC01		There are two different types of sensors room temperature sensors connected to BMS for adjusting HVAC loads and temperature sensors for HVAC systems (mechanical room, pump heat, etc.)

IDA-10-EPS: In the US context, this domain capabilities and related technologies are part of the energy efficiency and management. Also, various power supply and electrical feeds options are available in different states.

Levels of technology attainability		
	AU	US
EPS01	Levels are determined based on the electricity use breakdown by end-user.	Additional smart meter features (used for evaluation) include system-level metering (for types of use analysis) and time of day metering (for cost analysis)
EPS03	Levels are defined based on manual and automatic back-up	levels are defined based on the UPS capacity and efficiency
EPS04		It seems Wi-Fi GPOs/power points have limited market in US.

IDA-11-ICL: In general, there is not much difference between the two contexts. The US market evaluates the lighting system based on 1) selection of lighting fixtures, 2) automation and number of lighting controls, 3) integration to BMS and other related systems, and 4) lighting efficiency analysis and optimization.

Levels of technology attainability		
	AU	US
ICL02	Levels are determined based on the levels of automation	It has the same method, different levels (manual, programmed, pattern-based

		programmed, BMS-integrated control based on the room illuminance level)
ICL03	Levels are determined based on the levels of automation	It has the same method, different levels based on control automation, space-based separate controls, and dimming option

IDA-12-DBE: while intelligent building envelopes have various components the two main technology-related components are responsive shading system and intelligent operable windows.

IDA-13-SHD: In the US context, water efficiency and the related technologies is evaluated based on 1) the selection of bathroom and kitchen fixtures selection, 2) water metering and efficiency optimization, 3) water treatment and reuse systems, 4) intelligent water/sewer management systems, and 5) groundwater/stormwater management (for campuses)

Levels of technology attainability		
	AU	US
SHD04		Levels are defined based on number of meters (zone-based), sensor connectivity for data collection, supporting platform for data analytics

IDA-14-VT: Vertical transport (elevators, escalators, and lifts) is evaluated based on the 1) VT unit selection (e.g., elevator speed, double units in a shaft, etc.), 2) energy efficiency, 3) integration to BMS systems, 4) integration to AI and IoT for pattern recognition, performance optimization, and predictive O&M.

Levels of technology attainability		
	AU	US
VT04	Levels are defined based on the energy consumption	Numbers could be different based on the VT system

Pillar 3: Controls, Monitoring & Management

CMM-01-IBMS: In the AU context, the BMS intelligence is evaluated based on the functionalities of actual performance tracking, energy consumption breakdown, and platform for data analytics and benchmarking a system performance against other building systems. In comparison, the evaluation criteria in the US context include system architecture and hardware (e.g., meters, control devices, etc.), system integration (e.g., into IoT system), system components (e.g., HVAC, access control, lighting fixtures, and power system), and BMS technical features (e.g., performance evaluation (based on design criteria), fault detection and diagnostics, visualization & reporting, and system optimization).

Levels of technology attainability		
	AU	US
IBMS01	Levels are defined based on the systems integration into IBMS	Additional feature of the IBMS include system connectivity and data analytics platform (current capability levels need definition)
IBMS03	Levels are defined based on the two functions of the FDD system	FDD may be part of the BMS or CMMS so system integration (for fault resolution) can be a factor for levels definition.
IBMS04		The levels are defined based on 1) monitoring of energy consumption, 2) use-pattern detection, 3) performance evaluation & optimization (based on lighting design criteria such as illuminance)

CMM-02-IEM: In the US context, the energy management has many components including types of monitoring & control (e.g., manual inspection, automated monitoring systems, etc.), types of energy efficiency evaluation and analysis (e.g., traditional methods vs. AI-based methods), depth of analysis (overall energy consumptions, energy consumption breakdown and pattern detection, performance prediction, optimization feedbacks, etc.), types of visualization and reporting of performance evaluation, and integration of monitoring & control system (e.g., disconnected system for building systems vs. integrated system for energy generation, consumption, and performance for all building systems).

Levels of technology attainability		
	AU	US
IEM01		The levels may be defined based on the methods of visualization & reporting (internal tenants portal or personal devices),

		and types of information being reported including 1) overall approximate energy usage report, 2) actual energy usage report, 3) level 2 + energy usage pattern and prediction, and 4) level 3 + efficiency/improvement tips based on tenants' energy usage information.
IEM04	Levels are defined based on off-switch function in appliances	Additional feature is programmable turn on/off function in devices (could be added to level 2)

CMM-03-BMDV: Overall, there is not much difference between the two contexts. The building management dashboard may be present information extracted from databases of different separated or integrated systems such as BMS, IoT, CMMS, and DT.

Levels of technology attainability		
	AU	US
BMDV01	Levels are defined based on the inclusion of O&M database (assumed included in all levels) and spatial information (2D & 3D)	Additional data type for inclusion in the dashboard include financial information, CMMS database, space & tenant management database, and safety & security database

CMM-04-DSM: In the US context, demand-side management (other terms include integrated demand side management and smart grid) comprises a broad range of technologies and programs such as energy efficiency, distributed energy resources, demand response optimization, renewable energy, electricity storage and distribution, consumers engagement, integrated operation centers, and smart energy pricing. Accordingly, there is no standard way for definition and categorization of the DSM. Also, the existence of some programs and practices (e.g., DSO and VPP) is widely different in the U.S. states. Finally, there are overlaps between DSM, power supply, and BMS regarding relevant components.

Levels of technology attainability		
	AU	US
DSM06	Levels are defined based on the use of sensor data in other systems	Power flows measurement may also be evaluated based on the breakdown of

		electricity uses and patterns of power uses (location and time)
DSM07		The tracking method depends on the type of KPI.
DSM08	Levels are defined based on whether the FDD is operated locally or by DSO	Levels can also be defined based on the FDD system (manual vs. automated, reactive vs. AI/ML-based proactive)
DSM09		See DSM08 explanation
DSM11		Levels 2 and 3 may not be applicable in some states/districts

CMM-05-VTC: TBD (the related IB Index domain is to be developed).

CMM-06-OBC: In the US context, occupancy detection is discussed and evaluated based on 1) occupancy sensing network (detection on entrances, detection in building zones, and detection in individual spaces), 2) occupancy sensing technology (occupant counter, PIR, WiFi-based occupancy detection, RFID, face recognition, etc.), 3) uses of occupancy information (real-time occupancy sensing and occupancy pattern) in BMS for systems' management and optimization (e.g., HVAC control and predictive maintenance), and 4) other monitoring & management services provided based on the occupancy detection including actual space usage vs. designed space capacity comparison, unauthorized access detection, occupants' comfort and productivity assessment, building performance evaluation (e.g., energy and water efficiency), and emergency pathfinding

Levels of technology attainability		
	AU	US
OBC02	Levels are defined based on the accuracy of occupancy detection devices	The concept of space management refers to planning for efficient use of space and management of public areas and shared spaces (e.g., meeting rooms in offices or terminals in airports) based on occupancy information (new capability may be defined accordingly)

CMM-07-PCSC: Overall, there is not much difference between the two contexts. A cybersecurity program has three main components including 1) protocols and workflows, 2) technical hardware and software infrastructure, and 3) operator/tenant awareness and education. A cybersecurity system is required for information exchange/management (during the project delivery phase), for asset and building systems management (during the O&M phase), and for cybersecurity of tenants'/occupants' electronic devices.

CMM-08-VC: There is no difference between the two contexts. The evaluation factors for HVAC systems (in the US context) include 1) control system architecture, 2) types of control devices (e.g., direct digital control), 3) integration into BMS/BAS, 4) control system automation (manual, programable, and performance-/demand-based controls), and 5) reporting platforms. In addition, there are various HVAC management and control solutions (equipment and software applications) therefore some of the detailed capabilities may not be applicable to all HVAC systems and control technologies.

CMM-10-HHWC: Overall, there is not much difference between the two contexts. In general, the hydraulics controls consist of 1) water quality/pressure/temperature control, 2) water supply/storage fault detection and management, 3) integration into FDD/BMS/IoT systems, and 4) energy/water efficiency control. Also, no difference was found between controls of hot water storage charging using heat pumps or hot water generators.

Levels of technology attainability		
	AU	US
HHWC06	Levels are defined based on the types of information shared with tenants.	For advanced levels, the focus is more on usage pattern detection rather than predictive management and fault detection.
HHWC07		There is limited integration between hydraulics' controls/metering devices and other technical building systems.

APPENDIX G: IB Index Scorecard

Pillar	Domain	Capability	Weight	Score	Out of
Project Delivery (PD)	Project Planning & Specification (PPS)	PPS-01 Integrated & Intelligent Design Program	1.25		4
		PPS-02 Project Delivery Systems	1.5		3
		PPS-03 Intelligent Technology Adoption Roadmap	1.5		4
		PPS-04 Asset Management Planning	1.25		3
		PPS-05 Operation and Maintenance Strategy	1.25		3
		PPS-06 Physical Systems Specification and Plan	1.75		4
		PPS-07 Virtual Systems Specification and Adoption Plan	1.75		4
		PPS-08 Building Portfolio Evaluation & Management Plan	1.5		4
	Data Management Framework (DMF)	DMF-01 Information Management Plan	1.5		3
		DMF-02 Specification and Use of Common Data Environment (CDE)	1.5		4
		DMF-03 Data QA/QC Plan	1.5		3
		DMF-04 Data QA/QC Automation	1.25		4
		DMF-05 Asset Information Requirements & Specification	1.25		4
		DMF-06 Asset Information Interoperability Standards	1.25		3
		DMF-07 Proposal Assessment During Bidding	1.5		3
Infrastructure, Devices, and Applications (IDA)	Communication and Data Infrastructure (CDI)	CDI-01 Communication Network Infrastructure	1.25		3
		CDI-02 Communication Cabling Network Architecture	1.25		3
		CDI-03 Integrated Communications Network Infrastructure	1.5		3
		CDI-04 Level of Integration between Technical Systems (Quantity)	1.5		3
		CDI-05 Level of Integration between Technical Systems (Quality)	1.5		4
		CDI-06 IoT and Internet Connectivity	1.25		3
		CDI-07 A/V Cabling and Interface	1.25		3
		CDI-08 In-Building Wireless (IBW) System	1.25		3
		CDI-09 IoT Network Architecture	1.25		3
		CDI-10 Data Infrastructure Monitoring System	1.5		3
	Energy Generation (EG)	EG-01 On-Site Renewable Energy Production	1.25		3
		EG-02 Green Energy Procurement	1.25		3
		EG-03 Smart Energy Metering & Benchmarking	1.5		4
		EG-04 Energy Storage & Distribution	1.25		3
		EG-05 Uninterruptible Power Supply	1.25		2
		EG-06 Power over the Ethernet	1.25		4
	Safety, Security, and Well-being (SSW)	SSW-01 Building Access Administration	1.5		3
		SSW-02 Access Control Integration	1.5		2
		SSW-03 Access Control Systems	1.5		3
		SSW-04 Surveillance Systems	1.5		4
		SSW-05 Occupancy Detection System	1.25		4
		SSW-06 Fire Prevention System	1.5		4
		SSW-07 Carbon Monoxide Detection System	1.5		3
		SSW-08 Visitor Management System	1.25		3

		SSW-09 Indoor Environment Monitoring System	1.25		4
	Smart Parking (SP)	SP-01 Parking Guidance System	1.5		3
		SP-02 Unauthorized Occupancy Detection System	1.5		3
		SP-03 Parking Payment System	1		4
		SP-04 Parking Mobile Application Services	1		4
		SP-05 On-site EV Charging Station	1.25		2
		SP-06 On-Demand Charging	1.25		3
		SP-07 EV Charging capacity	1.25		3
	HVAC Systems and Sensors (HVACSS)	HVACSS-01 Heating/Cooling Emission Control Equipment	1		3
		HVACSS-02 Air Flow Rate and Pressure Configuration	1.25		3
		HVACSS-03 Distribution Pumps in Network	1.25		3
	Intelligent and Connected Lighting (ICL)	ICL-01 Lighting Control Coverage	1.5		4
		ICL-02 Lighting Control Automation	1.25		4
		ICL-03 Lighting Control Flexibility	1.25		4
		ICL-04 Interior Lighting Fixtures	1.25		4
	Dynamic Building Envelop (DBE)	DBE-01 Shading System Control	1.25		3
		DBE-02 Operable Windows Control	1.25		3
		DBE-03 Shading System Components	1.25		3
	Hydraulic Devices, Systems & Sensors (HDSS)	HDSS-01 Smart Flush Toilets/Urinals	1.25		4
		HDSS-03 Smart Faucets	1		4
		HDSS-04 Smart Water Meters	1.5		4
	Vertical Transport (VT)	VT-01 Lift / Elevator Dispatching	1.25		4
		VT-02 Lift / Elevator power recovery	1		3
		VT-03 Lift / Elevator Energy Consumption	1		3
Controls, Monitoring, and Management (CMM)	Intelligent Asset Management Systems (IAMS)	IAMS-01 Use of Data Analytics	1.25		4
		IAMS-02 Asset & Facility Management Technology Stack	1		4
		IAMS-03 Integrated Workflows	1.25		4
		IAMS-04 Maintenance of Physical Systems	1.25		3
		IAMS-05 Maintenance of Virtual Systems	1.25		3
	Intelligent Energy Management (IEM)	IEM-01 Energy Demand Prediction	1.25		3
		IEM-02 Energy Efficiency Monitoring & Management	1.25		4
		IEM-03 Energy Performance Optimization	1.5		4
		IEM-04 Energy Performance Evaluation & Visualization	1.25		3
		IEM-05 Demand Side Management	1		2
		IEM-06 Building Energy Portfolio Development	1.5		3
		IEM-07 Grid Integration System	1.25		3
		IEM-08 Energy Fault/Fraud Detection	1.25		3
		IEM-09 Smart Appliances/Devices Control	1		2
		IEM-10 Carbon Footprint Reduction Program	1.25		3
	Building Occupants' Experience (BOE)	BOE-01 Occupancy Data Analytics	1.25		4
		BOE-02 Building Dashboards & Portals (Content)	1.25		2
		BOE-03 Building Dashboards & Portals (Accessibility)	1		4
		BOE-04 Safety & Emergency Alarms	1.25		4

		BOE-05 Space Occupation and Room Booking	1.25		4
		BOE-06 Building Systems Controls	1.75		4
		BOE-07 Digital Artwork	1		3
	Safety and Security Controls (SSC)	SSC-01 Emergency Communication and Alarm System	1.5		4
		SSC-02 Security Monitoring and Control	1.5		3
		SSC-03 Physical Systems’ Safety Monitoring and Control	1.5		3
		SSC-04 Cyber Security Automation	1.5		3
		SSC-05 Cyber-Security Monitoring and Control	1.5		4
		SSC-06 Cyber Security Coverage	1.5		4
	Heating/Cooling Monitoring and Control (HCMC)	HCMC-01 Heating/Cooling Emission Control	1.25		4
		HCMC-02 Chilled Water Distribution Control	1.25		3
		HCMC-03 Distribution Pumps Control	1.25		3
		HCMC-04 Heating/Cooling Distribution Control	1.5		3
		HCMC-05 Thermal Energy Storage (TES) Operation Control	1.25		3
		HCMC-06 Heating/Cooling Generator control	1.25		3
	Ventilation Monitoring and Control (VMC)	VMC-01 Supply Air Flow Monitoring/Control	1.25		4
		VMC-02 Exhaust Air Flow Monitoring/Control	1.25		4
		VMC-03 Indoor Air Temperature Monitoring/Control	1.5		3
		VMC-04 Indoor Temperature Adjustments	1.5		3
		VMC-05 Supply Air Controlling Approach	1.25		3
		VMC-06 Heat Recovery Control	1		2
		VMC-07 Building Free Cooling System	1.5		3
		VMC-08 IAQ Performance Evaluation & Visualization	1		3
	Hydraulics Monitoring and Control (HMC)	HMC-01 Hot Water Storage Charging Control	1.25		4
		HMC-02 Control of Hot Water Storage Temperature	1.25		3
		HMC-03 Control of Hot Water Circulation Pump	1.25		2
		HMC-04 Water Efficiency Evaluation & Visualization	1		3

VITA

Alireza Borhani was born in 1986 in Tehran, Iran. After completing his bachelor's degree in civil engineering at the Bergische University Wupperal, Germany he moved to United States and earned his master's degree in construction management from the University of Washington (UW) in 2015. After graduation, he worked for the UW as a research analyst conducting several research and development projects. Alireza started his PhD studies in the College of Built Environments, UW in 2017 and his research was focused on implementation of emerging technologies in Architecture, Engineering, Construction, and Operations (AECO) Industry as well as sustainable development in the built environment. While pursuing his PhD, he worked as a research and teaching assistant in the department of construction management and also worked as a Virtual Design and Construction (VDC) intern and engineer at several general contractor companies.