INTEGRATING SMART CITY AND SMART BUILDING KEY PERFORMANCE INDICATORS (KPI) FOR DEVELOPMENT OF AN INTEGRATED SMART BUILDING ASSESSMENT METHODOLOGY

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ABSTRACT

INTEGRATING SMART CITY AND SMART BUILDING KEY PERFORMANCE INDICATORS (KPI) FOR DEVELOPMENT OF AN INTEGRATED SMART BUILDING ASSESSMENT METHODOLOGY

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Smart building (SB) concept has become and becomes more and more popular day by day with various benefits it presents to lives of people. Accordingly, the number of studies performed on SBs continuously increases. Even if SBs are a part of people's lives for approximately forty (40) years and many researchers have proposed different approaches on SB definition and SB assessment, no consensus has been reached on these approaches. Besides, a trend wider than SBs, namely Smart Sustainable City (SSC), has become prominent in recent years. Since SBs are part of SSCs, parallel development in the assessment of the performance of both SBs and SSCs, such as Key Performance Indicators (KPIs), is important. However, the literature lacks an integrated SB assessment study composed of a combination of KPIs fit for SBs and SSCs. Hence, the objective of this study is to compare and synthesize the KPIs of SBs from the building and city perspectives. In this study, primarily the existing SB assessment methodologies and their KPIs were examined. Similarly, SSC assessment methodologies were investigated. Then, the KPIs that are suitable in both city and building scales were synthesized into an integrated SB assessment methodology. A case study is performed to apply the methodology on an academic research park (a recently constructed building). In this way, the applicability of the methodology for the existing buildings is assessed. The results of this study are valuable due to their applicability as transition steps towards SSCs.

Keywords: Smart Buildings (SB), Smart Building Assessment, Smart Sustainable Cities (SSC), Smart Building Retrofits, Key Performance Indicators (KPI)

ÖZ

AKILLI ŞEHİR VE AKILLI BİNA ANAHTAR PERFORMANS GÖSTERGELERİNİN (KPI) ENTEGRASYONU İLE BİR ENTEGRE AKILLI BİNA DEĞERLENDİRME METODOLOJİSİ GELİŞTİRİLMESİ

Parlak, Ahmet Semih
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Akıllı bina (SB) kavramı insan hayatına sunduğu faydalar ile birlikte günden güne insan hayatına daha fazla dahil olmuş ve olmaya da devam etmektedir. Bu doğrultuda akıllı binalar üzerine yapılan çalışmaların sayısı sürekli olarak artmaktadır. Akıllı binaların kırk (40) yıla yakın bir süreden beri insan hayatında olmalarına ve birçok araştırmacının akıllı bina tanımı ile değerlendirilmesi hususunda çeşitli yaklaşımlar sunmalarına rağmen, bu konularda fikir birliği elde edilememiştir. Bunun yanı sıra son yıllarda akıllı binalardan daha geniş çapta bir akım olan akıllı sürdürülebilir şehir (SSC) kavramı öne çıkmaktadır. Akıllı binalar da akıllı şehirlerin bir parçası olduğu için akıllı bina ve akıllı şehir performans değerlendirmelerinin, örneğin anahtar performans göstergelerinin (KPI), aynı doğrultuda geliştirilmesi önemlidir. Fakat, literatür akıllı binalar ile akıllı sürdürülebilir şehirlere uygun anahtar performans göstergelerinin bir araya getirilmesi ile oluşacak bir entegre akıllı bina değerlendirme çalışması hususunda eksiklik yaşamaktadır. Bu çalışmada, öncelikle literatürde mevcut olan akıllı bina değerlendirme metodolojileri ile onların anahtar performans göstergeleri incelenmiş; benzer bir inceleme akıllı sürdürülebilir şehirler üzerine de yapılmıştır. Sonrasında, bina ve şehir ölçeğinden alınıp uygun olduğu tespit edilen tüm anahtar performans göstergeleri bir entegre akıllı bina değerlendirme metodolojisi çalışması için sentezlenmiştir. Bu akıllı bina değerlendirme metodolojisini bir akademik araştırma parkına (yeni inşa edilmiş bir bina) uygulayarak bir vaka çalışması yapılmıştır. Bu şekilde, metodolojinin halihazırda mevcut olan binalara uygulanabilirliği değerlendirilmiştir. Bu çalışmanın sonuçları, akıllı sürdürülebilir şehirlere geçiş aşamalarında kullanılabilecek olmaları itibarıyla değerlidir.

Anahtar Kelimeler: Akıllı Binalar (SB), Akıllı Bina Değerlendirmesi, Akıllı Sürdürülebilir Şehirler (SSC), Akıllı Bina Güçlendirme/ Yenileme/ Restorasyon İşlemleri, Anahtar Performans Göstergeleri (KPI)

Dedicated to my beloved family...

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AFA	Addressable Fire detection and Alarm
AC	Air-Conditioning
ANSI	American National Standard Institute
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AIIB	Asian Institute of Intelligent Buildings
BB	Basic Buildings
BKB	Blocks Building
BEMS	Building Energy and Management System
BEPAC	Building Environment Performance Assessment Criteria
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
BQA	Building Quality Assessment
BRE	Building Research Establishment
BREEAM	Building Research Establishment’s Environmental Assessment Method
BMS	Buildings Management System
CPI	City Prosperity Index
CMMS	Computerized Maintenance Management System
CABA	Continental Automated Buildings Association
DALI	Digital Addressable Lighting Control
DDC	Direct Digital Controls
DHW	Domestic Hot Water
EPIQR	Energy Performance Indoor Environmental Quality Retrofit
EPBD	Energy Performance of Buildings Directive
ERM	Energy Retrofit Measure

EU	European Union
GEM	Global Environmental Method
GWP	Global Warming Potential
GBCA	Green Building Council of Australia
GBI	Green Building Initiative
GBR	Green Building Rating
GB Tool	Green Building Tool
GGRS	Green Globes Rating System
GSR	Green Star Rating
GHG	Greenhouse Gases
H&S	Health & Safety
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
HK-BEAM	Hong Kong Building Environmental Assessment Method
HQAL	Housing Quality Assurance Law
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ICT	Information and Communication Technology
IT	Information Technology
IBMS	Integrated Building Management System
IBI	Intelligent Building Index
IBS	Intelligent Building Score
IBSK	Intelligent Building Society of Korea
ISO	International Standards Organization
ITU	International Telecommunication Union
IPTV	Internet Protocol Television
IB	Isolated Buildings
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
LEED-H	Leadership in Energy and Environmental Design for Homes

LEED-NC	Leadership in Energy and Environmental Design-New Construction
LS	Lifting System
LB	Live Building
LAN	Local Area Network
MSS	Maintainability Scoring System
NABERS	National Australian Built Environment Rating System
nZEB	Nearly Zero-Energy Buildings
NPV	Net Present Value
Opteemal	Optimized Energy Efficient Design Platform for Refurbishment at District Level
PV	Photo-Voltaic
PABX	Private Automated Branch Exchange
QEM	Quality Environment Module
RES	Renewable Energy System
ROI	Return On Investment
SB	Smart Buildings
SEC	Security Monitoring and Access
SCC	Shanghai Construction Council
SCIS	Smart Cities Information System
SSC	Smart Sustainable City
SSB	Suburban buildings
SBEnrc	Sustainable Built Environment National Research Centre
Espresso	Systemic Standardisation Approach to Empower Smart Cities and Communities
TIBA	Taiwan Intelligent Building Association
ITS	Telecom and Data System
TED	Thermal Energy Demand
TB	Traditional Boiler
U4SSC	United for Smart and Sustainable Cities
UNECE	United Nations Economic Commission for Europe

UN-Habitat	United Nations Human Settlements Programme
USA	United States of America
VIP	Very Important Person
VTGU	Vilnius Gediminas Technical University
VRM	Virtual Retrofit Model

CHAPTER 1

INTRODUCTION

1.1. Motivation of the Study

Within the last decades, Smart Building (SB) concept has become increasingly popular due to the diverse benefits SB concept presents to the lives of people. In line with the increase in popularity of smart buildings, the number of studies performed on smart buildings also increases. Focusing on the performance of SBs, the components, services, and systems of the buildings are being assessed (e.g., So et al. 1999, Wang 2010). However, in spite of nearly forty (40) years of history on SBs, researchers have not reached unanimity on what the smart building definition is and which methodology could be used to assess smartness of the SBs. It should also be noted that sometimes “smart building” and “intelligent building” terms have been used interchangeably to express the same concept in the literature. While there are different views on how these terms are different, in this study, the “smart building” term has been used as an umbrella term to cover both definitions given in the literature.

In recent years, a powerful, separate and wider trend, namely Smart Sustainable City (SSC), has arisen due to various factors such as air pollution, climate change, resource depletion, and technological advancements. Accordingly, various studies were performed by researchers and standardization organizations to formalize the definition and measurement of SSCs (e.g., International Standards Organization, Höjer and Wangel 2015). Some components of the built environment could be sorted according to scale, such as buildings, neighborhoods, districts, and cities. As could easily be noticed, smart buildings are a part of the city-scale built environment. Therefore, a disconnection occurs related to SB requirements (e.g., definitions, assessment approaches) from the smart building and smart sustainable city perspectives (Parlak et al. 2018).

There is a need to integrate the SB assessment methodologies that present Key Performance Indicators (KPIs) in the building-scale and city-scale studies. Hence, the examination of the SSC KPIs and SB KPIs for the development of an integrated smart building assessment methodology is the main motivation and research goal of this study. Moreover, since new buildings represent only a small percentage of the total building stock (SBEnrc 2012), the integrated building assessment should be applicable to existing buildings.

1.2. Research Questions

The following research questions are identified to address the aforementioned gap:

RQ1. What are the commonalities and differences between the smart building assessment KPIs on an SB-scale and SSC-scale?

RQ2. How can the smart building KPIs of the building-scale and city-scale methodologies be integrated?

1.3. Research Objective

The aim of this study is to combine the building-scale and city-scale smart building requirements to develop an integrated smart building assessment methodology. To achieve the overarching goal, the objectives are to:

- To examine the existing smart building assessment methodologies and their KPIs and SSC assessment methodologies and their KPIs
- To develop an SB assessment methodology to establish integration of smart sustainable city level features and smart building KPIs. The methodology should be suitable to meet today's needs (e.g., existing buildings) as well as expectations from smart buildings.

1.4. Scope and Outline of the Thesis

Chapter 2 presents a literature review on "Smart Buildings", regarding the smart building definitions and smart building technologies.

Chapter 3 presents "Smart Building Assessment". In this context; comparison of current SB assessment methods, existing KPIs of these methods, objectives/ motivations of SB assessment and limitations of existing SB assessment studies are examined.

In Chapter 4, a literature review on smart retrofit actions for existing buildings is presented. The data obtained as result of this examination is valuable due to their applicability on transition steps towards SSCs.

In Chapter 5, a study examining relationship between SBs and SSCs is performed. In this regard; existing SB assessment methodologies, existing SSC assessment methodologies and their KPIs are examined.

Chapter 6 presents the methodology that has been followed to develop an integrated SB assessment methodology integrating smart city and smart building KPIs.

In Chapter 7, details of the case study building is shown and features of the building is examined.

Results of this study, which are based on selection of the prominent studies in related fields, have been shown in Chapter 8 “Findings”. Moreover, the smartness of a case study building has been assessed with the developed integrated SB assessment methodology and results of the assessment are demonstrated in this chapter.

In Chapter 9, conclusion of this study is presented. In this context; findings are summarized, practical implications are examined and future research dimensions are revealed.

CHAPTER 2

SMART BUILDINGS

Since the beginning of life, sheltering has been one of the basic needs of humankind (Taormina and Gao 2013). Sheltering has evolved in line with the developments shown up in civilization and technology. Nowadays, sheltering has reached up to smart buildings level. Smart buildings have various advantages compared to conventional non-smart buildings due to the high technologies they incorporate (Ghaffarianhoseini et al. 2016). Under the favor of high technology, usage of automation in the buildings became possible in the first stages of adapting new technologies to buildings. Thereafter, reactive and responsive/adaptable buildings have come into picture by the contribution of developed technologies. Demand to smart buildings has risen steadily due to higher living standards proposed by smart buildings. As So and Wong (2002) stated that smart buildings have gained popularity with their features such as environmental friendliness, health and energy conservation, space utilization and flexibility, human comfort, working efficiency, culture, image of high technology, safety and security measures (including measures against fire, earthquake, disaster and structural damages), construction process and structure, life cycle costing, cost-effective operation and maintenance. Moghaddam (2012) also presented five (5) benefits: efficiency, cost, environmental impacts, health and security and widened coverage of function of smart buildings. Accordingly, construction of first smart building was completed in Connecticut/ USA in July 1983 (So and Wong 2002).

2.1. Smart Building Definitions

Buckman et al. (2014) defines smart buildings as the buildings optimizing total comfort level and energy consumption addressing usage of smartness and sustainability points with usage of computer and smart technologies.

So and Wong (2002) stated that during the past four decades, different smart building definitions had been asserted in different parts of the World. However, they were insufficient for architectural, engineering, construction industry professionals to construct new smart buildings properly. Also, they stated that smart building definition should be adjusted in line with building type such as dwellings, research centers, hospitals etc. (So and Wong 2002).

Discussions on smart buildings continued to be handled by different point of views, and the importance of adaptability concept came into the picture. Adaptability has been accepted as the next step of reactivity. As per this approach, adaptable buildings could be able to adapt themselves to people’s variable comfort perceptions depending on the current time period, changes in occupants of building, occupancy characteristics and change of yearly average climate. Adaptability has four (4) foundations namely intelligence, enterprise, material, design and control in order to meet high energy efficiency expectations, comfort and user satisfaction (Buckman et al. 2014).

Cole and Brown (2009) examined smart building concept in their study under automation, information processing, space management, passive intelligence, organizational intelligence and occupant intelligence. Automation concept provides efficient building operation; information processing concept makes the construction of responsive buildings possible; smart space management makes the design flexible and adaptive; organizational intelligence makes the multi-functional usage of buildings possible and occupant intelligence gives personal heating, ventilation and air conditioning (HVAC) and lighting adjustment option to occupants (Cole and Brown 2009).

Wang (2010) classified smart buildings and used performance-based definition, service-based definition, and system-based definition for their assessment. Performance-based definitions perform building assessment in terms of user demands instead of evaluating technologies and systems. Service-based definitions perform building assessment in terms of the quality of the services that building has. System-based definitions perform building assessment in terms of systems that building has (Wang 2010).

DEGW (1992) divided smart buildings into three categories. According to DEGW (1992), smart buildings could be classified as automated buildings, responsive buildings, and effective buildings. The automated building concept belongs to time periods of 1981-1985, responsive building concept belongs to 1986-1991, and the effective building concept belongs to 1992-today. Their development levels are sorted lower to higher as follows; automated buildings, responsive buildings and effective buildings (DEGW 1992 as cited in Chun et al. 2000).

So et al. (1999) stated that smart buildings are the future of the building industry. In the construction of these buildings, priority is given to smart building features. However, despite the popularity of smart buildings, standardization of smart building concept could not be realized yet. Different smart building definitions have shown up from all over the world. According to smart building definition coming from the USA; building systems consist of four different sub-branches as building structure, building systems, building services and building management. Definitions coming from

Europe generally have focused on information technologies (IT) and real occupant requirements. China and Singapore have mostly focused on the application of high-level of automation and high-level technologies. As per So et al. (1999), buildings' meeting capability of occupant demands has more importance than the image of buildings. In this manner, So et al. (1999) developed eight (8) quality environment modules (QEM) in the study they aimed to develop a smart building definition. These QEMs are as follows: environmental friendliness- health and energy conservation (M1); space utilization and flexibility (M2); life cycle costing- operation and maintenance (M3); human comfort (M4); working efficiency (M5); safety- disaster, fire, earthquake and etc. (M6); culture (M7); image of high technology (M8).

Wong et al. (2008) stated that as result of rapid developments in microprocessor-based technologies and demand for the working environment having high performance, studies trying to integrate the smartness concept to buildings have come into the picture and gained importance. By this means, it provides a chance to increase operational effectiveness and marketability of buildings (Wong et al. 2008).

Buckman et al. (2014) noted that smart buildings differ from non-smart buildings with their adaptability feature and underlined that adaptability is beyond reactivity. Adaptability means proactively adapting itself to further situations with evaluating the data coming from internal and external sensors. These function could be given as an example to adaptability: Determining differences between comfort perception of different people in different periods of the year, making necessary adjustments when occupants and building usage characteristics are changed, adapting itself to changes in yearly average temperatures (Buckman et al. 2014).

Ghaffarianhoseini et al. (2016) stated that smart buildings have become more popular due to their capability to present occupant comfort, occupant well-being, and sustainable design together. Also, they indicated that smart building definitions were focused on automation in the 1980s and new features have been added to smart building within time (Ghaffarianhoseini et al. 2016).

Smart buildings provide significant benefits and advantages to their occupants and owners and make their lives easier. These benefits constitute the foundation of the requirement for smart buildings. As So and Wong (2002) stated, smart buildings provide cost-effectiveness while they provide more comfort, convenience, safety, and flexibility. Besides, Kolokotsa et al. (2007) underlined the importance of these benefits in their assessment. They also emphasized the importance of cost of smart buildings to remain at market standard pricing levels while presenting the abovementioned benefits. Azari et al. (2016) expressed that the main advantage of smart buildings is to reduce energy consumption by its energy-saving and energy conservation features.

2.2. Smart Building Technologies

It is an incontrovertible fact that smart buildings' foundation mainly depends on technology. That's why most of the researchers have adverted the technology topic in their studies to intensify on smart buildings in different weights depending on the focus of their studies.

So et al. (1999) remarked that owner and occupant needs have been examined under four (4) main headings, which are building structure, building systems, building management and building services; by Intelligent Building Institute of USA. Building systems and building services headings are directly related to technology. In this classification, HVAC, lighting, electric power, wiring, controls, elevators, domestic hot water, access control, security, life safety, telecommunications, and information management are covered by building systems. Voice, data and video communications, office automation, shared office meeting and computer, fax and photocopying, electronic mail, voice mail, security management, telephone and computer equipment and this kind of points are covered by building services (So et al. 1999).

Fujie and Mikami (1991) noted that some specific features need to exist in smart buildings for the provision of automatically ensured efficient working environments. These particular features are a precise air conditioning system that adapts to a variety of working environments, an antiglare lighting system, a digital electronic exchange system, an optical fiber Local Area Network (LAN) system, a self-contained intelligent system, an in house central monitoring system, an entry-exit control system, an automatic measuring and billing system, a high-volume wiring system for flexibility and adaptability to parabolic antennas (Fujie and Mikami 1991).

Sinopoli (2010) performed a detailed study in his book, namely "Smart Buildings Systems for Architects, Owners and Builders." He focused on HVAC systems, lighting control systems, electric power management systems, access control systems, video surveillance systems, video-IPTV (internet protocol television)-digital signage systems, fire alarm and mass notification systems, voice networks and distributed antenna systems, data networks, facility management systems, and audiovisual systems in his study.

Ghaffarianhoseini et al. (2016) stated that smart buildings were defined with their capability of managing necessary systems and establishing necessary coordination between these necessary building systems to provide desired technical performance, investment as well as operational cost-saving and flexibility. So, it could be said that smart buildings, which represent the utmost form of building whole over history, was discussed from different point of views. Usage of automation and high technology are key elements of smart buildings. Smart buildings have provided benefits to their occupants and owners such as ease of usage, health-related technologies, energy conservation, usage area flexibility, occupant convenience, working productivity, safety and security providing technologies and ease of maintenance. However, no consensus even about the definition of smart buildings across the researchers has been set. While some researchers focus on the type of the buildings, some researchers focus on buildings' adaptability or usage of technology. Also, performance-based, service-based, system-based building definitions are proposed. Additionally, it has been observed that no concurrence has been obtained upon which technologies are required to be used in the smart buildings. In this regard, abovementioned points constitute a gap in the literature about which smart building definition could be used, which smart building technologies could be selected and how a foundation could be set for further smart building assessment.

CHAPTER 3

SMART BUILDING ASSESSMENT

Once the smart building concept was born and started to be developed, the number of smart buildings has increased day by day. As a result of increasing popularity of smart buildings, the requirement for assessment methodologies was born and different assessment methodologies for smart buildings were developed.

National Australian Built Environment Rating System (NABERS) is analyzed by Burroughs (2018) due an increase in the popularity of taking proactive measures to control the environmental effects of buildings during operation. In the analysis, the effectivity of NABERS energy rating is revealed. NABERS evaluates building energy performance with a grading system from 1 to 6 stars with 0.5-star steps. In a case study they applied NABERS rating, an office building in Sydney was retrofitted for new and efficient technology applications. NABERS assessment applied twice to this building, one before the retrofit and one after the retrofit. In before-retrofit assessment, building took 3.6 stars in NABERS's assessment and took 5.3 stars in after-retrofit assessment. Then energy consumption of the building in these two different setups was compared according to its long-term energy consumption values, a 48% energy conservation achievement observed. This showed that increase in a building's NABERS rating from 3.6 stars to 5.3 stars could result in energy conservation of nearly 50%. Besides, Burroughs (2018) stated that Green Star Rating (GSR) was similar to UK-based Building Research Establishment's Environmental Assessment Method (BREEAM) and the North America-based Leadership in Energy and Environmental Design

(LEED) from the point of their design-based assessments. However, NABERS performs its assessments based on its performance in an actual 12-month operation. Even if NABERS started its assessments only for energy performance assessment, today NABER’s assessment content covers water, waste and indoor environmental quality (IEQ) assessments (Burroughs 2018)**.**

3.1. Comparison of Current Assessment Methods

Since assessment of smart buildings are multidimensional and consists a vast number of different criteria, numerous KPIs have been developed by researchers and institutes for smart building assessment. Their studies contain differences in terms of their approaches to technological, cultural and geographic dimensions. Kolokotsa et al. (2007) indicated that the absence of commonly accepted building methods creates difficulties in overall performance assessments of the buildings. Under this condition, it could be said that it is nearly impossible to perform a fair smart building comparison between different buildings (Kolokotsa et al. 2007).

So and Wong (2002) stated that world's first quantitative assessment method for smart buildings was developed by AIIB. Authors underlined that quantitative assessment applied to smart buildings should provide a clear guideline to designers and should provide a fair platform so that occupants and the general public are able to evaluate the performance of the buildings. However, even if all the assessments in the scope of quantitative smart building assessment are applied 100% correctly, it is not certain that the result will be 100% correct objectively. Because even objective assessments rely on opinions of users and experts which are naturally subjective to some extent (So and Wong 2002).

Chen et al. (2006) compared six (6) different smart building assessment methodology/ technique/ rating systems in terms of architecture, engineering, environment, economics, management, and sociology. These six (6) methodologies consist of AIIB (Asian Institute of Intelligent Buildings) Method (Hong Kong, China), BRE (Building Research Establishment) Method (UK), CABA (Continental Automated Buildings Association) Method (Canada, USA), IBSK (Intelligent Building Society of Korea) Method (Korea), SCC (Shanghai Construction Council) Method (Shanghai, China) and TIBA (Taiwan Intelligent Building Association) Method (Taiwan, China) (Chen et al. 2006). Chen et al. (2006) revealed that:

- when these mythologies are examined in terms of **architecture**, AIIB came to the forefront with its criteria comfort, health and sanitation and space. BRE came to the forefront with its criterion-built environment; IBSK came to the forefront with its criterion architectural design; TIBA came to the forefront with its criteria health and sanitation. CABA and SSC do not have any criterion in terms of architecture.
- when these methodologies are examined in terms of **engineering**; AIIB came to the forefront with its criteria high-tech image, safety and structure, working efficiency; BRE came to the forefront with its criteria functionality, responsiveness, sustainability; CABA came to the forefront with its criteria automation, communications, security, structure, systems; IBSK came to the forefront with its criteria electrical system, information and communications, mechanical systems, system integration; SCC came to the forefront with its criteria communication, earthing, facility control, fire accident control, internal integration, office automation, power supply, security, structured cabling; TIBA came to the forefront with its criteria information and communications, safety and structure, structured cabling, system integration.
- when these methodologies are examined in terms of **environment**, AIIB came to the forefront with its criterion green; IBSK came to the forefront with its criterion environment, SCC came to the forefront with its criterion

environment; TIBA came to the forefront with its criterion energy consumption. BRE and CABA do not have not criterion in terms of environment.

- when these methodologies are examined in terms of **economics**, AIIB came to the forefront with its criterion cost-effectiveness; BRE came to the forefront with its criterion economic issues. CABA, IBSK, SCC and TIBA do not have any criterion in terms of economics.
- when these methodologies are examined in terms of **management**, AIIB came to the forefront with its criteria practice and security; CABA came to the forefront with its criterion property; IBSK came to the forefront with its criterion facility; SCC came to the forefront with its criterion property; TIBA came to the forefront with its criterion facilities. BRE has not any criterion in terms of economics.
- when these methodologies are examined in terms of **sociology**, AIIB came to the forefront with its criterion culture. Remaining ones do not have any criterion in terms of economics.

In light of the examination, Chen et al. (2006) remarked that the most comprehensive methodology between among these methodologies is AIIB’s methodology.

Chew and Das (2008) integrated existing green building assessment systems. The partial overlapping between the criteria of green building grading systems and smart buildings is important to notice. They classified green building assessment systems as first-generation (nominal, pass-fail type certification), second-generation (simple additive), third-generation (weighted additive) and others. Chew and Das (2008) evaluated R-2000 (1981, Canada), P-mark (1989, Sweden), ELO & EM scheme (1997, Denmark), Energy Star (2001, USA) building grading systems as first-generation systems. LEED (2000, USA) was evaluated in the second-generation systems category. Building Research Establishment Environmental Assessment Method (BREEAM) (1990, UK), Building Environment Performance Assessment

Criteria (BEPAC) (1993, Canada), Hong Kong Building Environmental Assessment Method (HK-BEAM) (1996, Hong Kong), Housing Quality Assurance Law (HQAL) (2001, Japan), Green Building Tool (GBTool) (2002, International), Global Environmental Method (GEM) (2002, UK), Green Building Council of Australia (GBCA) (2003, Australia), Green Globes (2004, USA), Go Green, Go Green Plus (2004, Canada), Maintainability Scoring System (MSS) (2004, Singapore), NABERS (2005, Australia) were evaluated as third-generation systems. Lastly, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (2004, Japan) did not fit to first three (3) categories and was evaluated in the others category (Chew and Das 2008). Chew and Das (2008) examined details of the prominent green building grading systems deeper as follows. BEPAC performs its evaluation mainly under five (5) different headings as ozone layer protection, the environmental impact of energy use, IEQ, resource conservation and site and transportation. Green Globes Rating System performs its evaluation mainly under seven (7) different headings as project management – policies and practices, site, energy, water resources, building materials and solid waste, emissions and effluents and indoor environment. GEM performs its evaluation mainly under six (6) different headings as energy, water, resources, environmental management and indoor environment and emissions. Go Green and Go Green Plus performs its evaluation mainly under five (5) different headings as resource consumption, waste reduction and recycling, building materials, interior environment and tenant awareness. HQAL performs its evaluation mainly under nine (9) different headings as structural performance, fire safety, durability, ease of maintenance and management, energy efficiency, air quality, ratio of exterior openings to total wall area, noise transmission and barrier-free design. Green Star performs its evaluation mainly under eight (8) different headings as management, IEQ, energy, transport, water, materials, land use & economy and pollution. NABERS performs its evaluation mainly under six (6) different headings as energy, transport, toxic materials, waste, indoor air quality (IAQ) and occupant satisfaction. HK-BEAM performs its evaluation mainly under five (5) different headings as site aspect, material aspect, energy use, water use and IEQ (Chew and Das 2008).

Liu et al. (2006) examined current building assessment tools under five (5) different categories as decision-making support tools, decision-making assessment tools, education tools, training tools, and performance assessment tools. One can easily understand from this discrimination that different assessment tools generally focus on different points of the buildings and it will be beneficial to select right tool in line with the purpose (Liu et al. 2006).

Asadian et al. (2017) indicated that some building assessment systems could be used to evaluate different kinds of demands of people. Authors noted that “Intelligent Building Score (IBS)” index could be used to evaluate level of system integration; “IBAssessor” could be used to evaluate the lifespan energy efficiency of smart buildings in design, construction, and operation phases; “Quality Facilities Strategic Design” could be used to analyze the design characteristics and determine stakeholder requirement priorities; “Building Intelligent Assessment Index” could be used to recognize the smart building level through eight building characteristics (intelligent technology, site specification, identity, intelligent architecture, system responsiveness, operational cost, access, and security); “Intelligent Building Ranking Tool” could be used to estimate the level of integrated systems in a smart building. The selection of assessment methodology considering the purpose is very significant (Asadian et al. 2017).

Bannister (2012) studied NABERS’s performance outcome within last twelve (12) years history. NABERS is the primary building assessment system in Australia. The author concentrated on various NABERS energy and water ratings and he realized that these ratings are generally based on the following points:

- NABERS take measurements from real building using actual consumption values instead of theoretical calculations.
- NABERS ratings have some corrections defined for hours of occupancy and climate and eliminating the errors is not possible. However, no correction was identified for efficiency-related factors (e.g., plant, building envelope, age) within the scope of the NABERS ratings.
- Ratings have been composed in a way that median buildings would get 2.5 stars and aspirational buildings would get 5 stars, and the minimum rating is 1 star. NABERS does not issue any certification for buildings that are not able to achieve even 1 star.
- As of 2010, NABERS rating scaling has been widened to a range that makes getting 6 stars possible (0.5 star comes from emission-related KPIs and 0.5 star comes from water-related KPIs). NABERS give stars to buildings with 0.5-star increments (i.e., 1.5, 2.5, 3.5, 4.5 and 5.5 stars ratings are possible).
- Rating scale of NABERS is bi-linear; slopes within 1-5 stars and slope within 5-6 stars have different inclinations. Since NABER’s energy ratings are dependent on actual energy consumption, it also depends on greenhouse emissions. Since emission values vary from state to state significantly, some adjustments have been applied to median building ratings in a state by state basis. In this context, NABERS has taken effective measures for greenhouses and adjusted median values of each state varying between 2.5-3 stars instead of decreasing the average rating of the states (Bannister 2012).

So and Wong (2002) noted that usage of Cobb-Douglas function might be effective in overcoming drawbacks of existing methodologies. The Cobb-Douglas function is able to explain non-linearity between inputs and outputs of the production (Basak et al. 2013). In many situations, a feature of buildings is being evaluated just by looking at the heading of the feature instead of looking into details. It is obvious that different assessments will come into the picture as a result of the evaluation of the same building by two (2) different assessors. Besides, real world is gray instead of white or black. It is not realistic to say only “yes” or “no” as an answer to a question. Also, adding points over and over with linear addition does not overlap with human thinking. And different types of smart buildings should be evaluated in with different criteria. In the near feature, healthy smart building assessment could be obtained by adding lease and sale values of smart buildings into assessment methodology Intelligent Building Index (IBI) (So and Wong 2002).

In summary, deficiency of a universally accepted smart building assessment methodology makes smart building assessment complicated. Although it is not realistic as well to expect a universally acceptable one set of criteria to evaluate the smartness of buildings. It is detected that currently, existing building assessment methodologies have different focusing points. While some building assessment methods focus more on engineering, others choose to focus more on environment, economics, management, and sociology. It would be appropriate to form a well-balanced or customizable methodology for further actions. In this context, a nominal, pass-fail type certification-based assessment, a simple additive grading-based assessment, or a weighted additive grading assessment has been considered. Besides, the purpose of preparation of smart building assessment methodology should be determined correctly. A corresponding methodology could be prepared aiming to form a decision-making support tool, a decision-making assessment tool, an education tool, a training tool and a performance assessment tool. Also, it should be noted that an assessment only based on yes/no type might result in inconsistent results. Assessment should be supported by the addition of a gradual grading system.

3.2. The Objectives/ Motivations of Smart Building Assessment

Azari et al. (2016) stated that the birth of smart building concept and BMS significantly depend on smart management of energy control and energy usage technologies. They also underlined that BMS is one of the most extensive and efficient smart control systems. with the main target of smart building transition to reduce energy consumption. Pérez-Lombard et al. (2008) stated that the rapidly growing world total energy use causes anxieties to rise considering resource scarcity and difficulties encountered in reaching energy resources. Besides, adverse environmental impacts such as ozone layer depletion, greenhouse effect, change in climate cause anxieties have been risen more. They remarked that the share of residential and commercial buildings' energy consumption within total energy consumption accounts for 20-40% of total energy consumption in developed countries. It means that energy consumption of buildings have exceeded the energy consumption in the industrial and transportation sector in some countries (Pérez-Lombard et al. 2008).

Pérez-Lombard et al. (2008) explained the increase in percentage in buildings' energy consumption in total energy consumption with an increase in population, higher occupant anticipations for building services and significant comfort levels, increase in time spent in indoor areas. They also indicated that these are indicators showing an increasing trend that will result in higher building energy consumption values. That's why; policies in the frame of regional, national and international levels regarding energy usage effectiveness have a key importance (Pérez-Lombard et al. 2008). Pérez-Lombard et al. (2008) also stated that HVAC systems have a district importance within other building systems since HVAC systems account for approximately 50% of buildings' overall energy consumption and approximately 20% of overall energy consumption of the country in USA.

3.3. Existing Key Performance Indicators (KPIs)

Smart building assessment methodologies consist of multiple evaluation criteria, namely Key Performance Indicators (KPIs). One of the major elements creating the difference between different building assessment methodologies is the utilized KPIs. In this context, KPIs given under various building assessment methodologies have been examined. An exemplary set of studies are presented in Table 3.1. As can be seen, mostly survey based methods are used to assess smart buildings.

Table 3.1 Exemplary Set of Smart Building Assessment Methodologies

Method Used	Purpose	Reference
AHP (Analytic Hierarchy Process)	Selecting smart building systems	Wong and Li (2008)
AHP	Determining main problems of sustainable smart buildings and developing a KPI selection model	ALwaer and Clements-Croome (2010)
AHP and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)	Performing smart building assessment in fuzzy conditions	Kaya and Kahraman (2014)
ANP (Analytic Network Process)	Development of key smart indicators and conceptual analytical framework	Wong et al. (2008)
ANP	Propounding an innovative SB asseessment approach using analytic network process	Chen et al. (2006)
General survey	Developing a Matrix tool for smart building assessment	Kolokotsa et al. (2007)
General survey	Performing smart building assessment	Moghaddam (2012)
Questionnaire survey	Developing a smart building assessment index	Arditi et al. (2015)
General survey	Proposing a comprehensive multi-criteria decision-making framework for selection of smart buildings	Azari et al. (2016)
General survey	Determining common specialties of the smart buildings	Ghaffarianhoseini et al. (2016)

Chew and Das (2008) examined foremost building grading systems that mostly focus on sustainability in their State-of-the-Art Review and found that:

- LEED-NC (LEED-New Construction) (2005a version) scores are divided into five (5) headings as sustainable sites, water efficiency, atmosphere, materials and resources and IEQ, (and a bonus for innovation and design) with a total of sixty-nine (69) points. However, assessment is performed in the LEED-H (LEED for Homes) by distributing different points to irrigation, landscaping and surface water management, materials durability. In LEED-H, it is possible to apply adjustment considering climate characteristics such as dry, wet and normal climates (Chew and Das 2008).
- BEPAC was developed at the University of British Columbia by the environmental research group in Canada in 1993. This method is based on the BREEAM method and this method evaluates new or existing offices and commercial buildings. The environment research group proposed four (4) modules and five (5) topic areas for design and management criteria prepared for base building and occupants. These five (5) topic areas are ozone layer protection, environmental impact of energy use, IEQ, resource conservation, site and transportation (Chew and Das 2008).
- Green Building Initiative (GBI) released the Green Globes Rating System (GGRS) in 2004. GGRS is also based on BREEAM like BEPAC. This is the only building grading system recognized by American National Standard Institute (ANSI). GGRS has an assessment protocol for the environment-friendly design of commercial and institutional buildings. Thirty-one (31) parameters of GGRS are gathered under seven (7) categories: project management - policies and practices, site, energy, water resources, building materials and solid waste, emissions and effluents and indoor environment (Chew and Das 2008).

- HQAL was put into force by the Japanese Government in 2001. HQAL performs an assessment in terms of structural performance, fire safety, durability, ease of maintenance and management, energy efficiency, air quality, the ratio of exterior openings to total wall area, noise transmission and barrier-free design characteristics (Chew and Das 2008).
- NABERS, which was showed up in Australia, performs its assessment evaluating overall greenhouse score – average of energy/greenhouse and refrigerant use, overall water score – average of water use, stormwater runoff and sewage outfall volume, site management score – average of stormwater pollution, landscape diversity, toxic materials, refrigerant ozone depletion and IAQ (Chew and Das 2008).
- HK-BEAM was showed up in 1996 in Hong Kong. HK-BEAM separated buildings into four (4) classes after assessment. Buildings having min overall 75% and min IEQ 65% are defined as platinum, buildings having min overall 65% and min IEQ 55% are defined as gold, buildings having min overall 55% and min IEQ 50% are defined as silver, buildings having min overall 40% and min IEQ 45% are defined as bronze (Chew and Das 2008).

Clift (1996) stated that Building Quality Assessment (BQA) stands for expressing a computerized system of building assessment. Building Research Establishment (BRE) has played a role in the development of the BQA. BQA measures buildings' performance to meet predefined occupant needs changing in accordance with the type of the buildings. With this feature, BQA could be used as aid for portfolio or asset management, rent reviews, investment appraisals, purchasing or selling properties, defining quality at briefing stage for new build and refurbishment, and judging alternative design proposals. One of the biggest problems encountered by potential property owners, managers, designers and agents is high subjectivity in comparative quality and feature assessment of the buildings to be used for investment and/or occupation (Clift 1996). BQA performs its assessment under the categories of:

presentation related to appearance and impression; space functionality determining operation of space; access of people and goods, access and circulation related to security; amenities covering facilities and spaces; business services related to electrical services and IT; working environment analyzing environmental conditions; health and safety comprising mandatory H&S (Health & Safety) issues; structural building concerning structure and condition; building management containing short and long term condition (Clift 1996).

The categories of BQA branches out sub-sections and sub-factors. For instance, access and circulation category branches out as follows: Under people section; entrance, entrance traffic capacity, building wayfinding, lift performance, lift controls, stairs, retail access and disabled access factors exist. Under vehicle section; number of car park spaces, car park layout, car park column intrusion, access – street to car park, access – car park to building, car park facilities and VIP (very important person) access factors exist. Under goods section; general accessibility, loading bay, goods lift and rubbish disposal factors; under security section; general, retail area, office floors, car park and site factors exist (Clift 1996).

Wong et al. (2008) developed an analytical framework with KPIs with the purpose of presenting a methodology to assess smartness levels of buildings. In this context, they propounded sixty-nine (69) KPIs gathered under eight (8) major smart building systems. They prioritized the KPIs using a systematical Analytic Network Process (ANP), and developed a model to assess smartness of buildings. ANP provided the necessary infrastructure to assign different independent relationships between KPIs and building operational goals/benefits (Wong et al. 2008). The evaluated systems were: Integrated building management system (IBMS) for overall monitoring and building management; HVAC control system provides occupant control over of comfort and IAQ; addressable fire detection and alarm (AFA) system having capability of firefighting and warning occupants in case of fire; telecom and data system (ITS) providing communication network infrastructure; security monitoring and access (SEC) system establishing access control and monitoring; smart/energy efficient lifting system (LS) to present multi-story transportation function; digital addressable lighting control (DALI) system controlling light design and control; computerized maintenance management system (CMMS) for control of and service works (Wong et al. 2008).

Smart buildings provide enhanced safety, improved reliability, high efficiency and lower maintenance costs with their features controlling complex dynamics, human-machine interaction, autonomy and bio-inspired actions (Bien et al. 2002, as cited in Wong et al. 2008). Under controlling complex dynamics; having a not traditional base, adaptation, direction planning and non-linearity features lie down. Under human-machine interaction; understanding and communication similar to human, expressing emotions, design ergonomy features lie down. Under autonomy; self-calibration, self-tuning, self-diagnosis application capability and fault tolerance features find themselves a position. Under bio-inspired actions; behaviors biologically motivated, cognitive-based, neuro-science features are presented (Bien et al. 2002, as cited in Wong et al. 2008).

Lavy et al. (2014) gave special importance to occupant perception in the study they performed to develop facility assessment KPIs. They stated that two (2) different approaches could be adverted when data collection for perception of people is the case: Subjective approach and objective approach. While the objective approach is a direct observation by an external observer oriented, the subjective approach is based on impressions of building occupants.

Shah et al. (2010) performed their study on sustainable smart buildings and existing building performance assessment methods and tools all over the world. Their findings showed significant details about these methodologies and tools. They evaluated BREEAM as a tool grading environmental performance of new and existing buildings. They assessed HK-BEAM, which presents guidance in line with local conditions and government policies and certifications, as a methodology based BREEAM. They highlighted the voluntariness-based side of LEED five (5) years update period of LEED rating. They noted that LEED is a national standard used by the USA to develop high-performance buildings. They also mentioned CASBEE to ensure buildings to meet political requirements and market demands for a sustainable society. In this context, CASBEE performs life through assessments. They also stated that IBI 3.0 is based on political requirements, requirements of the construction sector, and desires of occupants. Furthermore, they touched on methodology, which has been developed for international green building challenge (Shah et al. 2010).

Shah et al. (2010) stated that plenty of current building assessment methods followed multiple phase performance measuring and presented BREEAM as an example. BREAAM is divided into credits management, health and wellbeing, energy, transport, water, materials, land use & ecology and pollution categories in the first phase. Later, buildings are evaluated under these categories and points taken under these categories are multiplied with weightings of the categories. The sum of these weighted points give a single score and a pass, good, very good or excellent evaluation could be made for the building considering total point taken by the building (Shah et al. 2010).

Even if they contain some SB KPIs, most of the abovementioned methodologies examined in this study are greenness/ sustainability focused. Origins and main focuses of these methodologies are shown in Table 3.2.

Table 3.2 Origins and Focuses of the Abovementioned Methodologies

Methodology Name	**Country**	**Main Focus of Methodology**
LEED-NC	USA	Green
LEED-H	USA	Green
BEPAC	Canada	Green
BREEAM	UK	Green
CASBEE	Japan	Green
BQA	New Zealand	General
GBI	USA	Green
HQAL	Japan	Green
NABERS	Australia	Green
HK-BEAM	Hong Kong	Green

Ghaffarianhoseini et al. (2016) examined KPIs of the building assessment methodologies arisen from all over the world. Based on their examination, they proposed that a building must have minimum features to be accepted as smart buildings in terms of systems, performances, and services. The minimum features under smartness and technology awareness are: usage of advanced embedded systems for building components; unionization of smart technologies and economy; advanced sensors providing data to artificial intelligence; technological unification of building systems; current, adaptable, compatible building control systems; nestedness with ingenious future technologies. The minimum features under economy and cost efficiency are: economic effects and lifestyle analysis, cost-effectiveness; meeting productivity and effectiveness concern; effective resource management; unified facility management; the existence of cost/time-saving strategies. T minimum features under personal and social sensitivity are: considering needs and expectations of occupants; comfort, convenience, safety and security; responding to people's expanding and changing needs; being reactive to social and technological changes; being responsive to the needs for communication and globalization; well-being, emotional satisfaction and enhanced users' creativity. T minimum features under environmental responsiveness are: ecological sustainability; usage of renewable energy sources, existence of energy efficient strategies, and usage of conservation techniques; existence of energy management systems (Ghaffarianhoseini et al. 2016).

So et al. (1999) remarked that it is possible for each type of buildings (e.g., residential, commercial, transportation terminals, educational, public services or religious service buildings) to be smart with meeting different sets of smart building criteria. They proposed that differentiation in smartness assessments of different type of buildings could be derived by the selection of different QEMs accordingly. In this sense, they indicated that three (3) most important QEMs for a hospital are environmental friendly ± health and energy conservation (M1), safety - fire, earthquake, disaster and structure etc. (M6), human comfort (M4); three (3) most important QEMs for a residential building are human comfort (M4), culture (M7), safety - fire, earthquake, disaster and structure etc. (M6); most important QEMs for a commercial office are working efficiency (M5), space utilization and flexibility (M2), environmental friendly ± health and energy conservation (M1); three (3) most important QEMs for a transportation terminal are safety - fire, earthquake, disaster and structure etc. (M6); human comfort (M4); environmental friendly ± health and energy conservation (M1).

Studies Kaya and Kahraman (2014), Azari et al. (2016), Chen et al. (2006), Wong and Li (2008), and Wong et al. (2008) are detected as smartness oriented studies having clear SB assessment KPIs that could be used for development of the further smart building assessment methodology, which aims decision-making assessment and performance assessment. Kaya and Kahraman (2014) studied the comparison of smart buildings based on multi-criteria assessment and propounded various smart building assessment KPIs accordingly. Azari et al. (2016) also studied the assessment of multi-criteria assessment of smart buildings and they developed SB assessment KPIs taking So et al. (1999)’s abovementioned eight (8) QEMs as reference to form a foundation for their KPIs. The KPIs developed in . Azari et al. (2016) branch under these QEMs. Chen et al. (2006) developed a model for smart building assessment, namely IBAssessor. They developed smart building assessment KPIs for their model under the headings of green index, space index, comfort index, working efficiency index, culture index, high-tech image index, safety and structure index, management practice and security, cost effectiveness index and health and sanitation index. Wong and Li (2008) performed a multi-criteria analysis of selection of smart building systems. In that study, they composed a questionnaire group consisting of a total of one-hundred-thirty-six (136) construction experts (e.g., academics, developers, design consultants, quantity surveyors, and construction practitioners) to select SB KPIs and they presented the KPIs obtained as result of that study. Wong et al. (2008) developed sixty-nine (69) KPIs for SB system smartness assessment under eight (8) main building control systems.

3.4. Limitations of Existing Smart Building Assessment Studies

Chen et al. (2006) stated that index calculation method of the AIIB is not reliable due these major reasons: (i) criteria of AIIB cause unclear result to arise at the end of assessment, (ii) calculation method of AIIB could give inconsistent results, (iii) outputs of AIIB method is not unique i.e. it is possible for a building to get different assessment results in assessments performed in different times (Chen et al. 2006).

Chew and Das (2008) stated that it is hard and complicated for a practitioner to select the most appropriate tool considering project-specific needs even if significant improvements occurred in green building grading systems since 1990s. Clift (1996) mentioned the subjectivity encountered by landlord / facility managers / designers /agents when assessing the united quality and merits of the buildings.

So and Wong (2002) asserted that some shortcomings of HK-BEAM, GBR and BRM could be overcome by Cobb-Douglas function. They stated that these methodologies perform assessments with strict graded assessment criteria, however strict grading methodologies could not fit in the conditions of the real world. They underlined that typical issue encountered in current building assessment systems is the grading system that is based on linear addition of the points. They noted that this is similar to the conventional grading system being used in education. In this system, students are evaluated with a grading system granting a hundred (100) points to students answering all the questions right. However, this system could give eighty (80) points to a student who does not even answer five (5) questions out of twenty-five (25) questions. The human brain does not assess the surroundings in this machine-like manner and real-world is grey instead of white or black. Nearly all of traditional building assessment methodologies perform an assessment with yes / no questions, which do not match with realities. As per their point of view, an assessment methodology should not be a static methodology, it should be developed within time and it should have a learning capability.

CHAPTER 4

SMART RETROFIT FOR EXISTING BUILDINGS

Developments in the last century, such as the invention of steel-reinforced concrete, have given a chance to buildings to have a structural lifetime exceeding a hundred (100) years (Bogenstätter 2000). Buildings that were constructed a few decades ago were not constructed considering the application of current technologies and occupant demands. However, they are still in service and provide space for their occupants. Moreover, most of the developed countries completed most of their building constructions a long time ago. New buildings stand for only a minor percentage of total building stock (SBEnrc 2012). However, new building constructions increase in many rapidly developing countries that means buildings' total energy consumption increases all over the world (Karkare et al. 2014).

Brito and Silva (2012) underlined that retrofitting existing buildings are better than constructing new ones in most situations and retrofitting provides a chance to use fewer materials and local labor force. Basso et al. (2017) stated that building portfolio of Europe mainly consists of multi-story residential buildings constructed in 1960-1979 and there were few or no energy efficiency requirements in the period these buildings were constructed. Rey (2004) stated that a significant percentage, extending to 65%, of the office building stocks were constructed between 1947 and 1989 years. This means these buildings are in a position requiring the implementation of necessary retrofit actions as of now. They also noted that buildings are subjected to physical and functional obsolescence with the construction of each new building. Even if this obsolescence might be mitigated up to some extent with regular maintenance actions, after a point retrofit requirement becomes ineluctable (Rey 2004).

Kumbaroglu and Madlener (2012) performed a study to reveal an economically optimal set of retrofit methodology by their techno-economic evaluation method. They proposed a dynamic assessment based on Monte Carlo simulation instead of conventional static Net Present Value (NPV) calculation-based assessments. That study found that retrofit investment is highly sensitive to energy prices where buildings are located (Kumbaroglu and Madlener 2012).

4.1. Building Retrofit Overview

SBE-NRC (Sustainable Built Environment National Research Centre) (2012) mentioned about general tendency focusing on new buildings and underlined that new buildings only corresponds to just 1% of the total building stock referencing the data taken from The Centre for International Economics (2007). Asadi et al. (2014) stated that retrofitting existing buildings offer benefits in terms of enhancing occupant comfort and well-being, decreasing energy consumption all over the world and reducing global warming emissions. Also, they remarked the general judgment that building retrofit actions provide sustainability in the built environment with relatively low costs and high benefits. However, even if a significant amount of retrofit methodologies take place in the literature, the selection of a specific retrofit action for special projects is still confusing (Asadi et al. 2014).

Rey (2004) stated that the lifespans of different building components vary significantly. For office buildings, while the lifespan of some interior finishes in limited with a couple of months, the lifespan of a building facade could be more than thirty (30) years. Generally, arising need of facade retrofit is one of the main indicators that determine the time of a comprehensive retrofit action. In this context, the retrofitting cycle could be estimated a twenty-five and thirty (25-30) years (Rey 2004).

Di Giuda et al. (2016) studied the costs arisen from specific retrofit actions on school buildings. They recorded that cost distribution for the specific retrofit actions within all actions as follows: 1% control of lighting system, 1% heating control system upgrading, 2% solar thermal systems for DHW (domestic hot water), 3% thermal generator replacement, 6% lighting system upgrading, 10% thermal insulation of the roof, 12% thermal insulation of walls and roof, 19% external shading of south facade and 46% windows replacement. It could be seen that the most expensive part of the retrofit action is window replacement in this particular study. Vallati et al. (2017) believe that possible retrofit action to the school buildings located in the central Italy region would probably result in 38% thermal energy saving and 46% electrical energy saving.

Brito and Silva (2012) stated that noteworthy portion of building stock mainly suffers from lack of maintenance and need a retrofit intervention to accomplish fulfilling requirements of 20-20-20 goals, which aims 20% cut in greenhouse gas emissions, 20% increase in use of renewable energy, and 20% cut in energy consumption through improved energy efficiency by 2020 (“EU climate package explained” 2020). Martín-Garín et al. (2018) noted that an environmental monitoring device, which is developed for energy retrofits, should be a non-invasive system, be a low-cost development device, have flexibility to develop different equipment for special needs, have a wireless data transmission, have data storage reliability, have a big data storage capacity, and provide the infrastructure to review stored data online.

Ceo et al. (2016) stated that smart buildings provide a noteworthy enhancement in energy efficiency and reduction in operational cost with uninterrupted monitoring and optimization using the data gathered from related sensors. However, they underlined that only newer buildings are generally available to utilize these boons in full. Generally, building constructed before 1999 have been equipped with pneumatic and analog controls and they need very expensive and comprehensive retrofit actions to upgrade these buildings to smart building standards (Ceo et al. 2016). However, Ceo et al. (2016) expressed that innovative non-invasive technologies lowering the cost of retrofit actions have emerged in recent years. As an example, they stated they had applied retrofit action on a 65-story high rise building at Illinois, USA with non-invasive technologies with a cost 70% lower than direct digital controls (DDC) retrofit and derived a 1.7-year payback period.

Buildings stand for 30%-40% of the world's electricity consumption (Karkare et al. 2014, Ascione et al. 2018). SBE-NRC (2012) expressed that buildings have a 10% share in the greenhouse gases (GHG) emission of Australia. In the meantime, it is possible to decrease energy consumption with low-cost interventions such as HVAC, lighting and office equipment. A lot of countries have taken some remedial actions and examined this situation in the context of fighting against climate change. Global energy costs and GHG emissions would be reduced with cost-optimal solutions. There is still a big potential in improving energy performance of buildings in addition to intensive studies performed on green design and carbon emissions.

4.2. Building Features for Retrofit Actions

Kumbaroglu and Madlener (2012) examined their case study buildings under the headings of (i) general description, and (ii) building installation technology. They scrutinized buildings in terms of usage of buildings (type), year of construction, number of floors, net area, gross area, heated floor space, total consumption and primary energy demand under the general description heading. They focused on building energy systems under building installation technology heading and scrutinized model year of heating system, type of heating system, nominal heat output, and building components (e.g., basement, exterior walls, windows, attic and roof).

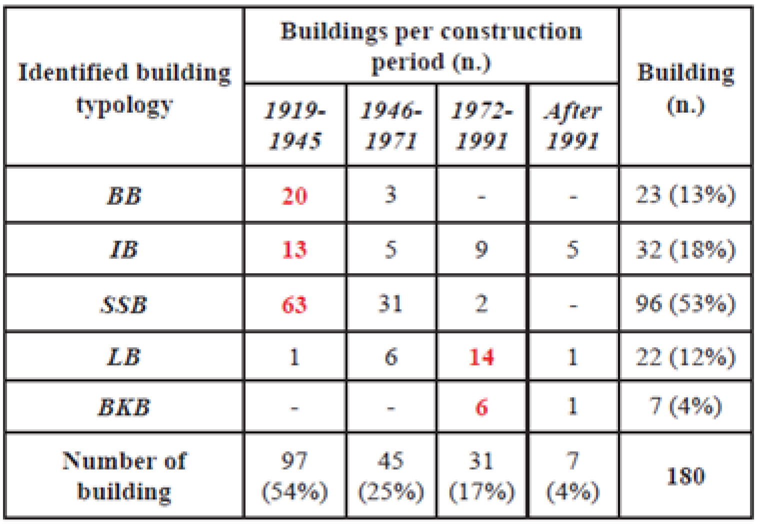
National Renewable Energy Laboratory's (2013) study on retrofit actions was composed of a guideline for considering climate impact in retrofit actions. They divided the USA into five (5) parts in terms of climate characteristics: hot-humid climate (covering Miami and Florida), hot-dry climate (covering Las Vegas and Nevada), marine climate (covering Seattle and Washington), cold climate (covering Chicago and Illinois), and very cold climate (covering Duluth and Minnesota). This kind of climate-specific classifications and corresponding adjustments to retrofit actions could be applied to further applications.

Ardente et al. (2011) stated that necessary information for retrofit actions could be gathered from design documentations having information related to construction materials and construction techniques, data gathered from previous retrofit application implementations also having information related to waste production and machinery energy consumption, data gathered from actual energy consumption of the building, data gathered form energy production system. Asadi et al. (2014) evaluated external wall insulation, roof insulation materials, windows type, solar collectors' type, and HVAC systems of the building they studied for retrofit action determination.

SBE-NRC (2012) focused on commercial building performance improvement in their green building industry report. In this topic, they focused on complex and independent factors for reducing energy demand in commercial buildings and increasing productivity: (1) design elements, (2) indoor environment quality, (3) occupant experience, (4) agreements and culture, and (5) building management (SBE-NRC 2012). They specified some questions could be asked to evaluate these factor such as whether lighting system is energy efficient or not for design elements, whether lighting levels are suitable for tasks or not for indoor environment quality, how occupants are satisfied with the light levels and controls for occupant experience, whether there is a maintenance schedule for lighting or not for agreements and culture, whether there is a fit-out guide in place for lighting systems. Ascione et al. (2016) analyzed the building for retrofit action in terms of geometry/shape, function (purpose of usage of different building parts, occupancy and usage schedule, evaluation of the building location in terms of internal heat gain), system (size and type of HVAC system and thermal zoning as per function) and envelope (thermo-physical properties) of the building.

Ferrante et al. (2016) determined the characteristics of their sample building with these features; context (environment of the building, medium and mean height of surrounding buildings, proximity of surrounding buildings, clearance between surrounding buildings, existence of green areas within close proximity), geometry (size of the building, volume of the building, surface area of the building, geometrical typology of the building), specific features that building has (wall surface characteristics, glazed surface characteristics, heating system characteristics, hot water heating system characteristics). Ferrante et al. (2016) divided district buildings into five (5) different residential architectural typologies as basic buildings (BB), isolated buildings (IB), suburban buildings (SSB), live building (LB), and blocks building (BKB). They also gave the number of buildings corresponding architectural typologies based on construction years in the district, which is in Palermo / Italy, in Table 4.1.

Table 4.1 Characterization of Identified Architectural Typologies of the District on the Basis of the Construction Period (Ferrante et al. 2016)



Identified building typology	**Buildings per construction period (n.)**				**Building (n.)**
	1919-1945	***1946-1971***	***1972-1991***	***After 1991***	
BB	20	3	-	-	23 (13%)
IB	13	5	9	5	32 (18%)
SSB	63	31	2	-	96 (53%)
LB	1	6	14	1	22 (12%)
BKB	-	-	6	1	7 (4%)
Number of building	97 (54%)	45 (25%)	31 (17%)	7 (4%)	**180**

As per Ferrante et al.'s (2016) definition, **BBs** are indeed sheds, that are generally used in rural areas with basic insulation. However, they have been generally expanded and used as residential buildings that are single-story with floor height generally varying between three (3) meters and five (5) meters. They are generally in a single dwelling form. **IBs** have a private garden and IBs are in a private area. They are generally single-story and double-story buildings and it is common for IBs to be in single dwelling or two (2) dwelling from. **SSBs**, differentiate with independent entrance and private outdoor space. They generally have two (2) common walls between adjacent buildings. SSBs generally exist in a linear settlement structure. One (1) dwelling stands at each floor. They generally have two (2) or three (3) floors, but having four (4) floor is rarely seen. **LBs** come to the forefront with a linear combination of housing units. It is not a must for LBs to have a straight placement. They generally have more than four (4) floors and standard story height of 3.20 meters. Each floor has two (2) or more dwellings. **BKBs** are an alternative to LBs. BKBs occur via linear aggregation of housing units change direction and tend to circumscribe an interior space. They generally have six (6) or more floors having floor height 3.20m. Two (2) of more dwellings exist on each floor (Ferrante et al. 2016).

Rey (2004) analyzed the KPIs for office building retrofit strategies under the categories of (i) environmental criteria (annual energy use for heating (MJ/m2 per year), annual electricity use (MJ/m2 per year), annual emissions (kgeq CO2/m2) and annual emissions (kgeq SO2/m2), (ii) sociocultural criteria (summer thermal comfort (daily overheating), acoustic comfort (noise level at workplace), visual comfort - natural lighting and visual comfort - artificial lighting), and (iii) economic criteria (renovation investment costs (per m2), annual on-going charges (per m2 per year)).

Hestnes and Kofoed (2002) stated that the retrofitting strategies they focused on concentrates on improving energy performance and indoor environment using passive solar techniques and energy conservation techniques. These are all gathered under three (3) levels of retrofit actions. First is the basic framework namely individual retrofit. In boundaries of individual retrofit, improved insulation, usage of shading devices, reduced air change rates and improved heating and cooling systems might be used. In the second step; a combination of building envelope improvements, passive cooling techniques, lighting improvements and HVAC improvements might be thought. In the third stage, different retrofit scenario packages are composed with the selection of different combinations of the abovementioned options (Hestnes and Kofoed 2002).

Di Giuda et al. (2016) found the cost percentage of various building retrofit actions for schools. Accordingly; control of lighting system composes 1.9%, heating control system upgrading composes 1.9%, solar thermal systems for DHW composes 2%, thermal generator replacement composes 3%, lighting system upgrading composes

6%, thermal insulation of roof composes 10%, thermal insulation of walls and roof composes 12%, external shading of south facade composes 19% and windows replacement composes 46% of overall building retrofit action (Di Giuda et al. 2016). In spite of such studies, the selection of building energy efficiency measures is greatly complicated. Besides, private and public perspectives have different point of views. While private sector aims financial benefits and minor indoor discomfort, public sector focuses on reducing energy consumption and polluting emissions in an exemplary vision (Ascione et al. 2018).

Various researchers identified also the building characteristics that should be known before starting any retrofit action. An exemplary set of such characteristics are presented in Table 4.2.

Table 4.2. Some Pre-Retrofit Building Characteristics

Building Characteristics	*Scope of The Study*	*Reference*
Usage of buildings (type), year of construction, number of floors, net area, gross area, heated floor space, total consumption and primary energy demand	Economically optimal energy savings retrofits	Kumbaroglu and Madlener (2012)
External wall insulation, roof insulation materials, windows type, solar collectors' type, and HVAC systems	Multi-objective optimization for building retrofit	Asadi et al. (2014)
Geometry/shape, function (purpose of usage of different building parts, occupancy and usage schedule, evaluation of the building location in terms of internal heat gain), system (size and type of HVAC system and thermal zoning as per function) and envelope (thermo-physical properties) of the building.	Optimization for energy retrofitting a developed hospital reference building	Ascione et al. (2016)
Context (environment of the building, medium and mean height of surrounding buildings, proximity of surrounding buildings, clearance between surrounding buildings, existence of green areas within close proximity), geometry (size of the building, volume of the building, surface area of the building, geometrical typology of the building), specific features that building has (wall surface characteristics, glazed surface characteristics, heating system characteristics, hot water heating system characteristics)	Energy classification of existing buildings	Ferrante et al. (2016)

Table 4.2 (Cont'd)

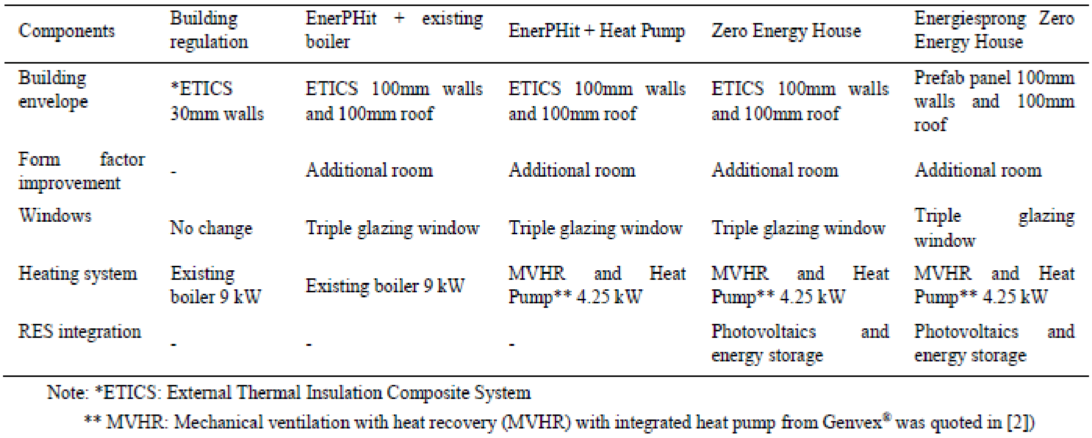
Building Characteristics	*Scope of The Study*	*Reference*
(i) Environmental criteria (annual energy use for heating (MJ/m2 per year), annual electricity use (MJ/m2 per year), annual emissions (kgeq CO2/m2) and annual emissions (kgeq SO2/m2), (ii) sociocultural criteria (summer thermal comfort (daily overheating), acoustic comfort (noise level at workplace), visual comfort - natural lighting and visual comfort - artificial lighting), and (iii) economic criteria (renovation investment costs (per m2), annual on-going charges (per m2 per year))	Office building retrofitting	Rey (2004)
Shape (rectangular etc.), height, volume, wall area, roof area, floor area, window area, living space area, number of windows and doors, U-value of exterior walls, U-value of roof and U-value of floor	Energy retrofit of old residential buildings in hot and arid climates	Al-Ragom (2003)
Built area, net usable area, heating days, heating degree days (HDD), heated area, heated volume, cooled area, energy consumption, annual gasoline consumption properties of the buildings	Application of energy and comfort retrofits to historic buildings	Torre (2013)
The number of actual occupancy, area for actual occupancy, actual area, school occupancy capacity, people density (people/m2), actual people density and utilization rate of these schools, Number of students, number of classrooms, number of laboratories, total heated volume, total walking surface and mechanical ventilation, condensing boilers, solar thermal (DHW), replacement of windows, wall insulation options	Retrofit of four (4) school buildings in the municipality of Melzo in Italy	Di Giuda et al. (2016)

Table 4.2 (Cont'd)

Building Characteristics	*Scope of The Study*	*Reference*
Location, geographic climate characteristics, degrees during the day, geographical coordinates, class size of building, period of construction, volume, Surface/Volume ratio, surface area, U-Value of walls, U-Value of roofs, U-Value of windows	Energy performance analysis and retrofit of a school building in Rome	Vallati et al. (2017)
Building's components subjected to probable retrofit action are building envelope, form factor improvement, windows, heating system and renewable energy system (RES) integration.	Energy retrofit of a block of houses in Nottingham	Cui et al. (2017)

Di Giuda et al. (2016) performed a case study analysis for retrofit of four (4) school buildings in the municipality of Melzo in Italy and some features encountered in this study could be accepted as a pathfinder. These schools were constructed between 1965 and 1971. Cui et al. (2017) determined different special retrofit actions for the building they evaluated and proposed related retrofit actions as shown in Table 4.3.

Table 4.3 Strategies to Achieve an EnerPHit District in Different Retrofit Scenarios (Cui et al. 2017)



Components	Building regulation	EnerPHit + existing boiler	EnerPHit + Heat Pump	Zero Energy House	Energiesprong Zero Energy House
Building envelope	*ETICS 30mm walls	ETICS 100mm walls and 100mm roof	ETICS 100mm walls and 100mm roof	ETICS 100mm walls and 100mm roof	Prefab panel 100mm walls and 100mm roof
Form factor improvement	-	Additional room	Additional room	Additional room	Additional room
Windows	No change	Triple glazing window	Triple glazing window	Triple glazing window	Triple glazing window
Heating system	Existing boiler 9 kW	Existing boiler 9 kW	MVHR and Heat Pump** 4.25 kW	MVHR and Heat Pump** 4.25 kW	MVHR and Heat Pump** 4.25 kW
RES integration	-	-	-	Photovoltaics and energy storage	Photovoltaics and energy storage

Note: *ETICS: External Thermal Insulation Composite System

** MVHR: Mechanical ventilation with heat recovery (MVHR) with integrated heat pump from Genvex® was quoted in [2])

Similarly, Torre (2013) proposed some retrofit actions linked these building features regarding energy efficiency, comfort and RES integration in accordance with their effects.Accordingly; internal/external insulation (passive solution) has been linked to energy efficiency, airtightness (passive solution) has been linked to energy efficiency, thermal distribution (active solution) has been linked to energy efficiency and comfort, efficiency of thermal or lighting equipment (active solution) has been linked to energy efficiency, solar PV system (active solution) has been linked to energy efficiency and RES integration, biomass boilers (active solution) has been linked to energy efficiency and RES integration, lighting system (control optimization) has been linked to energy efficiency and comfort, HVAC system (control optimization) has been linked to energy efficiency and comfort (Torre 2013).

Ferrante et al. (2016) developed a methodology that performs building retrofit action in six (6) parts. In the **first** step, climate data, building typology, construction period, geometrical characteristics, thermos-physical, and energy systems parameters affecting energy demand for heating and domestic hot water production have been analyzed. In the **second** step, they performed a study to detect beneficial features for existing buildings analyzing existing municipal maps and city databases. In the **third** step, they composed an architectural energy database making a data compiling from sources such as google maps for residential analyzed buildings, municipal maps, municipal energy register. In the **fourth** step, they analyzed heating and domestic hot water use amounts for residential buildings. In the **fifth** step, buildings are evaluated as per obtained data considering identified parameters. In the **sixth** step, they performed an assessment related to the energy classification of the buildings located in the district, even if they evaluate only one (1) building in their assessment.

4.3. Objectives/ Motivation and Scope of Building Retrofit

Torre (2013) detected significant problems in the building that was diagnosed for his own retrofit action. These problems are overheating during the months that average temperature is higher, insufficient heating distribution system, manual cooling system control method instead of an automatic one, corridor and halls lighting powerful than needed, insufficient lighting system in the classrooms and laboratories, insufficiency in usage of daylight, insufficient insulation and infiltration problems. These problems could be used as a guideline for further retrofits. Karkare et al. (2014) stated that building life through energy consumption might be reduced with the preparation of design strategies considering specific microclimate conditions. They found a 60% energy consumption reduction and a nine years (9-year) payback period using Sefaira-c energy consumption predictions

Jaggs and Palmer (2000) stated that the main target of the Energy Performance Indoor Environmental Quality Retrofit (EPIQR) method is to achieve improved IEQ, optimization of energy consumption, renewable solar energy and cost-effectiveness. Tokede et al. (2018) stated that life-cycle options provide opportunity to fulfill the future needs of buildings. Future needs may basically arise from economic benefits, technological benefits, social benefits and environmental benefits. They showed decreasing future maintenance costs as an example to economic benefit; harnessing infrastructure as example to technological benefits; response to legislative changes as an example to social benefits; minimizing embodied energy in the building as an example to environmental benefits. Ascione et al. (2018) stated that some energy efficiency measure options could be evaluated; once geometry, occupancy profiles, and climatic conditions are determined. As primary energy systems retrofit, low-emissive or selective glazing, the addition of thermal insulation, building envelope measures such as particular plasters and renewable energy resources such as efficient air-source heat pumps, PV generators could be considered. Similarly, Asadi et al. (2014) expressed that external wall insulation materials, roof insulation materials, windows type, solar collectors, and HVAC systems are five (5) decision variable alternatives for building retrofits and they play a role in retrofit alternative selection.

Di Giuda et al. (2016) proposed different progressive energy retrofit scenarios consisting of different combinations of condensing boilers, solar thermal (DHW), replacement of window and walls insulation. In the first combination, they advised only condensing boiler application; in the second combination, they advised application of condensing boilers and solar thermal (DHW); in the third combination, they advised only replacement of window; in the fourth combination, they advised condensing boilers and replacement of window; in the fifth combination, they advised replacement of window and walls insulation; in the sixth combination, they advised condensing boilers, replacements of window and walls insulation.

Jaggs and Palmer (2000) stated that EPIQR method performs building assessment in terms of four (4) different technical aspects as IEQ, energy use, costs, retrofit measures. They indicated that main components of **IEQ** aspect are humidity, noise, thermal comfort, air quality and ventilation, lighting, safety and security and apartment utilities; main components of **energy use** aspect are space heating domestic hot water, boiler replacement, space cooling, artificial lighting of shared spaces, insulation of heating distribution pipes, use of thermostatic radiator valves; main components of **costs** aspect are description of the refurbishment work, organization of the work classification, identification of costs; main components of **retrofit measures** aspect are area of foundation, area of exterior landscape, gross habitable area, commercial area, facade area, number of apartments, number of floors, number of staircases (Jaggs and Palmer 2000). Similarly, Ascione et al. (2016) examined a total of nine (9) energy retrofit measures (ERM) in the study they performed on the reduction of thermal energy demand (TED). These ERMs are heat recovery systems, solar shading systems, energy-efficient windows, variation of the roof's solar absorptance, variation of the roof's thermal emissivity, roof's thermal insulation of thickness t, variation of the external walls' solar absorptance, variation of the external walls' thermal emissivity, external walls' thermal insulation of thickness t.

4.4. Achievements and Challenges of Building Retrofit

Di Giuda et al. (2016) found an energy consumption saving varying between 10-91% depending on different scenarios in the retrofit project they applied to school buildings. On the other hand, Al-Ragom (2003) stated that significant savings at a national level could be obtained when cost of retrofit implementation is fully subsidized by the government in the analysis he performed on the retrofit analysis in Kuwait. He remarked that 3.25 million MWh yearly energy saving could be obtained as a result of retrofit of 42,403 old residential buildings in Kuwait corresponding $577 million saving in ten (10) years. Al-Ragom (2003) also underlined that the payback period of energy retrofits in the countries that energy prices are highly subsidized by the government could climb up to thirty (30) years and people might not be willing to apply to such retrofit in such conditions. He indicated the necessity of the existence of government incentives for these kinds of retrofit actions in countries having similar conditions such as initial retrofit cost subsidization and renovation loans.

Hestnes and Kofoed (2002) stated that the usage of energy-efficient and renewable energy-based technologies could provide energy savings in office buildings having high energy consumption. Characteristic features of building and selection of technology to be used should be in a rapport, and the selection of a combination of retrofit actions should be performed correctly so that the cost of retrofit action does not increase without getting additional performance increase (Hestnes and Kofoed 2002). It should be thought that cooling load does not only arise from an internal gain in the warm climate areas, but some additional benefits could also be obtained with the application of passive cooling technologies. Building envelope improvements and solar gain usage might reduce energy consumption in the areas that heating load is high. Energy-saving potential coming from lighting retrofit actions remains limited in all weather conditions; however, if building's lighting-related energy consumption is high, saving from lighting retrofits cold become tenable. Operational problems causing wastage of energy such as ventilation control and incorrect temperature exist in a vast amount of buildings. These problems might be overcome by using advanced control systems (Hestnes and Kofoed 2002).

Building retrofits offer some benefits; however, the challenge should not be overlooked. For instance, Monteiro et al. (2017) stated that European directives encourage EU members to apply retrofit actions to their existing buildings. However, this advice has been limped due to many issues, including financial, informational, behavioral, educational challenges. Ascione et al. (2016) noted that serious cost-optimal retrofit action determination studies related to optimization of building energy retrofit take excessive computational times that may be measured by days or weeks. Besides, they stated that current literature lacks methodologies presenting robust cost-optimal options in a reasonable computational time.

The trade-off between benefits and challenges can be seen in some studies. For instance, Ardente et al. (2011) applied various retrofit actions and measured energy and environmental benefits gained as a result of these actions applied to their public case study buildings in Brno, Gol, Plymouth, Provehallen, Stuttgart and Vilnius cities. In **Brno**, they applied PV panel, low-E windows, HVAC system retrofit applications to Brewery building. In **Gol**, they applied lighting, insulation, solar thermal plant, PV plant retrofits to Hol Church building. In **Plymouth**, they applied wind turbines retrofit to Plymouth College building. In **Copenhagen**, they applied PV/thermal plant, building insulation, low-E windows, HVAC system retrofit to Provehallen building. In **Stuttgart**, they applied solar thermal plants, PV, building insulation, windows, lighting, HVAC system retrofits to Nursery Home building. In **Vilnius**, they applied insulation and windows retrofits to Vilnius Gediminas Technical University (VGTU) main buildings. As a result of these retrofit actions, Ardente et al. (2011) obtained approximately 50% energy savings from heating. It should also be noted that retrofit action applied to building in Plymouth could not achieve this value since no heat-saving actions had been applied to that building. Additionally, energy savings in the Case study building in Vilnius had remained around 30%. Case study building in the Stuttgart had obtained the highest saving in terms of electricity consumption with a %90 saving value. On the contrary, wind turbines applied to Plymouth College had resulted in only a 2% contribution to yearly consumption and recorded as an unsuccessful application (Ardente et al. 2011).

4.5. Economic Dimensions of Retrofit Actions

Karkare et al. (2014) studied seven (7) different building retrofit options having different costs, savings and payback periods for their case study building located in India. In **option 1**, they applied doubled glazed windows retrofit only. They obtained 8% energy consumption saving, 11% cooling load decrease and 4.5 years payback period. In the **option 2**, they changed old air-conditioning (AC) units with a new efficient system having a high-performance coefficient. They obtained 26% cooling load reduction and 4.2 years payback period. In **option 3**, they applied a combination of options 1 and 2. They obtained a 35% decrease in cooling load and a 4.7 years payback period. In **option 4**, they applied retrofit for thermal resistance of walls, roofs and floors. They obtained a 19% cooling load reduction and 6.4 years payback period. In the **option 5**, they applied only solar PV panels on the building. They obtained an electricity production as much as 45% of total electricity consumption of the building and a 9.3 years payback period. In **option 6**, they applied a combination of options 3 and 5. They obtained 57% total energy consumption reduction and an approximately 8.9 years payback period. In **option 7**, a combination of all the retrofit actions given above is applied. They obtained 64% total energy consumption reduction and an approximately 9.3 years payback period. They summarized the results of the retrofit actions in the Figure 4.1 below (Karkare et al. 2014). Their study could be accepted as a notable indicator for benefits could be obtained as result of retrofit actions.

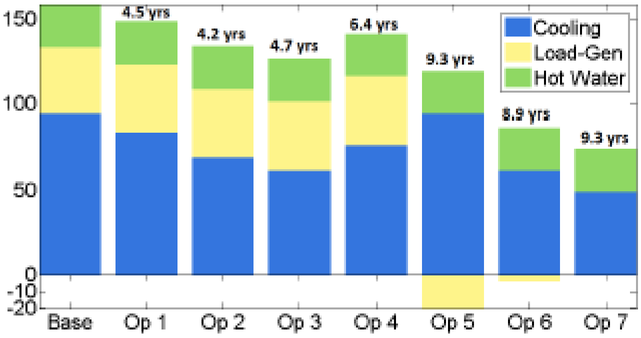


Figure 4.1 Gained Energy Consumption Reductions in Different Retrofit Scenarios (Karkare et al. 2014)

Kumbaroglu and Madlener (2012), studied on retrofit economical optimality in their case study and indicated that

- energy price changes could seriously affect the financial benefits of retrofit applications;

- German legislation, which allows rental price increase only 11% after retrofit application, does not provide necessary attraction for landlords to invest in building retrofit;
- assuming energy prices preserve its soft and flat trend as in nowadays, it would not be logical to spend time waiting for the application of building envelope retrofit;
- it might be logical to wait before building installation retrofits such as condensing boiler for fuel oil, condensing boiler for natural gas, pellet boiler and brine-water heat pump especially commonly used energy type is likely to change;
- highly volatile energy prices might reveal results waiting is more profitable.

In summary; retrofit action decision is required to be given upon assessment result of the current condition of the buildings. Building features such as shape (rectangular etc.), height, volume, wall area, roof area, floor area, window area, living space area, number of windows and doors, U-value of exterior walls, U-value of roof, U-value of floor, location, geographic climate characteristics, degrees during the day, geographical coordinates, class size of building, period of construction as well as latest retrofit action and used technologies/ systems (e.g. efficiency of HVAC system) could be assessed prior to retrofit actions. A smart building assessment methodology could also be used to assess current needs of the building components for retrofit actions. It would be unnecessary to demolish and reconstruct skeleton of a building unless its lifespan, which is approximately one-hundred (100) years for reinforced concrete buildings, expires. In this regard; building retrofit actions have a capability to present various benefits such as energy saving, GHG reduction, low payback periods, application of latest technologies to existing buildings etc. comparing the reasonable competitive cost instead of constructing a new building since lifespan of the building components vary significantly. However; a systematic building retrofit approach, which is based on a specific building assessment methodology, would contribute the benefits would be provided positively.

CHAPTER 5

SMART BUILDING AND SMART CITY RELATIONSHIP

There has been a growing interest in Smart Sustainable Cities (SSCs) in the last decade. Various organizations and initiatives developed standards and KPIs for the evaluation of SSCs. However, these approaches are limited to a city scale, and a smaller unit of analysis, which is a building, should also be considered to support these approaches (Parlak et al. 2018). While various smart building assessment tools had been proposed from various countries, there is no widely accepted standard/ formalization. Moreover, buildings might require additional criteria to be compatible with the environment while transitioning into SSCs since buildings are part of cities. Hence, there is a need to evaluate and tailor the smartness concept in city scale into a building scale. Since smart city concept is not prevalent and researched extensively in the literature, SSC concept is chosen as a pathfinder for this study. Following a top to bottom approach to identify SB requirements, the adaptation of the city-scale KPIs was evaluated regarding relevance (whether the KPIs were related in a building scale), and applicability (whether the data could be collected in a building scale) within the scope of this study, and has been published (Parlak et al. 2018).

Various organizations such as International Standards Organization (ISO) and initiatives such as United Nations Economic Commission for Europe (UNECE) and International Telecommunication Union (ITU) had developed standards and KPIs to formalize the scope and measurement of SSC (Parlak et al. 2018). In spite of the commonalities, each of these studies have a different scope and set of indicators based on their perspective, target audience, target location, and expectations. Since buildings were one of the elementary units of cities, buildings and cities should have been compatible with each other. Otherwise, it was not possible for SSCs to reach the desired performance. Therefore, there is a need to link these two related but separate concepts.

The boundaries of SSC concept have not been defined yet, and it would keep on evolving with new developments (Parlak et al. 2018). According to the definition of Höjer and Wangel (2015), SSC consisted of smartness, sustainability, smart and sustainable city, smart city, and sustainable city concepts within itself. City-scale sustainability consisted of citywide applications that met the requirements of that day without jeopardizing the needs of future generations to use those sources (Höjer and Wangel, 2015). In this context, smartness was defined as using advanced information and communication technologies. Moreover, SSC was an aggregate concept incorporating smart, sustainability and city concepts. UNECE-ITU defined SSC as an innovative city that improved quality of life, the efficiency of urban operation and services, and competitiveness, using information and communication technologies while ensuring that it met the needs of present and future generations with respect to economic, social, cultural and environmental aspects (UNECE, 2015).

There is no consensus on how to meet the requirements of SSCs, and a number of KPIs, standards, guidelines, and frameworks had been prepared to provide proper distribution of knowledge regarding SSCs (Parlak et al. 2018). Figure 5.1 presents that the most prominent SSC standardization efforts had started with UN-Habitat (2012) and until 2017 various institutions had made some assessment KPI systems (Parlak et al. 2018).

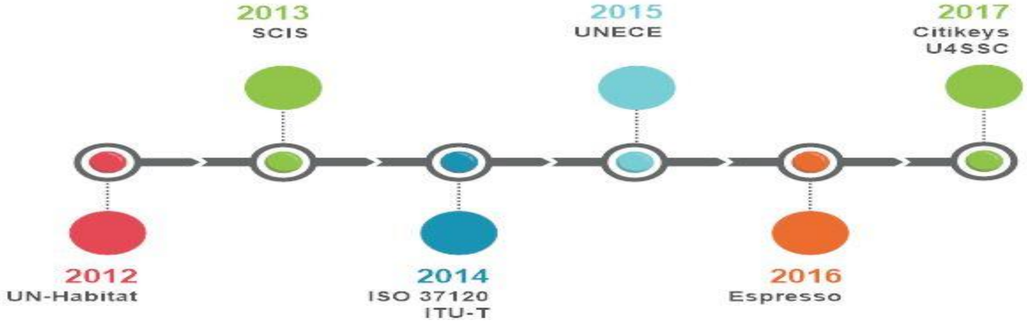


Figure 5.1 Most Prominent Standardization Efforts of SSC (Parlak et al. 2018)

The main criteria for SSC related KPIs had presented in these prominent studies were summarized in the Table 5.1 below. UNECE had proposed a set of SSC related KPIs with UNECE-ITU collaboration under four categories in 2015. UN-Habitat (2012), which was a global initiative, developed a tool to measure city sustainability had named as City Prosperity Index (CPI). CPI used six categories to evaluate SSC.

Table 5.1 Comparison of the Main Criteria of SSC KPIs (Parlak et al. 2018)

	UNECE	**UN-Habitat**	**U4SSC**	**ITU-T**	**City-keys**	**Espresso**	**SCIS**	**ISO**
Building as a part city						X		
Culture	X		X					
Economy	X		X				X	X
Education						X		X
Energy		X		X		X		X
Environment	X		X			X	X	
Equity and social inclusion		X		X				X
Finance								X
Fire & emergency response								X
Governance & legislation		X			X	X		X
Health						X		X
ICT related performance							X	X
Infrastructure		X		X		X		
People					X			
Physical infrastructure								
Planet					X			
Productivity		X		X				
Propagation					X			
Prosperity					X			

Table 5.1 (cont'd)

	UNECE	**UN-Habitat**	**U4SSC**	**ITU-T**	**City-keys**	**Espresso**	**SCIS**	**ISO**
Quality of life		X		X				
Recreation								X
Security						X		X
Society	X		X					
Solid waste								X
Technical performance							X	
Transportation						X	X	X
Urban planning								X
Wastewater								X
Water &								X

United Nations United for Smart and Sustainable Cities (U4SSC) Initiative (2017) has been established with contributions from many stakeholders, including the cities of Dubai, Singapore, Valencia, and Buenos Aires amongst others. With the goal of achieving Smart Sustainable Development, U4SSC (2017) had developed a KPI list under four categories. ITU (2014), which was the United Nations specialized agency in the field of telecommunications, ICTs, had established a Focus Group on SSCs in 2014. This focus group had developed a KPI list for SSC and suggested an evaluation under five categories. (Marijuán et al. 2017) had developed Smart Cities Information System (SCIS) with SSC assessment KPIs grouped under five categories. It should have been noted that SCIS also focused on applicability of these KPIs to building level. ISO (2014) had developed a set of standardized indicators that provides a uniform approach to SSC assessment in 2014, suggesting an evaluation in terms of sixteen categories (Watermeyer and Pham 2011) (ISO 37120:2014). The categories that were common to all efforts are economy, energy management, environment, governance and legislation.

The smart building concept was born in the USA in 1980s (Wong et al. 2005). There is no agreement on the difference between ‘smart’ and ‘intelligent’ terms, as these words were mostly used interchangeably. AIIB stated that smart buildings were the buildings that achieve long term value with satisfying occupant requirements such as green, comfort, safety, and technological image, varying according to building type (Chow and Leung 2005). According to Buckman et al. (2014), a smart building should have provided energy efficiency, longevity, comfort and satisfaction with its adaptability coming from its information-processing capability. Although the expectations from smart buildings and their general features such as green, comfortable, safe, and technological capability were common, there was a wide variety in these definitions (Parlak et al. 2018).

Only SCIS had studied the applicability of SSC evaluation criteria to smart buildings within the sources listed in Table 5.1 above. SCIS considered fifteen (15) KPIs under the categories of economy, environment, technical, ICT, and mobility. However, the other SSC assessment methodologies had a number of criteria that could also be applied to smart buildings such as domestic material consumption, renewable resource usage, emission reduction, and the number of e-charging stations. However, those SSC KPIs had not been considered in this perspective. Therefore, a top to bottom approach from SSC to SB should be identified.

A number of researchers had studied smart building evaluation. Kaya & Kahraman (2014) suggested a total of twenty-six (26) KPIs for the evaluation of smart buildings in terms of engineering, environmental, economic, socio-cultural, technological aspects. Alwaer & Clements-Croome (2010) suggested the evaluation of smart buildings in terms of environmental, socio-cultural, economic, and technological aspects, with a total of fifty-seven (57) KPIs. So & Wong (2002) suggested an evaluation of smart buildings based on IBI of AIIB. IBI evaluation was based on environmental friendliness, space utilization and flexibility, human comfort, working efficiency, culture, the image of high technology, safety and security, construction process and structure, life cycle costing and energy conservation; with a total of three-hundred-eighteen (318) KPIs in the evaluation system. Although smart building related KPIs existed, transition to SSC might require additional adjustments to buildings. For this reason, city scale standards and KPIs should be investigated in this regard to identify which SSC assessment KPIs could be implemented to building scale.

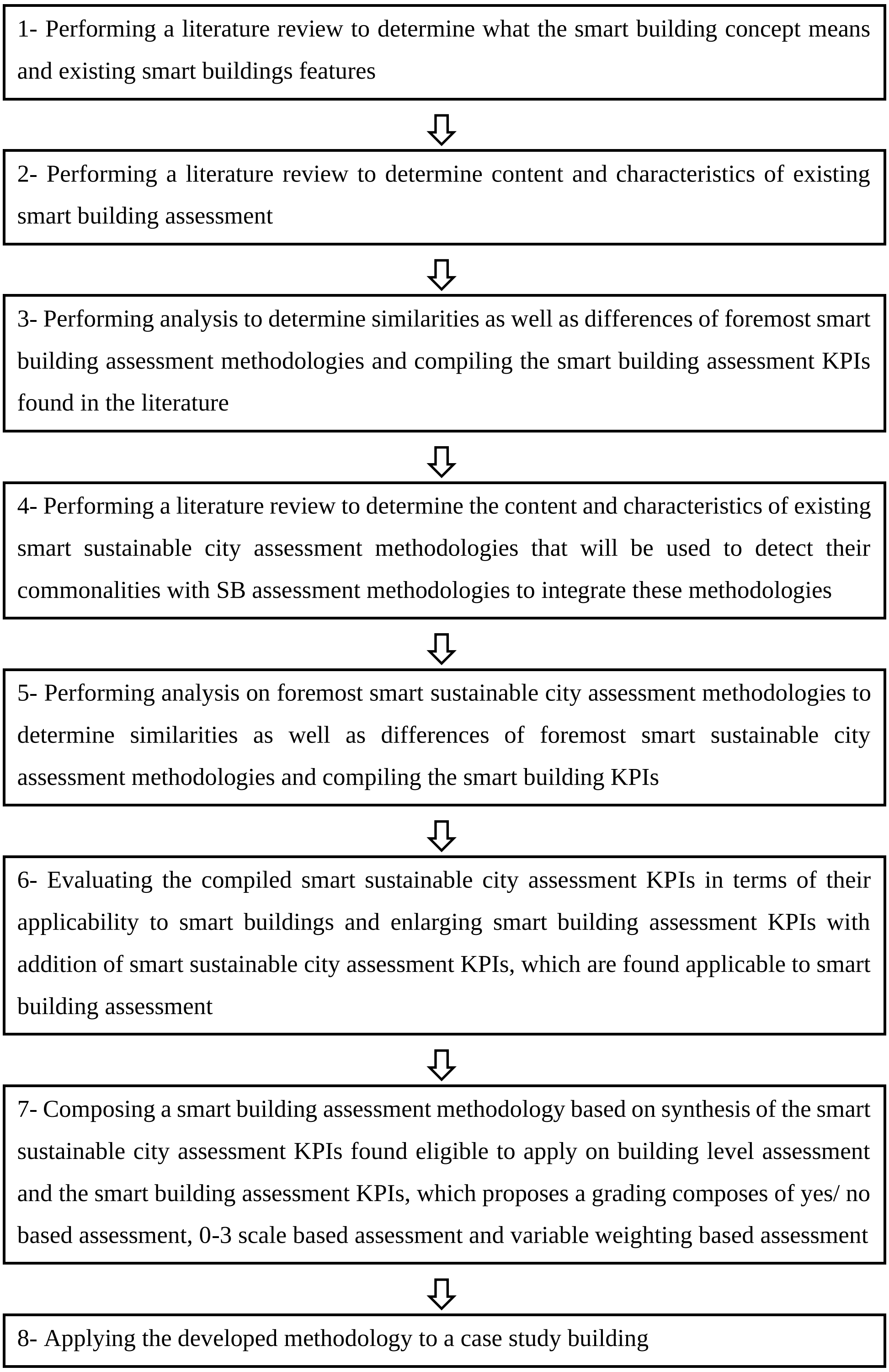
CHAPTER 6

METHODOLOGY

A multi-step methodology has been applied in the development of this study towards establishing integration of smart sustainable city level features and smart building KPIs to obtain a developed smart building assessment methodology, which is suitable to meet today's needs as well as expectations from smart buildings.

The methodology followed in this study is presented in Figure 6.1 below. Firstly, a literature review has been performed to determine the meaning of the smart building concept and the features that existing buildings have. Secondly, a literature review has been performed to examine existing smart building assessment methodologies. Their similarities, differences, limitations, objectives and KPIs were analyzed. Outputs of this review are shown in the "Smart Building Assessment" Chapter and in **Error! Reference source not found.**. A number of building assessment methodologies (such as LEED, BREEAM, HK-BEAM and NABERS) have been left out of scope due to being greenness oriented, not having clear assessment KPIs. Instead, prominent studies of Kaya and Kahraman (2014), Azari et al. (2016), Chen et al. (2006), Wong and Li (2008), and Wong et al. (2008) are selected for development of the smart building assessment methodology, which aims decision-making assessment and performance assessment. Thirdly, based on the analysis performed to determine similarities and differences of existing smart building assessment methodologies, KPIs of prominent methodologies are compiled.

Fourthly, a literature review has been performed to determine the content and characteristics of existing smart sustainable city assessment methodologies so that their commonalities with smart building assessment methodologies can be detected. Fifthly, the systematically given smart sustainable city assessment KPIs that belong to the foremost assessment methodologies found in the literature has been compiled. A top to bottom approach was followed to provide a connection from SSCs to smart buildings. In this context, KPIs for SSCs of various institutions (e.g., ISO, ITU, UNECE) had been examined and synthesized. Sixthly, smart sustainable city assessment KPIs have been evaluated in terms of their applicability to smart buildings and related KPI. Their applicability to buildings was evaluated according to their (i) relevance: whether the identified KPI was related to Smart Building and (ii) applicability: whether the scale of that KPI was convenient to support data collection from smart buildings (Parlak et al. 2018). Outputs of this analysis is presented in **Error! Reference source not found.**. Then, city-scale KPIs are compiled together with smart building assessment KPIs.



1- Performing a literature review to determine what the smart building concept means and existing smart buildings features

2- Performing a literature review to determine content and characteristics of existing smart building assessment

3- Performing analysis to determine similarities as well as differences of foremost smart building assessment methodologies and compiling the smart building assessment KPIs found in the literature

4- Performing a literature review to determine the content and characteristics of existing smart sustainable city assessment methodologies that will be used to detect their commonalities with SB assessment methodologies to integrate these methodologies

5- Performing analysis on foremost smart sustainable city assessment methodologies to determine similarities as well as differences of foremost smart sustainable city assessment methodologies and compiling the smart building KPIs

6- Evaluating the compiled smart sustainable city assessment KPIs in terms of their applicability to smart buildings and enlarging smart building assessment KPIs with addition of smart sustainable city assessment KPIs, which are found applicable to smart building assessment

7- Composing a smart building assessment methodology based on synthesis of the smart sustainable city assessment KPIs found eligible to apply on building level assessment and the smart building assessment KPIs, which proposes a grading composes of yes/ no based assessment, 0-3 scale based assessment and variable weighting based assessment

8- Applying the developed methodology to a case study building

Figure 6.1 Methodology

Seventhly, a three-step evaluation system has been developed to assess smartness of buildings. A classification for smart building assessment methodologies as first-generation (nominal, pass-fail type certification), second-generation (simple additive) and third-generation (weighted additive) have been applied for the development of new integrated smart building assessment methodology. In the development of this methodology, it is kept in mind that the real world is gray and linear addition with basic yes/ no questions is oversimplification. To overcome this issue, a 0-3-scale criteria grading and assignment of category-based variable weightings have been adapted to the assessment methodology. So, a three (3) step smart building assessment methodology development approach has been followed as yes/ no based assessment in the first step, 0-3 scale based assessment in the second step and assigning variable weightings to the KPI categories in the third step. In the evaluation stage, two types of KPIs were excluded: (i) KPIs that are not applicable to a building, and (ii) KPIs that need unreachable data. With their exclusion from final grading, the results are adjusted for providing total grade of one hundred (100). For instance; if two hundred (200) KPIs remain applicable for the assessment after KPI selection, at the end of yes/no grading there will be two hundred (200) total grade and it will be divided by two (2) to adjust it for a hundred (100) total grade. In the same condition, if there is a total of six hundred (600) points at the end of 0-3-scale, then it is divided by six (6) to adjust it for a hundred (100) total grade. It should also be noted that in 0-3 scale grading, grades are given with one (1) point increments (i.e., 0, 1, 2, 3 grades are available). The second step has proposed an opportunity to perform a fairer assessment due to its wider range grading. Also, a variable weighting based assessment has been included into the assessment as the last step to include personalization and priority determination possibility to the assessment. Also**, a minimum 30% grade criterion in yes/ no based assessment for the technological KPIs** has been set as a prerequisite to prevent non-smart buildings from being assessed using the newly developed smart building assessment methodology. Value of 30% has been selected as per the engineering judgement. If a building cannot gather this grade accordingly, that building cannot be assessed using the new developed methodology and its overall grade will be accepted as zero (0).

Additionally, specialization of the developed SB assessment methodology as per building type (dwelling, educational building, hospital... etc.) has been provided by flexible “not applicable” criteria election. KPIs that are not related to the assessed building type are excluded in this way.

Eighthly and lastly, the developed methodology has been applied to a Research Park building in the METU Campus as a case study. In this way, different scoring approaches to the methodology could be demonstrated in the assessment of the case study building.

Apart from other methodologies existing in the literature; this methodology provides combination of existing prominent SB KPIs as well as combination of prominent SSC KPIs suitable to SBs and this methodology provides a three-step assessment methodology enabling customization as per building type and geographic differences and other factors with the variable weighting assessment flexibility it presents.

CHAPTER 7

CASE STUDY

The smartness of the Research Park Building in METU Campus, whose construction is about to be completed as of beginning of 2020, has been assessed with the new developed smart building assessment methodology as case study under the scope of the METU research grant (BAP-08-11-2017-039). The exterior and interior views of the building are presented in Figures 7.1 to 7.4.

Figure 7.1 METU Research Park

Figure 7.2 METU Research Park Top View (Google 2020)

Figure 7.3 METU Research Park Interior - I

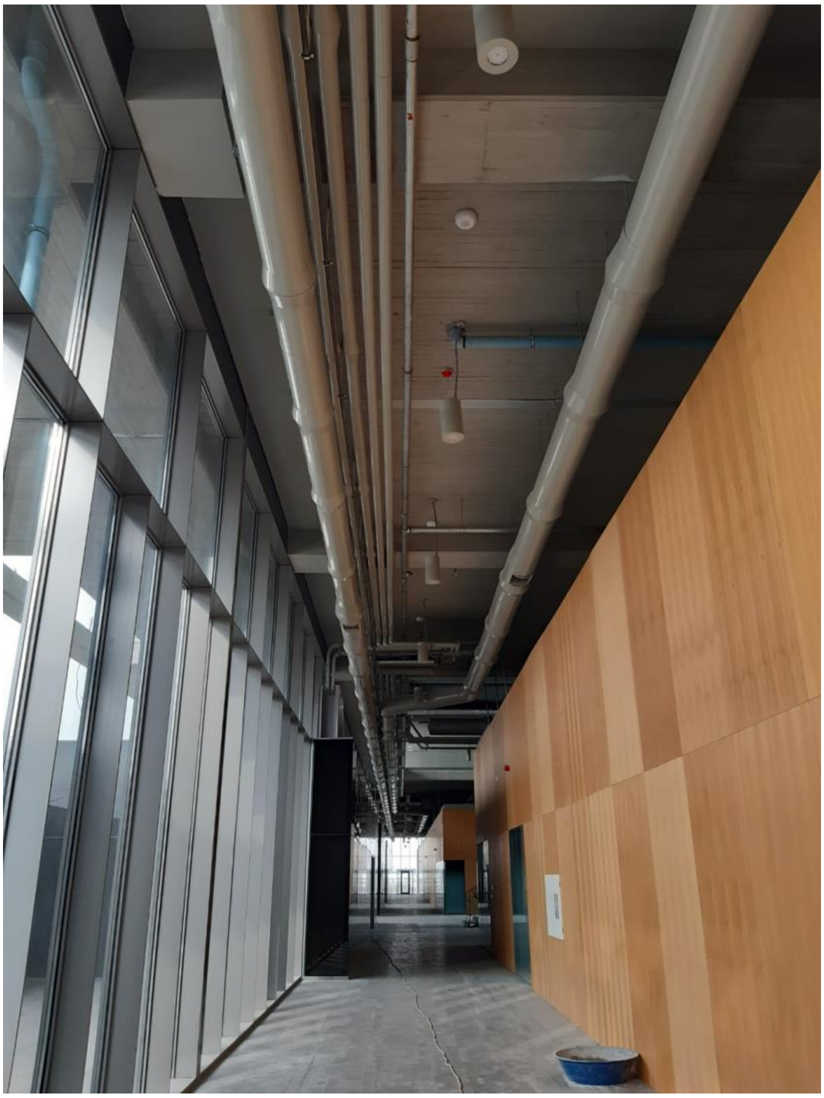


Figure 7.4 METU Research Park Interior - II

Detailed information regarding the METU Research Park has been obtained by buildings technical documentation.

Sitting area of the building : 10,800 m^2
Area of usage : 28,150 m^2
Geometry/ Shape : Rectangular prism
Floors : Basement + Ground + Three (3) Floors + Roof
    Basement floor : 10,800 m^2
    Ground floor : 5,691 m^2
    1st floor : 3,968 m^2
    2nd floor : 3,786 m^2
    3rd floor : 3,665 m^2
    Roof floor : 233 m^2
Car park capacity
    Indoor parking : 108 cars (3 reserved for disabled)
    Parking lot : 7 cars (3 reserved for disabled)

Laboratory, office and meeting room distribution in building floors are as in the Table 7.1.

Table 7.1 Laboratory, Office and Meeting Room Distribution in Building Floors

	Laboratories	**Offices**	**Meeting Rooms**
Basement	14	4	----
Ground	12	19	5
1st Floor	22	24	4
2nd Floor	14	16	4
3rd Floor	12	14	----
TOTAL	**74**	**77**	**13**

As energy conservation measurements, foundation and shear wall insulation, gas concrete walls, gypsum board wall with XPS/ Rockwool insulation inside, double-glazing partition wall, heat-insulating aluminum joinery, double-glazing building envelope, double-glazing roof skylight and insulated metal doors have been applied to the Research Park building.

It has been detected that the building has residual current circuit breaker, lighting intermittent relay, energy analyzer providing remote monitoring, three-phase electronic active-reactive electricity meter, motion sensitive sensor-fitted lighting controller, energy efficient lighting luminaries, battery powered emergency direction lighting fixture, occupant presence sensor, snow-ice melter mechanism on the roof (heaters, cables, thermostat, ice detection sensor, temperature sensor, control panel), data rack cabinets, UTP cat 6 data plugs, UTP cat 6 data telephone connection, UTP cat 6 data CCTV connection, UTP cat 6 wireless access point data connection, conventional smoke detector, conventional gas alarm station, CO detector, analog addressed fire alarm station, analog addressed fire enouncing system, analog addressed optic smoke detector, analog addressed temperature detector, analog addressed area control module, fire proof infrared gas detector, automatic gas and electric cutter in earthquake situation, door control unit, card reader, electronic door lock, magnetic contact and door hydraulic, reactive power control relay, heating system control panel, card entry control system, natural gas and LPG fueled condensing boiler, plate heat exchanger, fan-coil devices, heat recovery devices, roof radial aspirator, steam humidifier, ventilation ducts, fire damper with servomotor, hepa filter, air conditioning plants, HVAC BMS, fan-coil programmable room thermostat with screen compatible with telecontrol, HVAC CO sensor, fire hydrant, automatic fire sprinklers and fire water pumps.

Smartness assessment of the case study building is discussed in the following Findings chapter.

CHAPTER 8

FINDINGS

The findings of this study are presented in this Chapter according to the following sections: (1) Building-Scale Smart Building KPIs, (2) City-Scale Smart Building KPIs, (3) Comparison of Building-Scale and City-Scale SB KPIs, (4) Integrated Smart Building Assessment Methodology, and (5) Case Study.

8.1. Building-Scale Smart Building KPIs

As result of the examination of building assessment KPIs of existing building assessment methodologies; five (5) prominent building assessment methodologies providing comprehensive and pioneering KPIs that could be used for further smart building assessment development studies have been selected. In this process, plenty of building assessment criteria methodologies (such as LEED, BREEAM, HK-BEAM and NABERS) found in the literature has been left out of scope due to being greenness oriented and not having clear assessment KPIs. In this context; studies of Kaya and Kahraman (2014), Azari et al. (2016), Chen et al. (2006), Wong and Li (2008), and Wong et al. (2008) are selected for the development of the integrated smart building assessment methodology.

Relying on the existing methodologies, KPIs are categorized into five (5) groups of economical, social, environmental, technological and physical KPIs. In Kaya and

Kahraman’s (2014) study, a total of twenty-nine (29) KPIs are grouped such that there are four (4) KPIs under the economical heading, five (5) KPIs under the social heading, four (5) KPIs under the environmental heading, fifteen (15) KPIs under the technological heading. In Azari et al.’s (2016) study; a total of sixty-six (66) KPIs are grouped such that there are ten (10) KPIs under economical heading, eleven (11) KPIs under social heading, one (1) KPI under environmental heading, thirty-seven (37) KPIs under technological heading and seven (7) KPIs under physical heading.

In Chen et al.'s (2006) study; a total of forty-five (45) KPIs are grouped such that there are six (6) KPIs under the social heading, nine (9) KPIs under environmental heading, twenty-three (23) KPIs under technological heading and seven (7) KPIs under the physical heading. In Wong and Li's (2008) study, a total of seventy-three (73) KPIs are grouped such that there are five (5) KPIs under the economical heading, nineteen (19) KPIs under the social heading, six (6) KPIs under the environmental heading, forty-one (41) KPIs under technological heading and two (2) KPIs under the physical heading. In Wong et al.'s (2008) study, all ninety (90) KPIs are found only under technological heading showing technology orientedness of this study.

When the overlapping KPIs are deducted; a total of two-hundred-and-fifty-four (254) KPIs are acquired as shown in Figure 8.1. Nearly 70% of these KPIs stand under the technological heading. This shows the weight of technology usage in smart buildings.

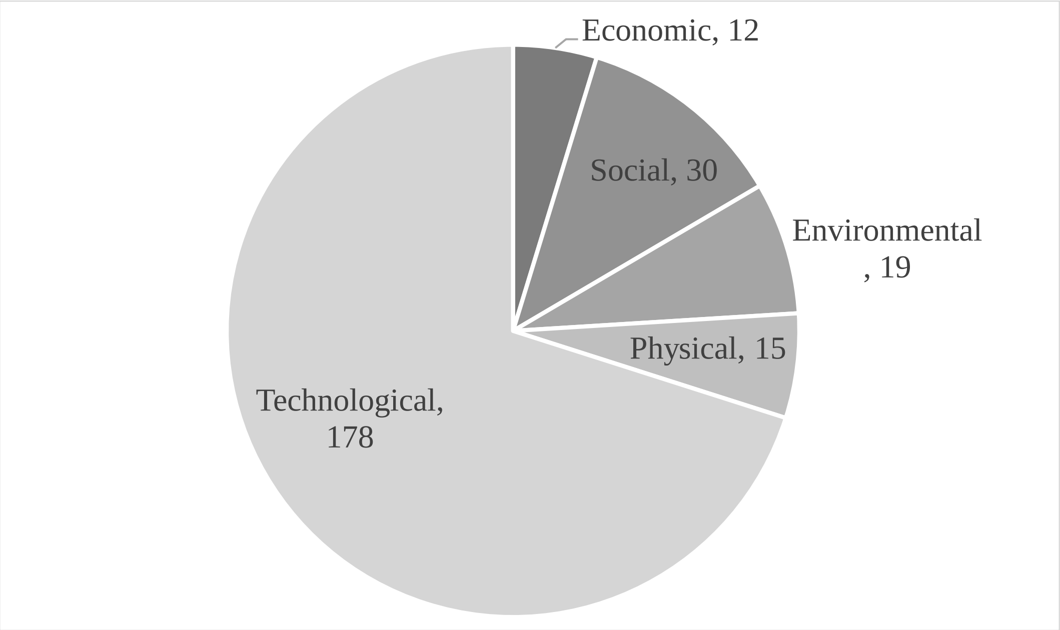


Figure 8.1. Synthesized SB KPIs with a Building-Scale Focus

8.2. City-Scale Smart Building KPIs

The most prominent standards and KPIs for SSC were identified as presented in Table 5.1. These KPIs were compared against each other and the compiled list was classified building up on the classification of the only SSC standard had been developed by ISO. The examination of existing KPIs had revealed a total of 503 KPIs (Parlak et al. 2018). Among those UNECE (2015), UN-Habitat (2012), U4SSC (2017), ITU (2014), Bosch et al. (2017) (Citykeys), (ESPRESSO 2016), Marijuán et al. (2017) (SCIS) and ISO (2014) included 73, 23, 95, 37, 74, 61, 40, 100 KPIs respectively. Even though the sum of the mentioned KPIs was equal to 503, the total number of unique KPIs was equal to 316 as sown in Table 8.1. The identical KPIs stated by different authorities were counted as one. It should also be noted that the KPIs with the same wording, and the KPIs with the same meaning but different wording were identified and regarded as identical KPIs. Additionally, when a relevant category was not available under ISO, a new category was created.

Due to the intense content of the compiled KPIs table, only a summary table, including the general categories and number of KPIs were presented in the first and second columns of Table 8.1. Classification methodology of ISO had been used to classify KPIs into the categories of economy, education, energy, environment, finance, fire and emergency response, governance, health, recreation, safety, shelter, solid waste, telecommunication and innovation, transportation, urban planning, wastewater, water and sanitation categories. Besides, the categories of society and culture, productivity, comfort, and attitude of people had been added to categories of ISO due to the additional KPIs that did not conform to the ISO classification.

Table 8.1. Number of KPIs for SSCs and Smart Buildings (Parlak et al. 2018)

Category	# of KPIs	# of KPIs relevant to building	# of KPIs to be adjusted
Economy	45	9	-
Education	17	2	-
Energy	29	17	2
Environment	23	13	2
Finance	5	1	-
Fire and Emergency Response	9	5	3
Governance	18	4	2
Health	16	6	-
Recreation	2	-	-
Safety	18	8	3
Shelter	10	5	-
Solid Waste	10	1	1
Telecommunication & Innovation	24	13	3
Transportation	28	4	-
Urban Planning	11	-	-
Wastewater	11	4	1
Water and Sanitation	19	9	2
Society and Culture	11	3	2
Productivity	2	-	-
Comfort	4	4	-
Attitude of People	4	3	-
TOTAL	316	111	21

Economy (45), energy (29), transportation (28), and environment (23) were the categories that contain the majority of the KPIs with a share of 40%. In consequence of detailed comparison and examination of SSC assessment KPIs, it was found that "*total percentage of total energy derived from renewable sources"* KPI was the mostly considered KPI. This KPI is included by five of the eight authorities. "*Greenhouse gas emissions"* and *"noise pollution"* were the second mostly considered KPIs. These KPIs were presented by four of the eight authorities*. "CO_2 emissions", "total electrical energy use per capita", "PM2.5 concentration"* and "*NO_2 concentration"* were the third mostly considered KPIs. These KPIs were listed by three of the eight authorities. Next step of the study was to check the relevance and applicability of the identified 316 KPIs to buildings. In a similar manner, as mentioned above, SCIS had identified the following 15 KPIs as applicable for both SSC and smart building scale: *grants, total annual costs, payback period, return on investment, total investments, primary energy demand and consumption, reduction of energy cost, energy demand and consumption, energy savings, degree of energetic self-supply by renewable energy sources, peak energy load reduction, CO_2 emission reduction, greenhouse gas emissions, consumers engagement, kilometers per passenger* and *private vehicle*. So, the other SSC KPIs should also had been investigated for their applicability to buildings.

8.3. Comparison of Building-scale and City-scale SB KPIs

The smart building KPIs that were acquired from city-scale studies were evaluated to determine their relevance and applicability to buildings according to the criteria of relevance and applicability. Figure 8.2 below presents that out of 316 city-scale KPIs, 111 KPIs are identified as applicable to buildings and 21 KPIs are identified as KPIs that need adjustment.

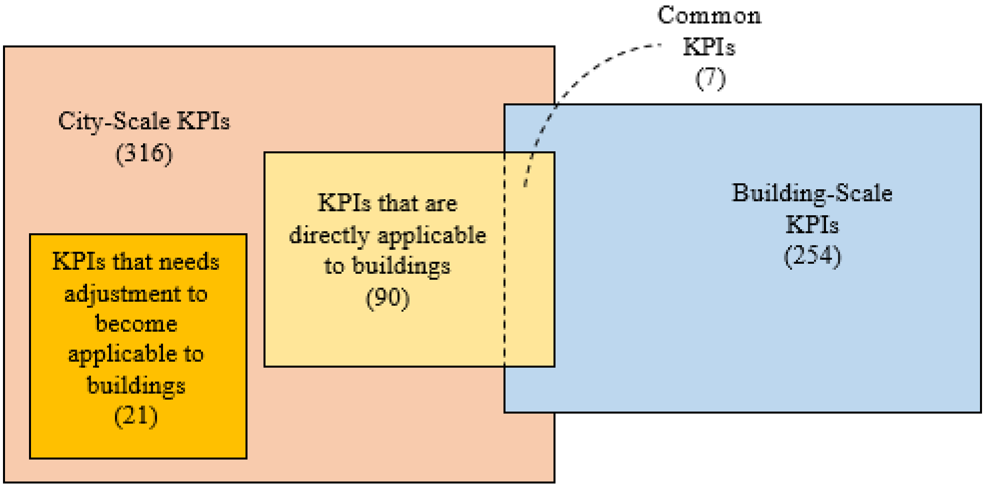


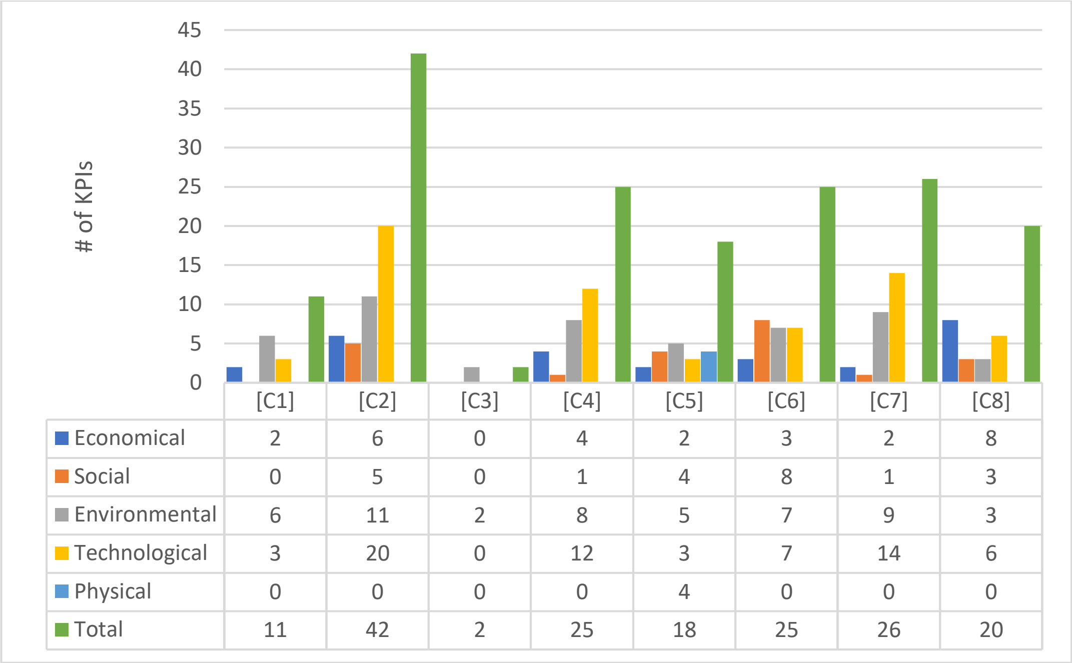
Figure 8.2. SB KPIs Acquired from City-Scale Methodologies

The categorical distribution of one-hundred-eleven (111) KPIs, which are found applicable to buildings by Parlak et al. (2018) are shown in the third column of Table 8.1 above. These KPIs are further examined in this study and these KPIs have been added to Table A.1, once smart building assessment KPIs arisen from the abovementioned five (5) smart building assessment methodologies are examined.

If a KPI was relevant and available for smart buildings, it was categorized as relevant. For instance, *smart electricity meters* under the category of energy could be directly applied to buildings. Hence, it was classified under “KPIs Relevant to Buildings”. Similarly, *total residential electrical energy use per capita (kWh/yr)* was directly relevant to smart buildings. On the other hand, if a rescaling or modification was required, that KPI was categorized as “KPIs Applicable with Adjustments”. 21 out of 111 KPIs might have needed a modification. For instance, *peak load reduction* was also applicable to smart buildings. As an adjustment, *peak load reduction* could have been applied to buildings with Building Energy and Management System (BEMS) optimization to control the instantaneous energy consumption of building devices.

Additionally, while the *number of firefighters* was a KPI for SSC assessment; it could also have been used for smart buildings with an adjustment: instead of the number of firefighters, the existence of a building-specific firefighting system could have been applied. Other adjustable KPIs were determined as *power quality and quality of supply, energy consumption of public buildings per year (kWh/m2), ozone concentration, noise monitoring, number of firefighters per 100000 population, response time for emergency response services from initial call, response time for fire department from initial call, public participation, availability of government data, city video surveillance penetration, level of data protection by the city, child online protection, % of the city's hazardous waste that is recycled, integrated management in public buildings, % of public space area with wi-fi coverage, integrated building management systems in public buildings, drainage system management, quality of water resources, % of the water distribution system monitored by ICT, smart libraries, culture infrastructure* (Parlak et al. 2018).

The sources of these KPIs, which are denoted as C1 through C8, are shown in Figure 8.3 below. In the figure, [C1] is ISO 37120 (2014), [C2] is UNECE (2015), [C3] is UN-Habitat (2012), [C4] is U4SSC (2017), [C5] is ITU (2014), [C6] is Bosch et al. (2017) (Citykeys), [C7] is ESPRESSO (2016), and [C8] is Marijuán et al. (2017) (SCIS). So, [C2]: UNECE (2015)’s methodology is the one that provides biggest contribution to formation of KPIs coming from city-scale methodologies. It provides forty-two (42) KPIs and nearly half of its KPIs belong to technological KPIs. [C3]: UN-Habitat (2012)’s methodology is the one that provides smallest contribution. It provides only two (2) KPIs, which all belong to environmental KPIs.



	[C1]	[C2]	[C3]	[C4]	[C5]	[C6]	[C7]	[C8]
🟦 Economical	2	6	0	4	2	3	2	8
🟧 Social	0	5	0	1	4	8	1	3
⬜ Environmental	6	11	2	8	5	7	9	3
🟨 Technological	3	20	0	12	3	7	14	6
🟦 Physical	0	0	0	0	4	0	0	0
🟩 Total	11	42	2	25	18	25	26	20

Figure 8.3. Categorical Distribution of SB KPIs from City-Scale Methodologies

When overlapping KPIs are deducted; it has been found that twenty-one (21) KPIs under economical heading, eighteen (18) KPIs under social heading, twenty (20) KPIs under environmental heading, forty-eight (48) KPIs under technological heading and four (4) KPIs under physical heading in combination of the abovementioned studies. Accordingly, one-hundred-eleven (111) total KPIs have been found in combination of these studies (Figure 8.4 below). It could be easily seen that nearly 43% of these KPIs stand under technological heading. Weight of technology usage has multiplied more than twice the closest value also in here in terms number of KPIs they have.

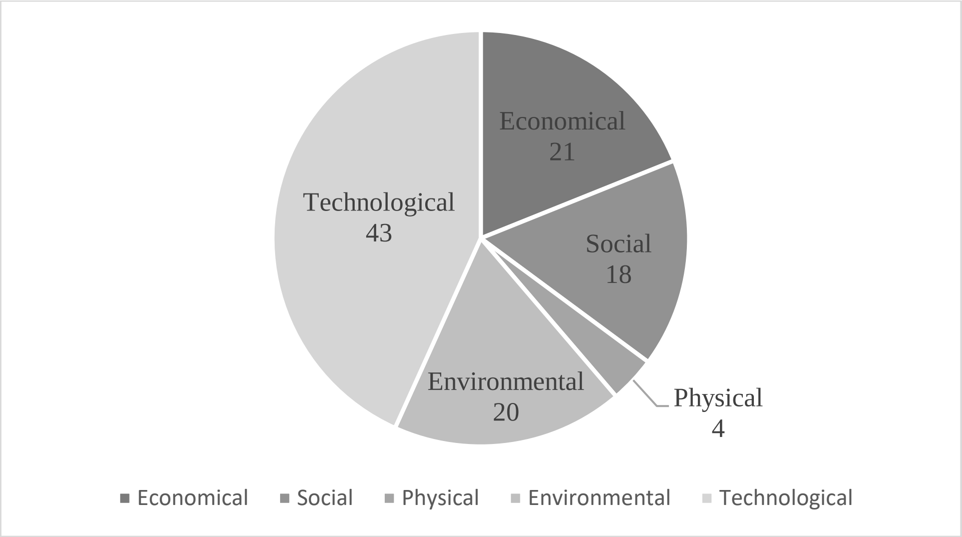


Figure 8.4 Number of SB KPIs from City-Scale Methodologies

8.4. Integrated Smart Building Assessment Methodology

For an enhanced smart building assessment and a better building-city collaboration, it is detected that it would be beneficial to provide integration of KPIs that have been acquired from SSC assessment methodologies and KPIs that have been acquired from SB assessment methodologies. KPIs of the integrated SB assessment methodology, which aims decision-making assessment and performance assessment, has been formed with the integration of such KPIs. A total number of three-hundred-fifty-eight (358) KPIs have been obtained as an output of the study as shown in Figure 8.5 below.

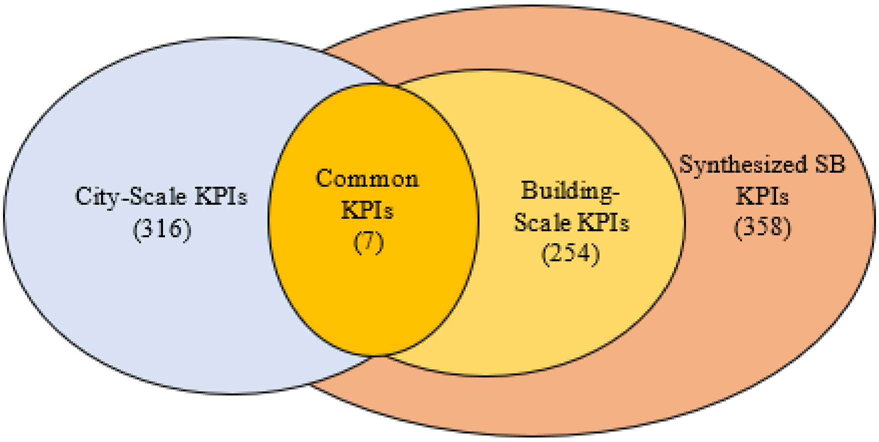


Figure 8.5. Integrated SB KPIs

It is found that systems intensively mentioned in the literature such as HVAC, lighting, electric power management, and access control must certainly be included in the newly developed SB assessment methodology.

Energy saving & conservation, health and sanitation, noise pollution, water drainage system, reliability (i.e. frequency of breakdown), electrical power quality, and *construction material characteristics* are the common seven (7) KPIs found both in SB KPIs and SSC KPIs.

A number of KPIs might have not been applicable to all building types. For instance, *ozone concentration* could have been applied to industrial buildings such as factories and plants. Moreover, *primary education student/teacher ratio* categorized under education could only have been applied to educational buildings such as schools. Overall, all of the KPIs under the categories of comfort and attitude of people could be used for smart buildings. However, none of the KPIs related to recreation, solid waste, society and culture and productivity could be used for buildings. In addition, as mentioned before, the majority of the city KPIs had been under the categories of economy, transportation, energy and environment. Examining those four categories, more than half of the KPIs within energy and environment were appropriate for buildings. On the other hand, within the economy, and transportation categories, only approximately 15% of them could have been implemented for building.

The conceptual representation of the integrated SB assessment methodology is presented in Figure 8.6 below.

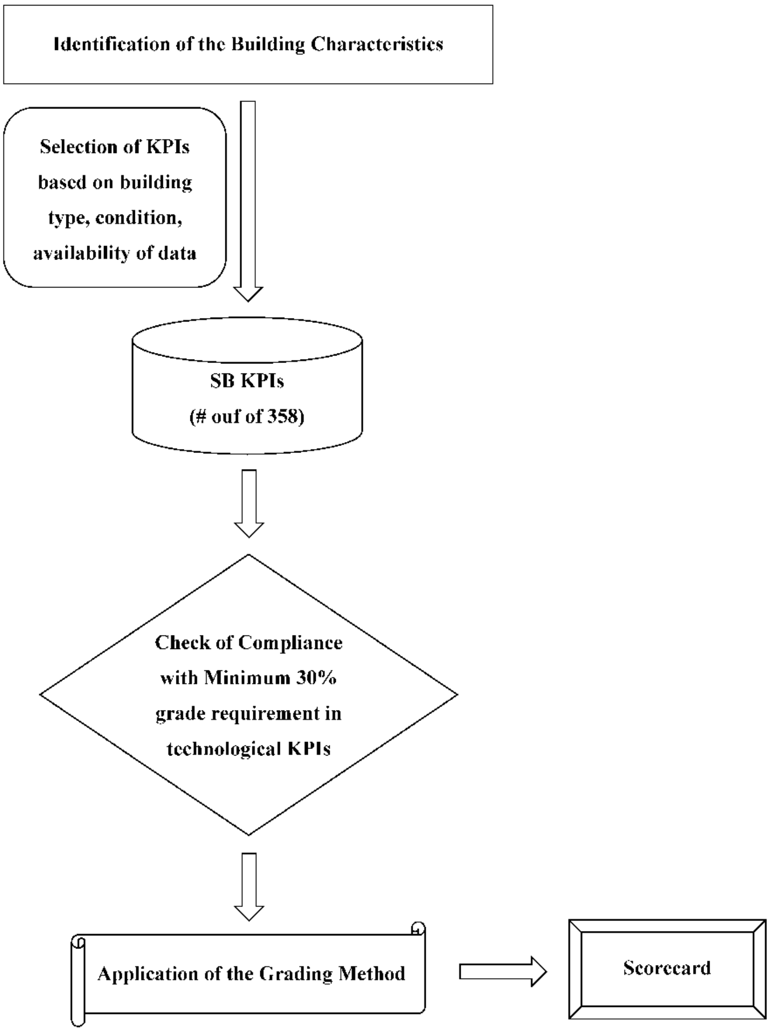


Figure 8.6. Conceptual Framework for the Integrated SB Assessment Methodology

In the first step, building characteristics are determined. In this step; building's physical characteristics such as total area of usage, sitting area of building, geometry/ shape of building, number of floors that building has and floor areas, car park capacity of building; building's existing energy conservation measures such as existence of foundation and shear wall insulation, wall material type, wall insulation material type, existence of heat insulation features in joineries and building envelope; building's technological features such as energy monitoring capability, existence of BMS, existence of presence sensors, data infrastructure, existence of entrance control system, existence of HVAC control panel are examined.

In the second step, selection of KPI selection based on building type, condition and availability of data is performed. All the KPIs provided by the assessment methodology are evaluated one by one and the ones "not applicable" to building and the ones requiring "not reachable data" are deducted according to type of building as well as local conditions and remaining KPIs are included into assessment.

In the third step, eliminated KPIs in the second step are deducted and available KPIs in out of the three-hundred-fifty-eight (358) KPIs are compiled for execution of the further stages of assessment.

In the fourth step, building's compliance with the minimum 30% grade provision in yes/ no based assessment for the technological KPIs, which has been defined as a prerequisite for usability of the testing methodology defined in the Chapter 6 Methodology part, is checked.

In the fifth step, grading method is applied to building pursuant to the equations 8.1, 8.2, 8.3 and 8.4 given below within the context of the assessment methodology.

Three (3) different grading methods have been enabled for compatibility with different building, company, country and cultural conditions.

Grading Method 1 (Grade Based on “Yes/No” over 100)

$$G_1 = 100 * \frac{\sum_{i=1}^{n} a_i}{\sum_{i=1}^{n} 1} \tag{8.1}$$

where:

n = Total number of KPIs that are applicable for the case study

a_i = Grade obtained (1 for all KPIs that are marked as Yes and a= 0 for the KPIs that are marked as No)

Hence, the score is identified by dividing the satisfied KPIs with the total number of KPIs.

Grading Method 2 (Grade Based on a “0-3 Scale” over 100)

$$G_2 = 100 * \frac{\sum_{i=1}^{n} a_i}{\sum_{i=1}^{n} b} \tag{8.2}$$

where:

n = Number of KPIs selected as applicable for the case study within the category of overall

a_i = Grade obtained by the case study building in each KPI within the category of overall (a can take the value of 0,1,2,3)

b = 3 (the maximum value in the scale)

Grading Method 3 (Weighted Grade over 100)

$$G_c = 100 * \frac{\sum_{i=1}^{z} a_i}{\sum_{i=1}^{z} b} \tag{8.3}$$

where:

c = Number of KPI categories, where categories range from 1 (economical) to 5 (physical)

z = Total number of KPIs in a category

a_i = Grade obtained by the case study building in each KPI within the category of overall (a can take the value of 0,1,2,3)

b = 3 (the maximum value in the scale)

Gc = Grade collected from each category

$$G_3 = \sum_{y=1}^{c=5} w_{c*}\, G_c \qquad (8.4)$$

where,

w_c is the weight of the category within overall KPIs.

In the last step, scorecard of building is issued as per grades obtained by building in the fifth step.

8.5. Case Study

The smartness of the case study building, which is METU Research Park, has been assessed as per the methodology demonstrated in the Figure 8.6 above, and the results presented in Table 8.7 below have been obtained.

Firstly; characteristics, mainly physical and technological characteristics, of the building has been determined as shown in the Chapter 7 Case Study. It has been determined that the building has energy conservation measurements such as XPS/ Rockwool insulation as well as double-glazing building envelope and technological features such as HVAC BMS system as well as electronic controlled entry control system.

Secondly; in the case study, all the KPIs have been evaluated one by one and the ones "not applicable" to the building and the ones requiring "not reachable data" have been deducted according to type of the building as well as local conditions and remaining KPIs have been included into the assessment. It has not been possible to reach the data related to total harmonics distortion, electromagnetic field exposure and percentage of the recycled hazardous waste. Criteria such as NO2 (nitrogen dioxide) concentration, SO2 (Sulphur dioxide) concentration, O3 (Ozone) concentration have been accepted as not applicable since these criteria are related to industrial buildings. Or return on investment and consumers engagement criteria have been selected as not applicable criteria since they are not related to a state university building built for scientific researches accordingly.

Thirdly; eliminated KPIs in the second stage are deducted and available KPIs in out of the three-hundred-fifty-eight (358) KPIs are compiled for execution of the further stages of the assessment.

Table 8.2 Analysis of the KPIs for the Case Study Building

	Total	**Not Applicable**	**Not Reachable Data**	**Applicable for the Case Study**	**% of Applicable in Total**
Economical	32	10	0	22	7.12%
Social	47	11	0	36	11.65%
Environmental	37	3	3	31	10.03%
Technological	224	22	0	202	65.37%
Physical	18	0	0	18	5.83%
Total	358	47	3	309	100.00%

Fourthly; the building’s current compliance with the minimum 30% grade provision in yes/ no based assessment for the technological KPIs, which has been defined as a prerequisite for usability of the testing methodology defined in the Chapter 6 Methodology part, has been checked.

Fifthly; grading method has been applied to the building and grades obtained by the building is shown in the Table 8.7 below.

Considering Research Park building belongs to a state University, it would be appropriate to apply a final weighting prioritizing environmental and social KPIs as in the Table 8.3 below. Accordingly, economical and physical concerns are considered as they have lower importance since the building is not a privately owned building. A coefficient will be applied to the KPIs accordingly at the weighted assessment step in account of type of the building, geography of the building, differences between public buildings and privately owned buildings.

Table 8.3 Building Specific Assessment Coefficients for the Case Study Building

	Determined Percentages
Economical	10.00%
Social	15.00%
Environmental	20.00%
Technological	45.00%
Physical	10.00%
Total	100.00%

Grading has been performed pursuant to the equations 8.1, 8.2, 8.3 and 8.4 given above. Assessment results of the case study building has also been obtained using the equations 8.1, 8.2, 8.3 and 8.4 given above. Equation 8.1 has been used to perform the assessment given in the Table 8.4 below, Equation 8.2 has been used to perform the assessment given in the Table 8.5 below and Equation 8.3 as well as Equation 8.4 have been used to perform the assessment given in the Table 8.6 below.

Then, firstly, yes/ no based smartness assessment of the case study building using these KPIs have been performed. The building acquired 75.40 points over 100 points as shown in Table 8.4 below.

Table 8.4 Yes/ No Based Assessment Applied to the Case Study Building

	Applicable KPIs for the Case Study	**Number of Yes Selections**	**Number of No Selections**	**Grade Based on Yes/ No over 100**
Economical	22	21	1	95.45
Social	36	31	5	86.11
Environmental	31	26	5	83.87
Technological	202	138	64	68.32
Physical	18	17	1	94.44
Total	309	233	76	**75.40**

Since the building has obtained a grade higher than 30% threshold value determined for validity of the developed methodology in the seventh step of the methodology, which is 68.32% (Table 8.4 above), in yes/ no based assessment for the technological KPIs, this building is eligible to be assessed with this methodology.

Then, a 0-3 Scale assessment of the KPIs has been applied on the case study building. It acquired 54.91 points over 100 points (Table 8.5 below).

Table 8.5 0-3 Scale Based Assessment Applied to the Case Study Building

	Applicable KPIs for the Case Study	**Available Total Points**	**Assessment Result**	**Grade Based on 0-3 Scale Assessment over 100**
Economical	22	66	46	69.70
Social	36	108	73	67.59
Environmental	31	93	55	59.14
Technological	202	606	297	49.01
Physical	18	54	38	70.37
Total	309	927	509	**54.91**

The weightings specific in the Table 8.3 above have been applied to the results and weighted grading of the case study building has been found as in the Table 8.6. The building acquired 58.03 points over 100 points (Table 8.6).

Table 8.6 Weighting Based Assessment Applied to the Case Study Building

	Grade Based on 0-3 Scale Assessment over 100	**Overall Weighted Grade of the Category**	**Weighted Grade over 100**
Economical	69.70	10.00%	6.97
Social	67.59	15.00%	10.14
Environmental	59.14	20.00%	11.83
Technological	49.01	45.00%	22.05
Physical	70.37	10.00%	7.04
Total	54.91	100.00%	**58.03**

Sixthly; scorecard of the building has been issued as per the grades obtained by the building in the fifth stage.

In the Table 8.7 below, results of all the three (3) gradings have been compared.

Table 8.7 Comparison of the Gradings

	Grade Based on Yes/ No over 100	**Grade Based on 0-3 Scale Assessment over 100**	**Weighted Grade over 100**
Economical	6.80	4.97	6.97
Social	10.03	7.87	10.14
Environmental	8.41	5.93	11.83
Technological	44.66	32.03	22.05
Physical	5.50	4.11	7.04
Total	**75.40**	**54.91**	**58.03**

As result of the application of the new developed SB assessment methodology to the case study building; Table 8.7 above shows that the overall grade of the building decreases when the particulars of the assessment is increased. Overall grade of the building decreases too much when all criteria is considered to have the same importance and it increases too much when a strict binary grading is applied. Hence, a balanced grading is needed that can be customized according to the expectations from smart buildings and the type of the buildings. In this manner, after proper weighting application, the grade of the building shows an increasing trend. Even if the application of only yes/ no scale grading for assessment of smartness of the buildings can be completed in narrow time period; the methodology recommends completion of all the steps and assessing the buildings as per weighted scale grading. However, it should also be noted that weighting application has not changed overall grading of the case study building since the building has a balanced grade distribution in each criteria varying between 49.01% and 70.37% in each category as could be seen in the Table 8.6 above. According to the assessment results, the case study building has been found as it has fundamental smart building features. Nonetheless, the building has still some points that could be improved or retrofitted. It is also possible to apply these improvements or retrofits with further cost optimality studies.

Moreover, the advantages that could be obtained as result of smart retrofit actions has already been presented in the “Smart Retrofit for Existing Buildings” Chapter. Lacks of the case study building also shown in Table A.1 and these could be taken as a reference for future retrofit actions. Considering that the building is a new constructed building and it already has various technological features as well as energy conservation providing features, subsequent retrofit action will predominantly be dependent on minor technological upgrades and foundation of a central building management system having the ability to control building technologies from a central control center. Suspended ceiling, raised flooring, modular indoor walls, uncovered mechanical piping/ ducts, as well as uncovered electrical cable trays, would make future retrofit actions easier to apply compared to standard buildings. In this regard, the building will have a chance to obtain higher assessment grades with the lowest additional cost possible.

CHAPTER 9

CONCLUSION

9.1. Summary of Findings

In this study, a smart building assessment methodology is proposed. This methodology integrates smart building KPIs that are presented in existing smart sustainable city assessment methods and existing smart building assessment studies. Using the building scale approaches, a total of 254 KPIs were identified, similarly using city-scale methods a total of 316 KPIs are identified. Within these 316 KPIs, a total of 111 KPIs were identified as applicable to buildings. As a result of data cleaning (e.g., identifying common KPIs with same or different wordings) a total of 358 KPIs were determined to assess the smartness of buildings for both building-scale and city-scale measurements.

Since SSC concept has generally been studied instead of smart city concept, city level KPIs have been taken from SSC studies due to their synchronous development with modern concepts.

An integrated smart building assessment methodology has been developed. The conceptual model of the methodology depends on identification of the building characteristics, selection of KPIs based on building type/ condition/ availability of data out of three-hundred-fifty-eight (358) SB KPIs, checking buildings compliance with the minimum 30% grade requirement in technological KPIs, application of the grading method to the building and calculation of score obtained by the building. The classification for smart building assessment methodologies as first-generation (nominal, pass-fail type certification), second-generation (simple additive) and third-generation (weighted additive) found in the literature was a pathfinder for this study. In the development of this methodology, it is kept in mind that the real world is gray and linear addition with basic yes/ no questions can be an oversimplification. To overcome this issue, 0-3 scale criteria grading and assignment of category-based variable weightings have been adapted to the assessment methodology. So, a three (3) step smart building assessment methodology development approach has been followed as yes/ no based assessment in the first step, 0-3 scale based assessment in the second step and assigning variable weightings to the KPI categories in the third step has been followed. The second step presented the opportunity to perform an assessment in a wider range grading, and the third step has provided the possibility to include personalization and priority determination. Also, a minimum 30% grade criterion in yes/ no based assessment for the technological KPIs has been set to prevent non-smart buildings from being assessed using the newly developed smart building assessment methodology. The methodology has been developed for decision-making assessment and performance assessment. It should also be noted that the newly developed smart building assessment methodology needs educated assessors to prevent the occurrence of subjectivity in assessment results.

The smartness assessment of a case study building, which is METU Research Park Building, has been performed. Related KPI selection and grading are shown in Table A.1. KPIs need unreachable data and not applicable KPIs are deducted from the assessment. Remaining KPIs have been evaluated mainly considering the climate of the geographical location of the building, geometrical characteristics of the building, type and envelope of the building and information arisen from design documentation of the building. This assessment shows the smartness level of the building and guides for determination of lack could be improved in further retrofit action tanks to its comprehensive KPIs.

Importance of public/ private building discrimination has also been underlined. Private one’s general financial benefit and indoor comfort focality and public ones’ exemplary role in reducing energy consumption and polluting emissions have been taken into account. The case study building has also been assessed in this manner.

In light of all the findings of this study, it is difficult to create international standards for smart building assessment due to many differences, including culture and development levels of countries. This study has overcome this issue by proposing a flexible assessment methodology making a variable coefficient assignment to KPI categories. Furthermore, country-based “not applicable” KPI selection –if necessary- could further specialize assessment methodology considering country-based differences.

9.2. Practical Implications

Gained knowledge and the new developed SB assessment methodology as a result of this study compose a significant background for stakeholders to give informed decisions on smart buildings which give particular importance to occupant comfort, well-being, convenience, safety, flexibility, technological infrastructure, energy consumption reduction coming out of energy-saving and energy conservation features. Also, it should be kept in mind that the newly developed SB assessment methodology has substantial potential to contribute enhancement of portfolio or asset management, rent reviews, investment appraisals, purchasing or selling property demonstration and judging alternative design proposals.

The developed SB assessment methodology gives an opportunity to specialize the assessment according to building type (dwelling, educational building, hospital... etc.) with flexible "not applicable" criteria election. KPIs that are not related to the assessed building type could be excluded in this way. Specialization (e.g., according to building type) gives a chance to compose a fair platform that all type of buildings and a chance for practitioners to use the assessment for all types of buildings instead of trying to find an appropriate assessment tool.

Since the number of existing buildings is far more than new building constructions, existing building smart retrofit options, which provide numerous benefits, have been included in the scope of this study. It is found that retrofitting existing buildings are better than constructing a new one in most of the situations and retrofitting provides a chance to use fewer materials, less wreck formation and usage of local labor force, especially if the building is just constructed as the case study building. The proposed methodology can be used by public and private sectors to assess the existing building stock.

9.3. Future Research Directions

Since significant number of building assessment methodologies (such as LEED, BREEAM, HK-BEAM, and NABERS) are generally greenness focused, lacking from clear assessment criteria, not cited by other researchers in a remarkable amount and obsoleted; these methodologies are excluded for development of a new smart building assessment methodology. These methodologies might be included to future studies if a country desires to shift focus of its national assessment methodology towards greenness and this would propound a smart sustainable building assessment methodology instead of smart building assessment methodology.

It is challenging, and maybe not even realistic, to expect a universal standard for smart building assessment. Further studies can be performed for the customization of smart building assessment KPIs.

All the 358 KPIs found and propounded for SB assessment methodology could be examined and developed by industry and academia experts for further assessment studies. Also, a KPI-based variable weighting assignment system could be developed to give opportunity to prioritize desired KPIs.

Besides all the outputs of this study mentioned above, some points could not have been scrutinized in detail in this study due to their requirements of performance of particular studies arisen from their depth and coverage. In this manner; preparation of various comparative smart building retrofit scenarios containing multiple criteria decision-making approach, development of cost-optimization techniques relevant to the developed SB retrofit actions, determination of country-based specific coefficients for SB assessment methodology adjustments and determination of specific set of KPI selections as per all widespread building types could be studied in future studies.

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APPENDICES

A. Sample of KPIs of the Developed Smart Building Assessment Methodology

Abbreviations listed below are used to identify column headings of the Table A.1.

[B1]: Kaya and Kahraman (2014)

[B2]: Azari et al. (2016)

[B3]: Chen et al. (2006)

[B4]: Wong and Li (2008)

[B5]: Wong et al. (2008)

[C1]: ISO 37120 (2014)

[C2]: UNECE (2015)

[C3]: UN-Habitat (2012)

[C4]: U4SSC (2017)

[C5]: ITU (2014)

[C6]: Bosch et al. (2017) (Citykeys)

[C7]: ESPRESSO (2016)

[C8]: Marijuán et al. (2017) (SCIS)

Table A.1 Sample of KPIs of the Developed Smart Building Assessment Methodology

	From Building Level						**From City Level**								**Case Study**		
KPI Definition	**[B1]**	**[B2]**	**[B3]**	**[B4]**	**[B5]**	**Building Applicability**	**[C1]**	**[C2]**	**[C3]**	**[C4]**	**[C5]**	**[C6]**	**[C7]**	**[C8]**	**Yes/No Scale**	**0-3 Scale**	**Case Study Applicability**
Technological																	
Student ICT Access						+				x			x		Yes	2	
Protocol standard compliance (Network etc.)		x		x											Yes	2	
Access to high speed internet						+						x			Yes	3	
Control and monitor fire detection interlock operation with “other services”					x										Yes	1	
Automatic and remote control/monitoring		x		x											Yes	1	
Reserve electric power			x												Yes	2	
Utilize natural ventilation control to reduce air-conditioning power consumption					x										No	0	