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A FRAMEWORK FOR COUPLING AND QUANTIFYING SUSTAINABILITY  
AND RESILIENCE IN INTELLIGENT BUILDINGS

by

Deena Ahmed Al Qurneh

A Thesis presented to the Faculty of the  
American University of Sharjah  
College of Engineering  
In Partial Fulfillment  
of the Requirements  
for the Degree of

Master of Science in  
Engineering Systems Management

Sharjah, United Arab Emirates

July 2020

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## **Acknowledgement**

I would like to thank my advisors Dr. Salwa Beheiry and Dr. Maruf Martula for providing knowledge, guidance, and motivation throughout this Journey. I'm deeply beholden for their great efforts. I also wish to express my deepest gratitude to Mr. Mustafa Al Tikriti, without his persistent help, the goal of this project would not have been realized. Special thanks to my committee members Dr. Ghassan Abu-Lebdeh and Dr. Irtishad Ahmad, I really appreciate their dignified advices and motivation. Not to forget the great roles of the Engineering Systems Management Program professors who taught me the master level courses with extraordinary teaching methods and skills. I also wish to express my sincere appreciation to the College of Engineering in the American University of Sharjah for granting me a Graduate Assistantship during my study period.

Finally, my deep and sincere gratitude to my family and friends for their continuous and unparalleled love, help and support. I am forever indebted to my parents for believing in me and giving me the encouragement to seek opportunities and experiences that have made me who I am. This journey would not have been possible if not for them, and I dedicate this milestone to them.

## **Abstract**

The concepts of sustainability and resilience have become increasingly important. Sustainability is often related to implementing best practices in many facets of the construction industry and resilience typically refers to the adaptability and endurance of systems in harsh conditions. Both concepts are studied over the lifecycles of buildings. On the other hand, smart buildings are growing in use and scope and tend to be more dependent on technology and complex systems. Therefore, they also tend to be more prone to unexpected failure. While the two concepts of sustainability and resilience are interrelated, there is limited research that quantifies and/or combines them, and none studying how the two behave when developers aim to apply both in smart buildings. Hence, this study constructed a framework that developed a financial model where the Net Present Value (NPV) was used to study the implications and limitations of the investment in both concepts, i.e. the NPV was measured using direct and indirect costs and benefits resulting from having sustainability and resilience integrated in smart buildings. Thus, translating the benefits of this integration into monetary values. Sustainability was essentially quantified via translating the costs and benefits of the three main components: environmental, social and economic. While resilience was measured via the impact frequency of faults and the absence of detection tools on the calculated NPV. The two were then coupled by measuring the costs and benefits of installing and maintaining resilience tools in sustainably designed smart buildings and studying this impact on the resultant NPV. The designed model was also applied on four case studies of selected smart buildings in Dubai. The results of the study indicate that integrating the targeted sustainable approaches in smart buildings, with tools that improve resilience, yield a higher NPV. However, to maintain the positive effect on the NPV and to minimize the cost of failure, fault detection and diagnosis tools need to be assimilated in the initial smart and sustainable buildings design.

**Keywords:** *Sustainability; Resilience; Intelligent Buildings; Net Present Value*

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## **List of Abbreviations**

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
BAS	Building Automation System
BREEAM	Building Research Establishment Environmental Assessment Methodology
CDM SD	Clean Development Mechanism Sustainable Development
CePRED	Certification of the Predisposition of Resistance of Edifices to Disasters
CMS	Communication Management System
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
EMS	Energy Management System
FDD	Fault Detection and Diagnosis
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
LCA	Life Cycle Assessment
LEED	Leadership in Energy & Environmental Design
MFA	Material Flow Analysis
NPV	Net Present Value
OA	Office Automation
PERT	Program Evaluation and Review Technique
TBL	Triple Bottom Line

## Chapter 1. Introduction

In this chapter, a short introduction to the topic will be provided as well as a quick brief for the problem investigated. The thesis contribution will be elaborated upon and the general organization of the rest of the thesis will be presented.

### 1.1. Overview

As the two concepts of sustainability and resilience have become the main pivots of many research trends and applications in different sectors, the need to quantify each one of them has become a necessity. Therefore, researchers have started to look for ways not only to quantify them but also to integrate both concepts together, due to the numerous benefits that could be obtained from such integration [1]. These attempts started to emerge in different fields, such as civil infrastructure, buildings, urban drainage systems, landscape and urban planning. This study will be targeting buildings and specifically the intelligent buildings sector. That is because they have sophisticated systems and a more complicated maintenance scheme, which makes them unpredictable structures with a high probability of failure and higher risks [2].

The world has been in the process of rapid modernization, where new technologies have been emerging every day and designers and engineers have started taking an interest in the performance of buildings. There has been much rethinking of the design and construction processes to implement intelligent technologies into new buildings in order to create smart structures that fulfil their users' needs and to attain a highly sustainable performance [2]. Additionally, there have been several approaches for implementing resilience in smart buildings, resulting in creating highly resilient structures, yet very few of those implementations aim at combining both sustainability and resilience at the same time in smart buildings [1]. This means that some buildings could have new and highly advanced technologies that enable them to meet sustainability goals and to become environmentally friendly structures, while other buildings could have other types of highly advanced technologies that enable them to detect defects in their systems, allowing them to prevent failure or even recover quickly if failure does occur. However, there have been very few studies on how to combine those two concepts in smart buildings. Therefore, this study will be aimed at coupling the concepts of sustainability and resilience in smart buildings using a cost-benefit

evaluation method, and using NPV as the main tool to quantify both sustainability and resilience, and test for the importance of this integration.

## **1.2. Research Rationale**

Although there are different studies that target both sustainability and resilience, it seems that there are only a few investigations into building a financial model that couples the two terms in one approach, especially in intelligent buildings, where it was found that the two concepts would be coupled in a theoretical framework, where no financial analysis was conducted, or using a financial analysis but for a normal building, not a smart one, assuming a very specific type of failure to quantify resilience. However, building resilience might be hard to quantify due to the diversity of the systems involved in a building, whereas the resilience of a smaller structure, like a bridge, would be easier to quantify. Not to mention that some of the methods would quantify either sustainability or resilience using data that is hard to collect, or even ignore one of the sustainability pillars to simplify the calculations. Therefore, the intention of this study is to create a framework that builds a simple and realistic financial model to quantify the sustainability of a smart building, including its three pillars (environmental, social and economic). Then I will add the resilience to that model by testing the financial performance of the smart building both and without the resilience being integrated.

## **1.3. Research Problem**

The fact that few studies have managed to couple the two concepts of sustainability and resilience in one study and without creating a model that quantifies both in monetary values for smart buildings, represents the starting point of this research.

## **1.4. Research Aim**

The aim of this work is to quantify the sustainability benefits of having smart systems in buildings, while at the same time quantify the benefits of having resilience integrated alongside sustainability in these buildings, using a financial model.

## **1.5. Research Objectives**

Driven by the fact that the new emerging intelligent buildings are becoming a growing trend in the modern world, the need for integrating the concept of resilience

with sustainability in those intelligent buildings is of high importance due to the numerous benefits of such integration. Therefore, the main objective of this work is to build a framework that develops a financial model to couple both sustainability and resilience. In order to attain the aspirations and accomplish the aims of this study, the following sub-objectives were set:

- Exploring methods to quantify both sustainability and resilience.
- Identifying the affected attributes of sustainability due to the implementation of smart systems in buildings.
- Identifying possible resilience implementations that could be used in smart buildings.
- Proposing an approach that translates benefits of this integration into monetary values.

#### **1.6. Research Significance**

The findings of this study will contribute to the benefit of other researchers, developers, investors, managers, engineers and anyone who is involved in the design or construction process of intelligent buildings. Therefore, the contributions of this research will be divided into two parts, contributions to the body of knowledge and contributions to the business. The following points will summarize the contributions to the body of knowledge:

- Quantify the resilience of smart building systems.
- Couple both sustainability and resilience using a cost-benefit evaluation method.

The contributions of this study to the business are summarized in the following points:

- Measure the financial damages that might occur when resilience is not coupled with sustainability.
- Minimize the possible financial losses and turn them into a potential profit.
- Measure the financial benefits of this integration.

### **1.7. Research Questions**

Some of the questions that this study will be investigating: What can be gained from integrating both sustainability and resilience in smart buildings? And how could the two concepts be coupled in one financial model?

### **1.8. Research Hypothesis**

It is hypothesized that integrating resilience with sustainability minimizes the potential losses in case of failure and improves the financial performance of the intelligent building.

### **1.9. Thesis Organization**

The rest of the thesis is organized in the following order: Chapter 2 includes general information about the topic, definitions, quantification methods, examples of the applications of sustainability and resilience in the construction sector, the new emerging technologies used in the intelligent buildings and some previous related works that have similar goals and apply similar research approaches. As for chapter 3, it discusses the proposed methodology that will be used to achieve the goals of this study. While chapter 4 discusses the results and the outcomes of the conducted analysis. Chapter 5 concludes and summarizes the final findings of the study.

## Chapter 2. Background and Literature Review

In this chapter, the fundamentals and definitions of sustainability and resilience will be discussed, as well as the different methods that could be used to integrate and quantify them. The application of sustainability and resilience in the construction sector will be discussed, along with the new emerging technologies used in intelligent buildings. Related work and similar applications where resilience and sustainability are coupled and quantified will also be looked at in this chapter.

### 2.1. Sustainability Definition and Dimensions

Sustainability has grown in importance in recent years, and it is now a key factor in almost all new projects [3]. Different opinions about sustainability exist, with one defining it as a normative concept that promotes balance between different generations. Sustainability is seen as the ability to use the earth resources to meet present needs without those resources being depleted so that future generations' needs are met [4]. This definition also means that sustainability is a way to balance the Triple Bottom Line (TBL), which is the economic, environmental and social consequences of a development. Those three parts of the equation, also known as dimensions or pillars, should be given equal importance, where sustainability should be the fair interplay between those three ends, connecting them and making sure that the social end (humans and their well-being) is not affected negatively, the environmental end (natural resources) is not over-burdened, and the economic end (money and reputation) is used efficiently [4], [5]. Nevertheless, others have tended to look at sustainability as a concept that is related to the ability to sustain, which means that it is seen as a way to preserve a certain state of something at a certain level for a certain amount of time [6].

**2.1.1. Sustainability in construction.** Buildings seem to be the most important structures in a human's life, since they represent the basis of our daily activities, where we live, work, sleep, shop and entertain ourselves [7]. These kinds of structures tend to have a complicated relationship with sustainability, especially that it is not easy to integrate sustainability in buildings. The design, operation, construction, renovation, maintenance, and destruction of these massive structures could be causing many problems and leaving harmful effects when it comes to the environmental, economic and social dimensions of sustainability. To be more precise, buildings seem

to consume a huge amount of energy and deplete natural resources, especially the nonrenewable ones. Therefore, it is considered a challenge to make those structures environmentally friendly [7]. Below are the effects of the construction industry activities on the three dimensions of sustainability:

1. Environmental: during the construction and deconstruction processes of buildings many unwanted outcomes seem to be produced, such as liquid wastes, solid wastes and harmful gas emissions. It was found in a study that was conducted in 2010 that buildings caused 50% of greenhouse gas emissions, 40% of cities solid wastes, as well as 40% of their water pollution. Buildings consume 45% of the world's energy and deplete 50% of the available water bodies. In addition, some other impacts of construction activities on environment could be decreasing biological diversity, eliminating many spacious green areas, and contributing to global warming [7].
2. Economic: when it comes to the construction process of a building, it becomes very challenging to control monetary losses as these are directly related to the delivery time of the project. In the construction industry, buildings are treated as a demand-derived commodity that will be utilized for a short-term horizon, meaning that their financing is always adjusted to the short or even the medium term, which contradicts the concept of sustainable construction that plans for the long term. Therefore, it can be concluded that the construction industry is not considered very efficient from the economic perspective of sustainability [8].
3. Social: considering that the construction industry provides many job opportunities for the low-income working class, which in turn improves their life quality and prevents poverty in societies, it can be concluded that it has a good impact on the social dimension of sustainability, and it would be good to maintain this impact and even improve it further [7].

Although the construction industry seems to have many conflicts with sustainability, as mentioned before, there are many new emerging attempts to improve this practice and

to convert it into a fully sustainable practice to produce green and sustainable buildings, considering the environmental, social and economic dimensions of sustainability [3].

**2.1.2. Methods to assess and quantify sustainability.** Using new technical innovations, under the name of sustainability, to improve the environmental performance of buildings, is now common [9], and the need for assessment methodologies to capture and quantify the benefits of integrating sustainable solutions in buildings has become a necessity. Some of the most commonly used methods in recent studies will be mentioned in the next subsection.

**2.1.2.1. First method: Award points rating systems.** One of the most well-known assessment tools that is widely used nowadays is dependent on a points system which is used to weigh the environmental impacts of the evaluated building. Some of those assessment methodologies are: (BREEAM), which is an abbreviation of Building Research Establishment Environmental Assessment Methodology, and was launched in 1990 in the UK by the Building Research Establishment; (LEED), which is an abbreviation of Leadership in Energy & Environmental Design, developed in 1993 in the USA by the Green Building Council; and (DGNB), which was established in 2007, coming from the abbreviation of its developer Deutsche Gesellschaft für Nachhaltiges Bauen, the “German Sustainable Building Council”. Nevertheless, these tools do not explicitly consider any monetary value nor a real measured quantification [10].

**2.1.2.2. Second method: Life cycle assessment (LCA) and net present value (NPV).** In an attempt to quantify the benefits of sustainability, this new assessment method counts on quantifying the outcomes of producing a certain product. Life cycle assessment (LCA) is considered one of those methods, and it is used in many industries, including the construction industry. LCA aims to measure the impacts of constructing a certain structure (building) from the first moment of its construction until it reaches the end of its life by quantifying the building’s consumed energy, gas emissions (greenhouse gases), solid waste and water waste. The retrieved information from this analysis could be used to compare two options: improve efficiency or control and reduce the environmental impact. However, LCA seems to address the environmental aspect of sustainability and sometimes the social aspect by focusing on human health. Another similar method for sustainability assessment is the NPV method, which focuses more on the economic aspect of sustainability. This method is mostly used to

get a more accurate analysis for costs and benefits, converting them into an equivalent present value that could be positive or negative. A negative number indicates that the project is not worth investing in, while a positive number indicates that the project is worth investing in [11], [12], and [13].

**2.1.2.3. Third method: Risk assessment.** This method tends to quantify the monetary value, where it measures the expected cost that would result from a certain process or function of a building or structure. To be more precise, this method measures the costs incurred by a function in the building that could affect the environmental, economic and social aspects of sustainability. In some cases, this cost could be defined as the environmental cost, social cost and economic cost. Such costs could be divided into direct and indirect costs. For example, considering the environmental cost, if a building tends to produce carbon in a certain amount, if carbon taxes are imposed, then there will be a direct cost from the tax. As for the economic cost, an indirect cost will be imposed due to the loss of the company's reputation, especially if it is a company that promotes itself as being environmentally aware. The last cost is the social cost which can be represented as an indirect cost that would be associated with the loss of employment if a shutdown action was enforced on the company/building due to some harmful emissions that affect the environment [14]. Summing the three abovementioned costs would help to quantify the sustainability of a building or a structure.

**2.1.2.4. Fourth method: Cost benefit analysis (CBA) and cost effectiveness analysis.** Some other commonly used approaches to quantify sustainability are the cost benefit analysis and the cost effectiveness analysis. The first one measures the cost of implementing a sustainable solution as well as the resulting benefit and compares to each other, while the latter only considers the cost of implementing a sustainable solution. Therefore, it can be concluded that both of those approaches only consider the economic aspect of sustainability [5].

There are many other methods that could be used to quantify sustainability such as the Clean Development Mechanism Sustainable Development (CDM SD) benefits assessment method and the Climate Community Biodiversity (CCB) method, where those two methods measure the qualitative benefits of sustainability. In other words, they compare a situation where a sustainable solution is implemented with the baseline

situation where the solution is not implemented. For example, the emission of carbon after implementing a sustainable solution to the carbon emission before implementing the sustainable solution [5]. The aforementioned methods are the ones that will be focused on in this study.

## **2.2. Resilience Definition and Dimensions**

The concept of resilience has been defined, reviewed and discussed widely in many studies. Some of them described it as a method or a plan to prevent a building or a structure from failing, while other studies referred to it as a self-reorganization way to accommodate extreme external changes while increasing the learning and adaptation capacity [15]. Some considered it a tool to measure the durability of a structure and its ability to withstand certain conditions before it fails [16]. While others defined it as a restoration process of the original state or condition of a building or a structure and they measured that by the amount of time that this structure would take during this rebounding process [17]. Another study connected resilience to the term vulnerability because it is believed that resilience measures the amount of resistance to failure a system can have, indicating how vulnerable a system is [4]. However, one study defined resilience as the ability of human communities to withstand and recover from the perturbations to their built environment and infrastructure, connecting resilience directly to communities and societies and how they deal with the failure of built structures [1].

Figure 2.1 illustrates the meaning of resilience by studying the performance of three systems before and after a disruptive event. As can be seen, system 1 managed to get back to its original performance level after having a drop in its performance, being exposed to a disruptive event. While system 2 could not fully recover without being affected by the disruptive event, where the new level of performance that it started functioning with was less than the original one. As for system 3, the system started to collapse gradually after being exposed to the disruptive event. Those three examples demonstrate the difference between the performances of three systems with different resilience levels. Where system 1 was the one with the highest resilience, system 2 had a lower resilience and system 3 had no resilience at all [18].

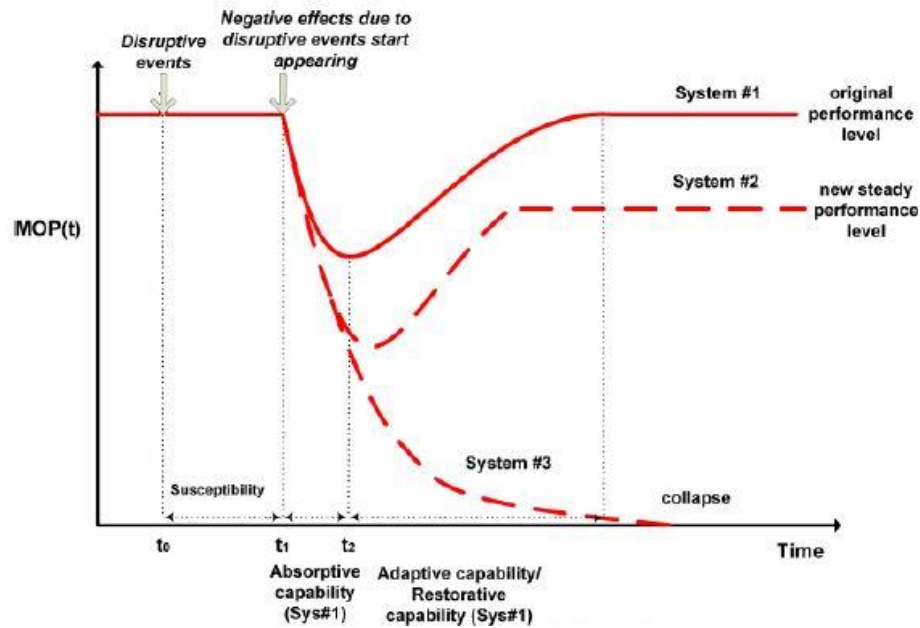


Figure 2.1: Illustration of resilience capabilities [18].

**2.2.1. Resilience in construction.** The importance of buildings and the built infrastructure was discussed earlier in the sustainability section. Maintaining those built structures and making sure that they are able to withstand disasters, harsh conditions or any kind of challenges are of equal importance. As integrating the resilience approach within the construction industry seems to be not only boosting some countries' overall economies but to be an extremely effective factor in improving the quality of their communities' lives [19]. Therefore, it can be argued that when it comes to communities and their infrastructure, resilience seems to have four dimensions, the first one is the technical dimension, which includes all of the construction's associated aspects as well as the technological ones. The second one is the organizational dimension, which includes whatever arrangements and plans have been made to respond to emergencies. The third one is the social dimension, which measures the impact on society and suggests mitigation methods. The last dimension is the economic one, which deals with the direct and the indirect costs incurred due to the loss of functionality of certain parts of a structure.

Resilience in construction can be characterized by four properties: robustness, rapidity, redundancy and resourcefulness. Where robustness and rapidity can sometimes be considered resilience goals, while redundancy and resourcefulness can be treated as the tools required to achieve resilience. Robustness measures the ability

of a building or a structure to withstand harsh extreme events and continue to function at the same level, this property could be measured by the residual level of functionality after the occurrence of the disruptive event. Rapidity measures how fast a structure rebounds to its original functionality level after being exposed to the challenging conditions. Redundancy measures the availability of elements and components required to maintain a system or structure. Resourcefulness indicates the capability of identifying problems, establishing priorities, and providing the required resources and reallocating budget when it comes to recovering from extreme events. Finally, when resilience is applied to a building or a structure, three outcomes can then be obtained: reliability, fast recovery and low socioeconomic consequences. If a structure is designed to be resilient, then it will be considered reliable, as resilience guarantees a decreased reduction in functionality, if any occurs, under extreme events. Furthermore, in case a building could not maintain its functions, then loss of functionality will occur, but the fact that the building is resilient allows for fast recovery and restoration of the original state. Due to the low probability of failure, as well as the fast recovery in case of failure, the impact of the extreme events on the society will be significantly reduced leading to noticeably low socioeconomic consequences [1].

**2.2.2. Methods to assess and quantify resilience.** One of the definitions mentioned in the resilience definition section defined it as the ability of human communities to withstand and recover from the perturbations to their built environment and infrastructure. Where this definition connects resilience directly to communities and societies rather than the built structures. For example, whenever a bridge is constructed, its ability to withstand any kind of shocks or external perturbations goes back to its structural characteristics, while its recovery process is strongly affected by the economic, political, and technological conditions of the community that is interested in restoring the bridge. Due to this relationship, it can be concluded that the impact of the bridge damage can be quantified by the traffic disruptions costs and the socioeconomic benefits of its prompt recovery [1]. This means that one way of indicating the amount of resilience a structure has is by studying the effect of the structure's failure on its surrounding as well as the benefits of its quick recovery. The next subsection will discuss some of the most common used methods to quantify and measure resilience.

**2.2.2.1. First method: Labelling systems.** Similar to the concept of the awarded points rating systems used to quantify sustainability in buildings, new assessment tools have started to be used recently to quantify and rate the resistance strength of structures. One of the emerging methods is the Certification of the Predisposition of Resistance of Edifices to Disasters (CePRED). This certification tends to evaluate buildings by offering them a “Blue shields” labeling system, where five blue shields indicates a very high resistance against potential disasters and extreme conditions, while one blue shield indicates poor performance when it comes to withstanding those extreme conditions. Figure 2.2. Promoting communities that are disaster resilient, such certificates encourage the use of proactive adaptation methods [20].



Figure 2.2: Blue shields labeling system in CePRED [20].

**2.2.2.2. Second method: Resilience triangle.** This method seems to be the origin of all of the analytical definitions of resilience, where it measures and quantifies the loss of resilience rather than resilience itself [1]. Figure 2.3 provides a clear example where this method was applied on a transportation network (bridge). The illustrated graph has two axes, x and y, the x-axis indicates time (t) while the y-axis indicates the level of functionality as a percentage [Q (t)]. The resilience triangle created has three edges, the vertical one resembles the loss of functionality, where 100% is the full functionality and 20% is the amount of functionality left in the structure, which means that 80% is the amount of functionality that was lost due to exposure to an extreme

event. Another way to interpret those readings is to say that 20% resembles the “robustness” or resistance of the structure to a complete failure and 80% resembles “1-robustness”. The second edge of the triangle resembles the time required for the recovery process; it starts from  $t_0$ , the moment that the extreme event occurs and 80% of the functionality is lost, and ends at  $t_r$ , the moment that all functionality is restored. The last edge, the hypotenuse, resembles the approximate and the real recovery paths, measuring the “rapidity”, which is the decrease in the loss of functionality through time until this value reaches zero, meaning that the structure restored all of its functionality [1].

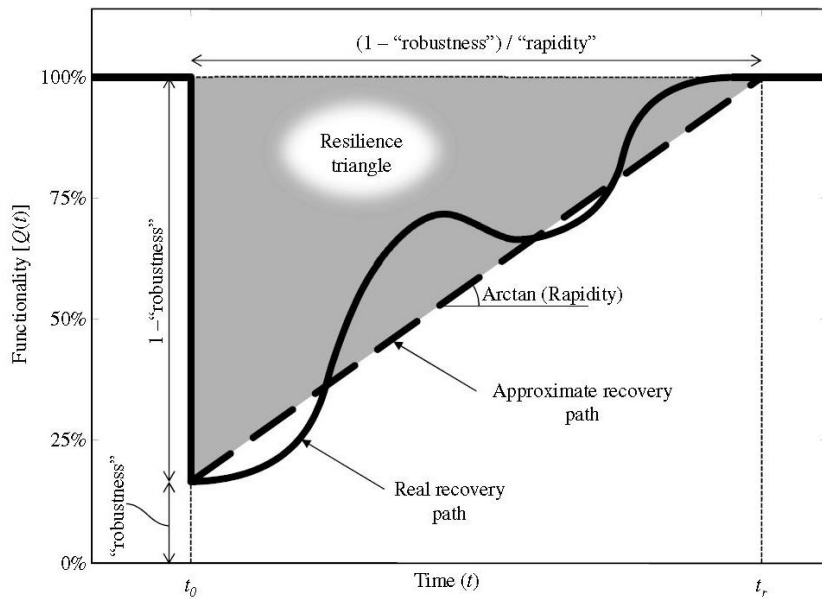


Figure 2.3: Resilience triangle [1].

Therefore, to assess the structure resilience considering the approximate recovery path, this equation could be used [1]:

$$rapidity = \frac{1 - robustness}{t_r - t_0} \quad (1)$$

Accounting for the actual recovery path shape, another more accurate equation could be used [1]:

$$R_L = \int_{t_0}^{t_r} [100 - Q(t)] dt \quad (2)$$

Where  $R_L$ , represented by the grey area above the recovery path in the graph, is the loss of functionality / resilience of the system,  $t = t_0$  is the time the extreme event occurs,  $t = t_r$  is the time when complete functionality is restored,  $Q$  is the functionality / quality of service of the structure [1].

**2.2.2.3. Third method: Risk assessment.** As mentioned earlier in section 2.1.2.3 this method tends to quantify the monetary value, where it measures the expected cost that would result from a certain process or function of a building or a structure. But when it comes to resilience, this method is used to quantify the damages that would result from the failure of that process or function, or even the losses incurred during the recovery period of that process or function. To be more precise, in order to quantify risk using this method, a function that multiplies the probability of failure occurrence by the resulting consequence of failure, estimated in monetary units, is used. For example, assuming an earthquake where certain functions of a building are lost for a certain amount of time, this method quantifies the incurred damages due to the temporal loss in functionality in monetary units [14].

However, due to the growing need to measure and quantify resilience, many other different methods were used to get to that goal, such as benefit assessment models, cost to benefit assessment models, resilience index, decision flow diagrams, performance-based frameworks, etc. [1], [18], [20].

### **2.3. Intelligent Buildings**

Due to the rapid increase of the earth's population, intensifying urbanization, and the scarcity of land, compacted design approaches need to be implemented, allowing for a wider spread of higher buildings all over the world [21]. This emerging trend has evolved rapidly over time, where people did not only focus on reaching new heights, but they sought to provide comfortable spaces, energy efficient systems, environmentally friendly structures and iconic landmarks that are more than just places to live and work [22], [23]. In an attempt to attain these aspirations, a variety of advanced technologies were integrated into buildings, leading to the emergence of the intelligent buildings concept. Although intelligent buildings could be the solution to many dilemmas, they have some challenges of their own. For example, intelligent buildings have a very high initial cost, a higher probability of failure due to their sophisticated systems and a more complicated maintenance scheme. This indicates that

they are structures with unpredictable behaviors and have a higher risk, making them more prone to failure compared to normal buildings [2], [24], which is the main reason behind selecting them for this study. Also, not to mention the fact that striving for a very high level of sustainability would increase the levels of complexity and risk, which in turn might lead to having a negative impact on resilience [1]. This makes the attempts to couple the two concepts even more challenging in smart buildings.

**2.3.1. Integrating new technologies in buildings to create intelligent buildings.** As the world evolves rapidly, and the needs of the people change accordingly, a unity between the information technology and the buildings sector was formed. At the beginning of the 1980s, in the United States of America, the term “intelligent” was used in this context for the first time. An intelligent building could be defined as a unit that aims at governing and controlling the building services environment by optimizing user comfort, safety, energy consumption and work efficiency, using new computer technologies [25]. According to the UK-based European Intelligent Building Group, intelligent buildings could be defined as ones that make use of an efficient management of resources and have a minimum of lifetime costs, providing a comfortable internal environment that maximizes its inhabitants’ productivity. While the Intelligent Building Institute of the United States defines intelligent buildings as entities that provide both a cost-effective and productive environment for their inhabitants by optimizing the four basic elements of a building, which are structure, systems, services and management [26]. Nevertheless, almost all the definitions of intelligent buildings indicate that they are sustainable, adaptable, flexible, and technologically aware structures that are designed and built to meet the needs of their users and provide them with the perfect environment that maximizes their effectiveness.

As for what makes those buildings intelligent, the integration of the emerging advanced innovative technologies within the buildings systems seems to be the key. Those abovementioned technologies will be installed within the building subsystems services, and they include lighting, HVAC, fire detection and protection, security, communication and vertical transportation systems. As soon as the building starts functioning using those services, the qualities that create its efficient and productive environment starts to be generated, providing high levels of functionality, safety,

flexibility, energy conservation and thermal, acoustical and visual comfort. Utilizing those advanced systems within the intelligent buildings could also allow for solving some of the most substantial environmental issues of today's world, which in turn leads to meeting the goals of "sustainable development" [26].

Nevertheless, using very advanced and sophisticated technologies is not enough on its own, as the key to successful implementation is the proper integration between these technologies, each other and the building. Incorporating the Internet of Things (IoT), Building Automation System (BAS), Communication Management System (CMS), Office Automation (OA), as well as Energy Management System (EMS) allows for controlling, supervising and enhancing the integration process between the implemented subsystems [26].

*2.3.1.1. Sustainability in intelligent buildings.* As intelligent buildings are becoming an essential part of sustainable development, a clear understanding of how buildings impact the environment in both a positive and a negative way has been developed. Yet, in order to fulfill the sustainability requirements in intelligent buildings, a series of basic principles and practices needs to be employed, some of the most common practices used in current implementations are: selective material choice, determination of building orientation to maximize solar gain, customization of building products, and implications of advanced building and construction techniques. According to some studies, implementing these sustainable practices contribute in providing environmental, social and economic benefits. These benefits could be measured by the amount of reduction in greenhouse gas emissions, increase in employees' productivity levels, amount of savings in expenses in the long term, reduction in heating and cooling needs, the need for fewer lighting fixtures, and reduced levels of energy consumption [27].

However, as there are many examples of new and sustainable intelligent buildings, some of them will be selected and discussed in this study. The first example is an 80-floor mixed-use tower in Dubai known as the **Dynamic Tower**, Figure 2.4. The Dynamic Tower has been described as the "first real green building", according to its architect Dr. Fisher, as it was designed to produce a huge amount of power that could run another five buildings of the same size. The building uses a highly sophisticated technology that allows for floor rotation in order to capture the maximum amount of

natural light at different times of the day. Also, large photovoltaic cells were installed on the roof to make use of solar power. In addition, in order to use wind power, 48 carbon fiber wind turbines were installed between the floors, capturing wind and turning it into a clean form of power that keeps the building running. Furthermore, the new technologies and practices will not only be implemented in the design phase of the tower, they will also be used in the construction process as well because along with being the first real green building, it will be the first “factory-built skyscraper”, as the only thing that will be constructed on site is the building’s core while the rest of the structure will be prefabricated and procured from a factory in Italy [27].



Figure 2.4: The Dynamic Tower in Dubai [28].

The second example is also in Dubai and is known as the **Nakheel Tower**, Figure 2.5. The building was designed in a way that aspires to achieve an LEED Gold rating, challenging the current typical model of what a sustainable building should be. This sustainable structure will be built to defy one of the most common issues that face extremely high buildings, which is wind. As the building design consists of four stand-alone towers that are connected with sky bridges after every 25 floors. It allows wind to pass through the structure, reducing the impact of its forces on the building. In addition, advanced nanotechnology is incorporated in the building façade allowing for the maximum light transmission while withstanding high humidity levels and direct sunlight [29].

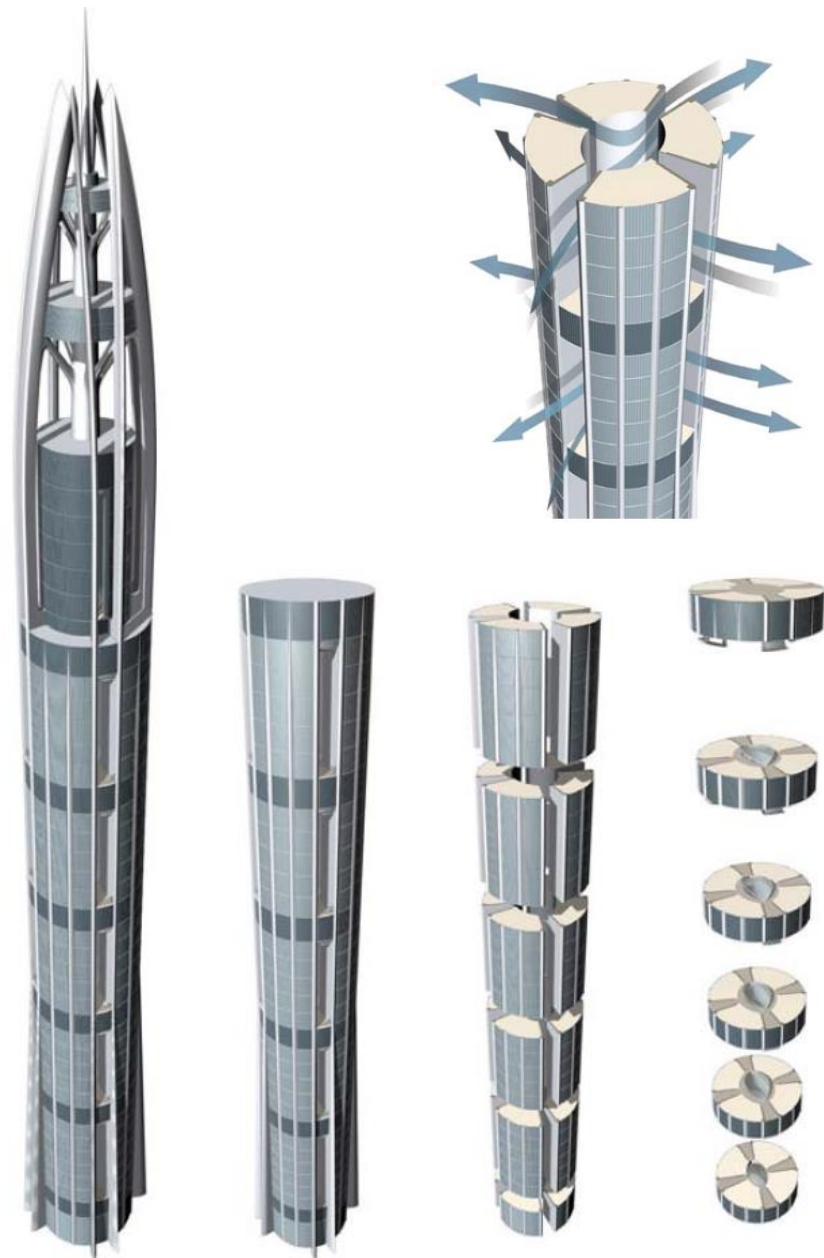


Figure 2.5: The figure shows the working mechanism of the tower [29].

The third example is the **Pearl River Tower** in China, Figure 2.6. The tower was designed and constructed to generate clean energy for itself and for the local power grids as well. Incorporating some of the latest green technologies, such as radiant slabs, solar panels, vented facades and geothermal heat sinks allow the building to be a completely environmentally friendly structure. As for its main function, along with the way it was designed, the building uses advanced technologies to direct wind into its body, channeling it through internal wind tunnels to generate huge amounts of clean energy [30].

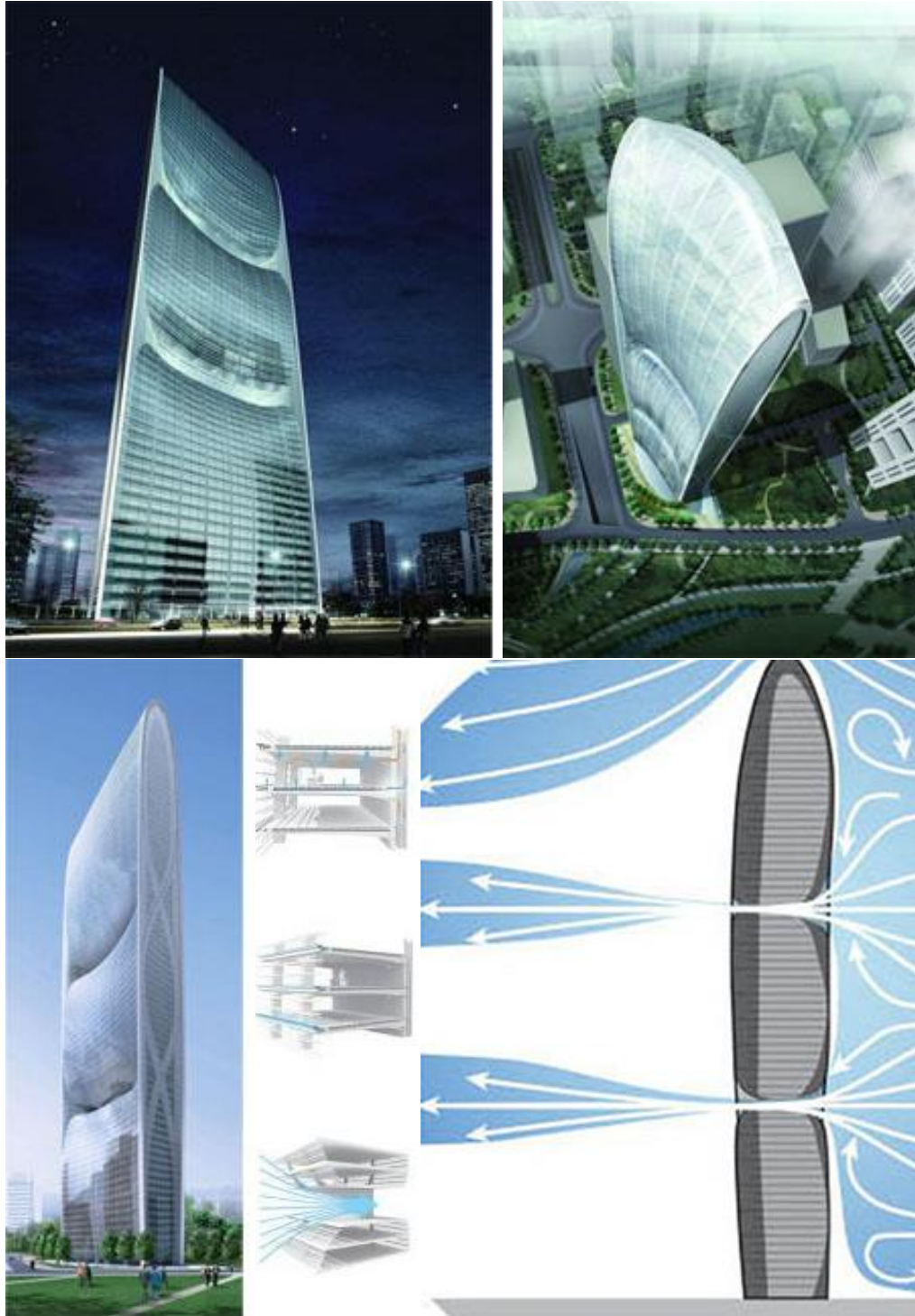


Figure 2.6: Pearl River Tower in China [30].

There are many other examples that integrate advanced technologies into buildings to fulfil sustainability requirements, such as the **Okhta Tower** in Russia, the **World Trade Center Towers** in Bahrain, the **Lighthouse Tower** in Dubai, and many others. Figures 2.7, 2.8 and 2.9 show these buildings.



Figure 2.7: Okhta Tower in Russia [31].



Figure 2.8: World Trade Center Towers in Bahrain [28].



Figure 2.9: Lighthouse Tower in Dubai [28].

**2.3.1.2. Resilience in intelligent buildings.** As can be seen from the previous section, when it comes to intelligent buildings it seems that the greatest focus is directed towards sustainability. Yet there seems to be some resilience implications in this field, where some contemporary studies have been trying to develop approaches that use automated diagnostic tools in an attempt to introduce fuzzy logic, neural networks, as well as other artificial intelligence-based technologies. Such technologies could be implemented through using control devices, sensors, and other building services' systems, in order to detect issues and problems that cannot be detected by human beings. For example, a research program that included many universities and research facilities conducted an extensive research on applying a Fault Detection and Diagnosis system or software for buildings' HVAC systems [26]. Therefore, it can be concluded that there are a significant number of attempts to develop monitoring and controlling methods and techniques in modern building management systems. Yet it is very rare to find a modern building that uses intelligent technologies for both meeting sustainability goals and at the same time preserving the complete functionality of the smart system or anticipating a future failure.

#### **2.4. Coupling Sustainability and Resilience**

Both of the terms “sustainability” and “resilience” seem to be dominating many research trends in different fields, such as civil infrastructure, buildings, urban drainage systems, landscape and urban planning. Yet it seems like there are only a few investigations into coupling the two terms in one methodology or approach, especially in intelligent buildings. And since this study will be focusing on quantifying and integrating both sustainability and resilience in smart buildings, a similar scope of studies was looked at. One of them was under the name of “Coupling and quantifying resilience and sustainability in facilities management”. This paper focused on studying the effects of losing buildings' cooling system functionality due to failure that happens when strong heat waves hit the building. A risk assessment model was used in order to measure and integrate both resilience and sustainability, where this model used two variables to quantify the incurred losses whenever the systems' functionality is lost. Those variables are cost and probability. In order to quantify the losses in terms of sustainability, its three dimensions - environmental, social and economic - were quantified separately. And for the sake of simplicity the social dimension was not quantified in this paper. As for resilience, it was measured by the amount of money lost

due to the decrease of employees' productivity whenever the cooling systems seemed to go down, starting from the moment the heat wave hit the building until those systems regained their full functionality. Then the quantified losses in terms of both sustainability and resilience were added to each other, to get the total losses quantified in a monetary value [14]. However, aside from ignoring the social aspect of sustainability as it could be hard to quantify it using a cost and a probability method and being specific with the type of failure quantified, the study was conducted on a regular building, not a smart one. As for the other study that was found, "Cost-benefit evaluation for building intelligent systems with special consideration on intangible benefits and energy consumption", this study's main focus was to evaluate the costs and benefits of the intelligent systems then perform a sensitivity analysis to assess the durability of the building's systems and decide whether these systems are worth investing in or not. Yet, nothing explicit about sustainability or resilience was mentioned in that study and the sensitivity analysis was based on a rough hypothetical assumption of an increased level of energy consumption. However, the evaluation method proposed in that study could be used to quantify both sustainability and resilience then tie them up together. In other words, in the process of performing the calculations, the research considered the tangible and the intangible costs and benefits of the intelligent building then used them to get the NPV. The tangible part of the calculations consisted of the future values of the energy cost saving, labour cost saving, fire insurance cost saving and the additional maintenance cost of the smart system. As for the intangible part of the calculations, it consisted of one future value that represented the benefits an intelligent building would bring. And that was measured using the Analytical Hierarchy Process (AHP) to give values to the intangible benefits, which were the increased work efficiency of the employees, the reduced service time, a better propagating effect, and an increased rental rate [32].

Therefore, using four smart buildings as case studies, a similar approach was used, where the three components of sustainability were quantified separately as annual values, constructing a framework that uses NPV to translate the environmental component into energy cost saving and some environmental incentives. Then translate the economic component into labour cost saving, fire insurance cost saving and the additional maintenance cost of the smart system. And finally translate the social component into the total annual savings that would result from having a better indoor

environment quality, higher productivity levels, better reputation, extra profit, and a higher level of services and safety. Then use the Relative Importance Index method (RII) to quantify the annual savings of this component, then converting all the annual costs and benefits into a single present value using the NPV method. However, the suggested framework did not focus on a specific type of failure as in the previous study, as it followed a general approach where the occurrence of any type of fault would affect the calculated NPV. Then it was suggested that implementing some tools/systems would add resilience to the smart systems of the building and the effect of such implementation on the calculated NPV was checked.

## 2.5. Benefits of the Integration

After studying “sustainability” and “resilience” in the context of intelligent buildings, numerous benefits could be counted from this integration. Yet a real validation was required to prove that this integration is beneficial in every aspect. In other words, intelligent buildings with sustainability and resilience implementations seem to provide convenient, highly efficient and a comfortable built environment. However, what happens when a flaw or fault eventually occurs? What kind of impact on the stakeholders might this have? How much would such a failure cost? And finally, the key question: “Is it worth investing in a sustainable / resilient intelligent building?”

All of these questions should be taken into consideration to be able to figure out if the advantages of this integration outweigh the disadvantages. Therefore, many studies that analyzed the effect of implementing smart technologies, sustainability and resilience on the total cost of the project were looked at and summarized in Table 2.1.

Table 2.1: Summary of literature about the relation between financial benefits and different implementations

Study type	References
Financial benefits due to implementing smart technologies	[33], [34], [35], [36], [37], [38], [39], [40]
Financial benefits due to implementing sustainable approaches	[34], [35], [36], [37], [38], [40], [41]
Financial benefits due to implementing smart and resilient technologies	[42], [43], [44], [45], [46]
Financial benefits due to implementing smart technologies and sustainable approaches and maintaining their resilience	[47], [32]

According to the studies found in Table 2.1, it can be concluded that almost all smart buildings are meant to be sustainable. In other words, integrating smart technologies into any building is usually meant to make that building more convenient, highly efficient, comfortable and even environmentally friendly, which means a sustainable building. Yet, only a very few number of studies tackled the four concepts all together; of them two are mentioned in the Table above. One of them consists of studies on smart resilient systems and the financial savings that would result from such integration [47], while the other one suggests a cost-benefit evaluation method for integrating smart systems into buildings, using LCA and NPV to determine if investing in those systems is worth it or not. Also, a sensitivity analysis was integrated in this study to check the effects of the increased energy consumption, which indicates the failure of the intelligent building systems on the NPV [32].

## **2.6. Attributes Quantification**

To formulate the model and to determine the values of the sustainability components variables that would help in performing the calculations, the data of costs and benefits of four smart buildings in Dubai was retrieved, some other data was extracted from a conducted survey and some was taken from other studies.

**2.6.1. Environmental attributes.** As mentioned in the literature review, sustainable approaches have been used widely in many intelligent buildings, varying from providing natural ventilation to natural lighting and so on. The utilization of these approaches seems to help reducing the total energy consumption of the building, knowing that HVAC, lighting and security systems account for almost half of the building total energy consumption [33]. However, Table 2.2 and the following points summarize the most common attributes used to measure the environmental component.

- **Energy expenditure:** According to some studies, buildings account for around 40% of the world's total energy consumption. As energy expenditures might vary by region or even by industry, the use of advanced emerging technologies in buildings has always been known for being a means to make them environmentally friendly and to control their energy consumption [48], [49].
- **Environmental Incentives:** Green buildings have been getting increasingly common in the last few years. Although, they could be

considered one of the most profitable and marketable type of investments, investors might be put off by the high initial upfront costs. Therefore, some governments have decided to encourage stakeholders by providing some incentives and deals that would motivate them to go for such investments. For example, the Dubai Electricity and Water Authority (DEWA) launched an initiative known as the Shams Dubai smart initiative. It encourages people to install photovoltaic panels on their rooftops, in order to provide their own electricity and to send the excess to DEWA's grid, where this surplus would be used to offset future electricity consumption. This way people would be counting on a renewable energy resource in their daily electricity consumption while at the same time making significant savings on their electricity bills. In order for people to be part of this initiative, DEWA provides a list of contractors and consultants that can help people throughout the entire procedure. The provided incentive could be represented in financial savings that can range from 10% to 30% due to being part of this initiative [50], [51], [52]. However, one research indicated that certified green buildings are eligible for 10% financial benefits [53]. Therefore, a 10% reduction in the energy consumption will be used in this study to account for the incentives provided in the UAE.

Table 2.2: Summary of literature on the quantified attributes of the environmental component.

Attribute	Reference
Energy expenditure	[48], [49], [24]
Environmental Incentives	[50], [51], [52], [53]

**2.6.2. Social attributes.** When it comes to quantifying the social costs of a structure or a system, many attributes could be considered. Such as, the functionality and usability of the created space that utilizes that system, the indoor environment quality and comfort, reputation (measured by the number of people coming to rent spaces in the building whether it is a residential or an office building), rate of

productivity of people working in the space (in case it is an office building), quality of services, profits coming from the exclusive rental rate, and market position. Nevertheless, almost all of the abovementioned attributes are difficult to measure. Therefore, the RII method was used to make that quantification more tangible. As for the first step to initiate the quantification process, some of the most used indices to quantify the social component are shown below, where a summary of each index and the list of references it was mentioned in can be found in Table 2.3.

- Productivity and indoor environment quality ( $I_1$ ) & ( $I_2$ ): Assuming that the building tackled in this study is an office building, using some simple smart technologies to optimize energy consumption and automate the inner adaptations, like sensors and actuators, would result in increasing the levels of comfort, satisfaction and productivity of the users [54]. For example, adjusting the lighting settings in an office according to the employees' needs could significantly improve their level of productivity, according to some studies [55]. And in the case of a residential building, the ability of the system to manipulate room temperature according to the human body temperature could be a good example of providing a high-quality indoor environment.
- Reputation and extra profit ( $I_3$ ) & ( $I_4$ ): As we are living in a world where advertising has a very great impact, having an intelligent system that provides the users with their dreams houses or offices could create a remarkable propagating effect. This in turn might lead to attracting more investors and even more tenants, resulting in a noticeable increase in the sale/rental income and guaranteeing an outstanding position in the market environment [32].
- Services and safety ( $I_5$ ) & ( $I_6$ ): The ability of some smart systems to use machine learning and be aware of the users' states and activities could be a game changer. And as humans seem to favor the use of any kind of technology that would save them time and effort, a smart building with such technology could be exactly the place they would want to live/work in. And as technology could be used in numerous ways, one example could be: Using Artificial Intelligence (AI) to better

the interaction between people and elevators, in such a way that would allow the elevator to be ready for the user once the smart system manages to sense when a person is leaving his/her apartment or even hotel room [56]. Therefore, it can be concluded that using smart systems would contribute in delivering services within a minimum amount of time compared to a normal building. Nevertheless, aside from having the best and fastest services, smart systems tend to provide a high-quality level of protection and safety. In other words, some intelligent buildings could be equipped with smart fire protection systems that manage the situation according to the type of building and the use of the spaces inside that building. For example, in buildings that do have computer rooms, gas suppression system will be used for the sake of protecting valuable assets. While other installed systems could evaluate the need to evacuate the floors in a systematic way by turning the fire alarm on gradually, showing adaptive escape routes on mobile devices or even evaluate the necessity of deploying fire services [57]. Nevertheless, safety could also be measured with the security level of the building, systematic maintenance that results from smart systems intervention and prevention mechanisms, and others. Figures 2.10 and 2.11 illustrate the way smart buildings use machine learning to provide better services and improve the level of safety [58].

Table 2.3: Summary of literature on the used Indices to quantify the social component.

<b>Indices</b>	<b>Reference</b>
Productivity and indoor environment quality	[40], [54], [55], [59], [60], [61]
Reputation and the extra profit	[40], [32], [62]
Services and safety	[56], [57], [58], [63]

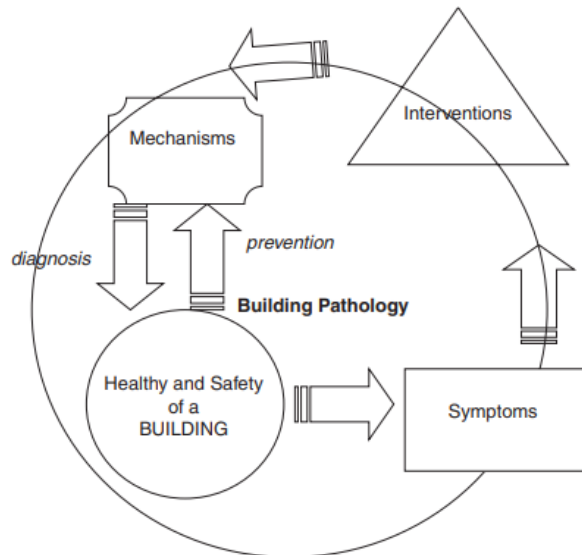


Figure 2.10: A smart building maintenance system [58].

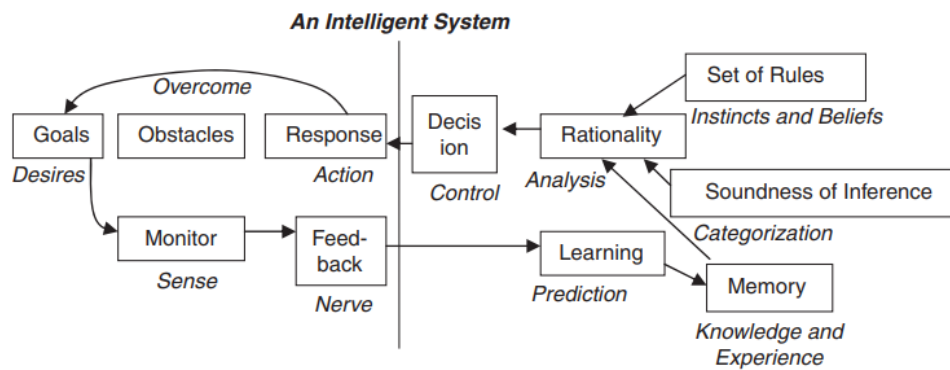


Figure 2.11: A smart building learning model for safety and better services [58].

**3.4.3. Economic attributes.** Quantifying the economic cost is probably the easiest one of them all, since it is already expressed in monetary value. Yet, similar to the other two dimensions of sustainability, there are many attributes that could be used to quantify this dimension. For example, the whole life value of the structure, adaptability and flexibility of the system, property performance assessment, maintenance, fire insurance and the number of workers [2], [32], [60]. Nevertheless, not all of the abovementioned attributes can be measured, nor related to this study. Therefore, Table 2.4 and the following points summarize the most common attributes used to measure the economic component.

- **Maintenance:** It is considered the first and the most direct cost incurred, especially when it comes to using a new advanced technology. And that

is due to the differences between the intelligent buildings maintenance systems and the un-intelligent buildings ones. For example, intelligent systems should be adaptive to dynamic environmental changes which cannot be attained without using a learning algorithm that would eliminate the reliance on external manual interventions by humans. Thus, their maintenance system shall be as smart to monitor, control, respond, record, compare and learn the best ways to keep this smart system working perfectly with extremely low chances of failure. Whereas having such a maintenance system would add an additional cost comparing to any normal one [58].

- Fire insurance: As smart buildings tend to have advanced technologies to manage disasters and provide emergency services, their fire protection systems seem to be designed to mitigate or even eliminate the effects of any fire outbreak. For example, in the case of a fire, some smart buildings are usually equipped with alerting systems that provide building users with information about the fire location, the severity of the fire and the best escape route [57], while other systems are programmed to deal with a fire outbreak according to that outbreak location in the building. In other words, if the fire occurs in a server room or even in an office space then fire suppression systems will be initiated in order to stop the fire from spreading without damaging the valuable assets [64]. Therefore, when it comes to insuring smart buildings against fire incidents, it seems like using the fire automation systems tend to reduce the fire insurance cost [32].
- Number of workers: The utilization of building automation is generally used as a means to contain and reduce the reliability on human labour. This does not mean a complete elimination of human intervention, but a limited level of intervention. In other words, it means reducing the number of workers needed when it comes to building management, services, maintenance and any other operations [32], [65], [66], [67].

Table 2.4: Summary of literature on the quantified attributes of the economic component.

<b>Attribute</b>	<b>Reference</b>
Maintenance	[58], [68], [69], [70]
Fire insurance	[32], [57], [64]
Number of workers	[32], [65], [66], [67]

## **Chapter 3. Methodology**

This chapter will be about applying the previously discussed literature, about coupling resilience and sustainability and quantifying them with reference to some of the world's modern intelligent buildings. The methodology will be further discussed and the steps of the suggested model will be elaborated.

### **3.1. Research Problem**

As mentioned in the previous chapter, investing in a sustainable or a resilient building might have great financial benefits. Yet, the integration of the two would even result in greater benefits. However, after extensive research was conducted it was found that some studies managed to quantify the sustainability and resilience of smart buildings separately. But the process of quantifying and coupling both for smart buildings in one financial model was the missing connection. One of the studies that was used as a starting point for this study managed to evaluate the costs and benefits of the intelligent systems then performed a sensitivity analysis in an attempt to assess the durability of the building's systems. However, the sensitivity analysis was based on a rough hypothetical assumption of an increased level of energy consumption, which was considered an indication of the failure of the smart building systems [32]. Whereas the other study managed to couple sustainability and resilience successfully, focusing on the concept of functionality loss to quantify resilience. Yet, the study was conducted on a regular building, not a smart one, and was focused on a specific type of failure which was a cooling system failure [14].

Therefore, the concept of functionality loss or the resulting fault cost was used to quantify the general resilience of the smart building systems. The cost-benefit evaluation method was used to measure the sustainability of the smart systems then coupled with these systems' resilience. This created a framework that develops a realistic financial model where the net present value was used as the main tool to analyze the actual data of four smart buildings in Dubai. Two of the four buildings were residential buildings, one was an office building, and one was a labor camp. Using the four buildings as case studies, the first part of the analysis was about quantifying sustainability, where it was reduced into its three main components: Environmental, Social and Economic. And in order to be able to quantify sustainability, its three

components had to be quantified. For the environmental component, the reduced energy expenditure and the government environmental incentives were used to perform the calculations. For the economic component, the workers cost saving, fire insurance cost saving, and system maintenance additional costs were used to perform the calculations. As for the social component of sustainability, it measured some attributes that were hard to quantify, such as productivity, indoor environment quality, reputation, extra profit, services and safety. However, in order to be able to quantify them, a survey was conducted and the RII method was used. The survey was sent to 15 people: project managers, architects, engineers, and academics who were familiar with the use of intelligent systems in buildings. Yet, only 10 out of the 15 managed to take the survey. The responses were used to rank the 6 social attributes, weight them and eventually get the social benefit coefficient. Then the social component was calculated by multiplying the social benefit coefficient by the rental profit of the building. Using the results of the three components, the net annual savings were calculated, then used alongside with the capital investment of the smart system to get the NPV. However, it would have been very beneficial having a baseline or a benchmark for the NPV of the smart buildings, but no literature was found in this regard.

As for the resilience part of the analysis, resilience was quantified and coupled with sustainability by measuring the effect of having faults on the calculated NPV and by observing how much the NPV would drop when faults occur in these buildings. In order to do that the following information should be available: the number of faults occurring annually in a smart system, the incurred losses due to having these faults, the cost of fixing these faults and how long would it take to fix them. However, it was somewhat challenging to have access to such data. Therefore, in order to demonstrate an example of what the ideal calculations of the model could look like, some literature review articles and studies were used to get a rough estimation for these numbers. The retrieved data included: the number of faults occurring yearly in smart buildings, the cost of these faults and the initial cost of having fault detection and diagnosis tools. However, using this information won't give accurate results as it is not dependent on the number of floors in the building, assumes a fixed number of faults, and considers a fixed cost from within the range of costs. Therefore, a better approach to get an estimation for the fault cost was using a percentage that tied up to the total energy consumption of the building. Which means that each one of the four buildings (case

studies) had a different fault cost, according to the building energy expenditure. Using the PERT (Program Evaluation and Review Technique) model, three scenarios were assumed: a pessimistic scenario, an optimistic scenario and a most likely scenario. Where those scenarios were used to test the effects of having different fault costs (low, average and high) on the NPV. Exploring the financial effects of integrating resilience tools within the smart systems of sustainable buildings. Figure 3.1 represents an overview of the methodology.

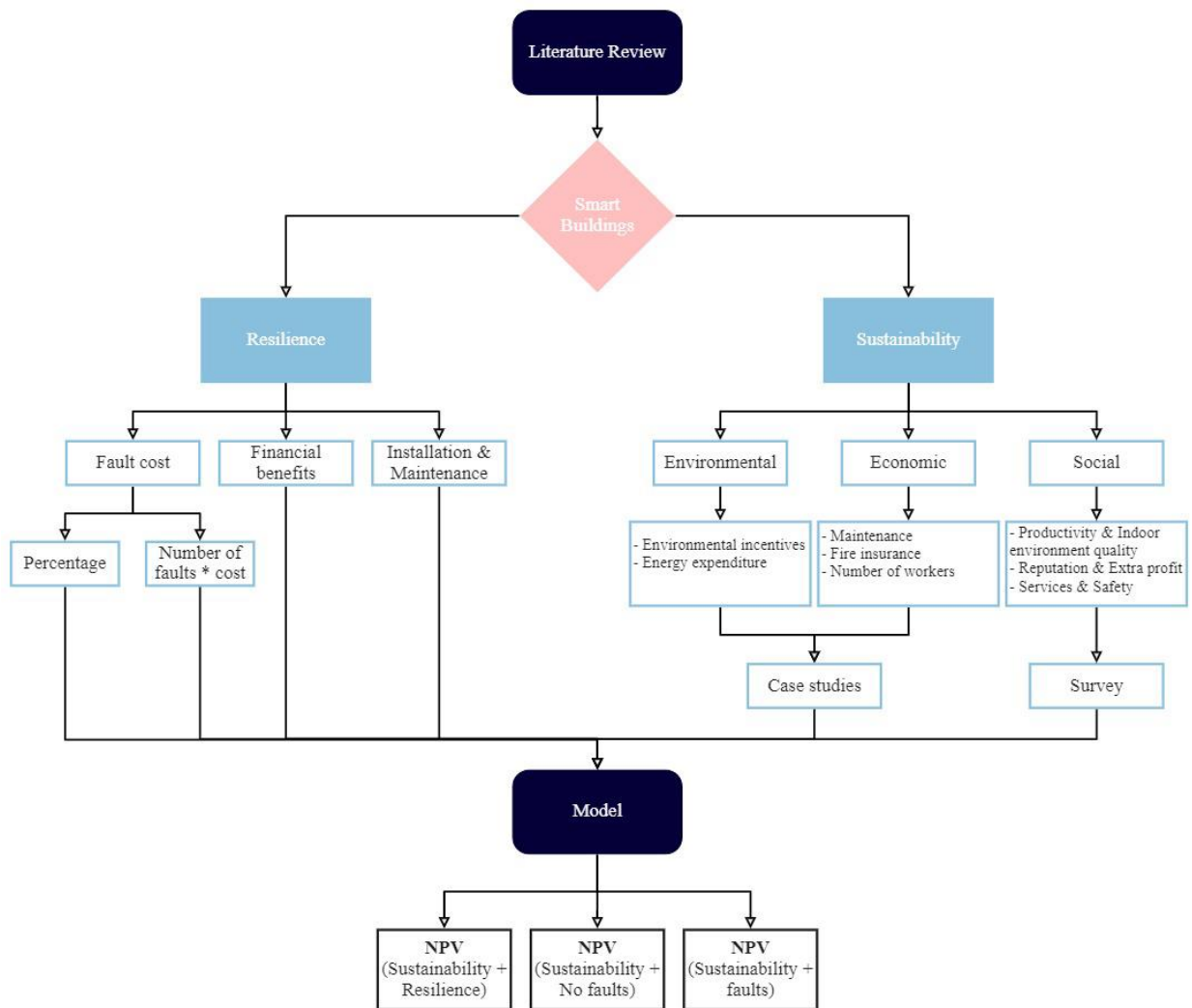


Figure 3.1: Methodology flowchart.

### **3.2. Study Scope**

An overall expanded system was taken into consideration when conducting the analysis, focusing not only on the standing building but also on whatever and whomever interacts with it. For instance, the suggested model considered people interacting with the building, such as owners, project managers, designers, inhabitants and visitors. It also considered the products used to create the smart building such as equipment, facilities and services, as well as the processes used to keep it running such as monitoring and controlling, performance evaluation, automation, system installation and maintenance [2]. Thus, as mentioned in the literature review, only certain attributes of smart systems' sustainability were considered, and more details can be found in the following sections.

### **3.3. The NPV Method**

Referring to the previously mentioned study, “Cost-benefit evaluation for building intelligent systems with special consideration on intangible benefits and energy consumption”, the study used the LCA-NPV method to analyze the cash flows during the lifespan of the intelligent building to make sure that integrating its smart systems is worth investing in [32]. Not to mention the wide use of LCA and NPV in projects, where the first would be used to get a general evaluation for the costs and payback of any project, while the latter would be used to get a more accurate analysis for costs and benefits, converting them into an equivalent present value that could be positive or negative [12], [13]. Therefore, in order to get a better understanding of the cash flow over a certain period of time in a smart building, the NPV method was the better option to use. After identifying the attributes needed to perform the calculations in the literature review, the following section will list all the equations used to quantify them.

### **3.4. Model Formulation**

The concept of coupling and quantifying resilience and sustainability as well as the NPV method were both used to evaluate whether it is worth combining smart systems, sustainability and resilience in one building.

As concluded earlier, utilizing smart systems in buildings makes them sustainable, leading to the first integration or combination that was tackled in this study.

## Smart systems + Building = Sustainability

$$\text{Sustainability} = \text{Environmental} + \text{Social} + \text{Economic}$$

In order to perform such calculations, the following equations were used:

$$NPV = A_{net} \left[ \frac{(1+i)^N - 1}{i(1+i)^N} \right] - C_0 \quad (3)$$

$$A_{net} = \underbrace{A_i + A_e}_{\text{Environmental}} + \underbrace{A_w + A_f - A_m}_{\text{Economic}} + \underbrace{A_s}_{\text{Social}} \quad (4)$$

Where in equation (3),  $A_{net}$  is the net annual savings that could be obtained by installing a smart system in a building and  $C_0$  is the initial cost of the smart system installation.  $N$  is the number of years (time horizon) used in the analysis, a 10-year study period was used in this study [32], [71], [72]. While  $i$  is the discount rate in the UAE, which is 2.25% [73]. As for equation (4), it consists of three parts which are the three aspects of sustainability. The environmental aspect was quantified by  $A_i$  representing some possible given incentives or financial discounts that could be given by the government, and  $A_e$  representing the cost saving from optimizing energy levels. The economic aspect was quantified by  $A_w$  which represents the cost saving that results from reducing the number of workers,  $A_f$  representing the cost saving that results from not having fire insurance, and  $A_m$  which was an added cost that represents the maintenance cost of the smart system. As for the social aspect, it was quantified by  $A_s$  representing the cost saving due to some intangible benefits. However, after retrieving the data of the four smart buildings, the environmental and the economic calculations were easily done. As for the social calculations and the resilience part, further data had to be collected. Therefore, the following two sections of this chapter will be dedicated to explaining the processes used to get the data of both the social component of sustainability and the resilience part.

**3.4.1. Survey development.** After identifying the used indices to quantify the social component of sustainability, a survey was conducted in order to get two values. The first was the evaluating scores ( $E$ ) of the indices, while the second was the weights of those indices ( $W$ ). In order to find the proportion ( $\delta$ ) of the total profit ( $P$ ) that represents the social benefits ( $A_s$ ), equations (5) and (6) were used [32]:

$$\delta = WE \quad (5)$$

$$A_s = \delta P \quad (6)$$

To put it more simply, as the weights of the selected criteria were multiplied by the evaluating scores, the social benefit coefficient ( $\delta$ ) was achieved. Where the social benefit coefficient represents the percentage or proportion of the profit or rental income that was attained by the social aspect of sustainability (social benefits). Therefore, in equation (6), the coefficient ( $\delta$ ) is multiplied by the total profit ( $P$ ). The survey was sent to 15 people, those were project managers, architects, engineers and academics who are familiar with the use of intelligent systems in buildings, making sure that the indices were evaluated based on different perspectives. However, only 10 out of the 15 managed to take the survey. The two following sections contain further explanations of the structure of the survey and the way it was built. The full survey can be found in appendix A, and a summary of the survey results can be found in appendix B.

**3.4.1.1. Indices quantification.** As mentioned before, a survey was conducted in order to evaluate each of the selected indices and determine their weights, where three questions were asked about each index. As for this part of the study, the respondents were asked two questions about each index. The first one was if they approve that the selected index is appropriate for the study or not, while the second one was to what extent they think that having smart systems would improve that index compared to not having smart systems. Also, one small example was provided along with the first question, in order to make the idea clearer to the respondents. Taking the improved indoor environment quality as an example, the respondents were asked if “installing smart systems in buildings would improve the indoor environment quality and make users more comfortable practicing their daily activities”. And the simple explanatory example was automatic lighting / temperature adjustment. The respondents were given three options to choose from “Yes, No and Irrelevant” [32]. Then the following question would be directed to the respondents for which the answer was “Yes” for the first question, asking them to “To what extent do you think having smart systems would improve the indoor environment quality compared to not having smart

systems?” and providing them with four options to choose from “High, Relatively high, Moderate and Low” [32]. Thereafter, a scoring system was assigned to the previous scales, using ratios that would reflect the level of contribution of each index in the total profit. Thus, after using the results of the survey each index shall have an evaluating value  $E_j$  ( $j = 1,2,3,4,5,6$ ), which eventually forms the evaluating vector  $E = [E_1, E_2, E_3, E_4, E_5, E_6]$  used in equation (5). The assigned scoring system used in this part of the study was 20% for High, 15% for Relatively High, 10% for Moderate and 5% for Low [32].

**3.4.1.2. Indices weights.** As for this part of the study, the answers of the third question about each index are the ones to be used to get the weights of the indices. Where respondents were asked “In your opinion, how important do you think this index (For example, indoor environment quality) is to quantify the social benefits of sustainability?”, then given five answers to choose from: “Extremely important, Very important, Somewhat important, Not so important, and Not important at all” [32]. Using the respondents’ answers and the RII to weight and rank the indices, a 1 to 5 rating system was used. In other words, each one of the previously mentioned answers was given a weight, where 5 is the weight of the “Extremely important” answer and 1 is the weight of the “Not important at all” answer (Table 3.1). Those weights were multiplied by the number of people choosing each answer, as in equations (7) and (8) [74].

Table 3.1: The assigned weights for the 5-point Likert scale used.

Extremely important	5
Very important	4
Somewhat important	3
Not so important	2
Not at all important	1

$$RII = \frac{\sum W}{AN} \quad (7)$$

$$\sum W = 5n_5 + 4n_4 + 3n_3 + 2n_2 + 1n_1 \quad (8)$$

Where  $\sum W$  is the summation of each weight multiplied by the number of answers (frequency) for each index  $n_i$  where  $i$  ranges from 5 to 1.  $A$  is the highest weight in the used Likert scale, which is 5, and  $N$  is the total number of respondents, which is 10 in this study. Obtaining the RII for each index indicates the rank of this index in terms of importance among the other ones, nevertheless it does not reflect the weight of that index. Therefore, in order to get the weights that correspond with the ranks of these indices, three non-pairwise weighting methods were used: rank sum, rank reciprocal and rank exponential [74].

- **Rank sum method:** In this method the weights of the indices are elicited by dividing the inverse rank value by the summation of all the ranking values, as in equation (9) [75].

$$W_j = \frac{n - r_j + 1}{\sum_{j=1}^n (n - r_j + 1)} \quad (9)$$

- **Reciprocal rank method:** In this method the weights of the indices are elicited by dividing the reciprocal of each rank by the summation of all reciprocal values, as in equation (10) [75].

$$W_j = \frac{1/r_j}{\sum_{j=1}^n (1/r_j)} \quad (10)$$

- **Rank exponent method:** This method is exactly similar to the rank sum method, yet the only difference is that this method allows for more separation between the weighted values. And that is by allowing the individual ranking values to increase exponentially then dividing them by the summation of all the exponential values, equation (11) [75].

$$W_j = \frac{(n - r_j + 1)^P}{\sum_{j=1}^n (n - r_j + 1)^P} \quad (11)$$

**3.4.2. Resilience.** As demonstrated in the literature review section, resilience measures the ability of a structure, building or even a system to resist failure and to maintain the same level of functionality, and in this study the concept of resilience is paired with the smart systems. In other words, the resilience measured in this study is

the smart systems resilience, where the damage that can hit those smart systems if not fixed immediately or even detected prior to its occurrence can cause a lot of losses. And after defining smart buildings as being sustainable buildings, this study aims to measure the resilience of those smart / sustainable systems. However, since having smart and sustainable systems might come with great complexity, it is very important to make sure that adding another system for resilience won't be counterproductive. Therefore, the effect of having faults on the calculated NPV of the sustainability part was studied, observing how much the NPV would drop when faults occur in these buildings. In an ideal world, where we get to have access to smart buildings data, the information that could be used to make the perfect model would be: The number of faults occurring annually in a smart system, the incurred losses due to having these faults, the cost of fixing these faults and how long would it take to fix them. However, it could be a bit challenging to have access to such data. Therefore, in order to demonstrate an example of what the ideal calculations of the model could look like, some literature review articles and studies were used to get a rough estimation for these numbers. The retrieved data included: the number of faults occurring yearly in smart buildings, the cost of these faults and the cost and benefit of having fault detection and diagnosis tools. According to a paper on fault detection and diagnostics for smart buildings, a substantial amount of energy is wasted due to faulty and wrongly configured smart systems equipment, including the fault detection ones [43]. Some examples are: faulty sensors, wrongly positioned sensors and actuators, stuck equipment, mis-scheduled operations and many others [76]. Therefore, it is very important to equip Fault Detection and Diagnosis (FDD) tools in Building Management Systems (BMS), as it contributes to saving around 15-30% of the total energy expenditure of the building, reducing its total operational cost [44]. Whereas nothing was discussed in the literature about the operational cost of the FDD system itself. However, deploying an FDD system could cost around 10% of the total energy expenditure in the first year and might require around \$50,000 for annual maintenance and monitoring, which is equivalent to a 180,000 AED a year [46], [77].CGnal, a software firm based in Milan, conducted a one-year study on a building in Italy. Where sensors were implanted into the different systems of the building, and a machine learning algorithm was used to take the readings for the first half of 2015. As for the second half of the year, the installed system started picking up data for abnormalities, which resulted in predicting 76 faults out of a total

of 124 real faults. Therefore, using the predicted number of faults throughout the 6 months duration, a  $(76 \times 2 \approx 150)$  potential faults per year shall be used for the sake of this study [78], then the number was rationalized in order to be used for the different types of buildings. As for the cost of single faults, it was estimated to range between \$130 and \$16,000, which is equivalent to 500 and 59,000 AED [76]. For the sake of simplicity, a single fault shall be assumed to cost 5000 AED a year. However, using this method won't give accurate results as it is not dependent on the number of floors in the building, assuming a fixed number of faults and considers a fixed cost from within the range of costs found in the literature. Therefore, a better approach to get an estimation for the fault cost was using a percentage that would tie up to the total energy consumption of the building. According to some studies, degraded and faulty equipment would contribute to a 15% to 30% waste of the building's energy [79], [80], [81]. This means that each one of the four buildings (case studies) will have a different fault cost, according to the building energy expenditure. Using the PERT (Program Evaluation and Review Technique) model, three scenarios were considered:

- A pessimistic scenario (P): Fault cost = 30% waste of the total energy.
- An optimistic scenario (O): Fault cost = 15% waste of the total energy.
- A most likely scenario (M): Fault cost = 20% waste of the total energy [82].

Then those three values were used to calculate the weighted average using equation (12) [83]:

$$PERT \text{ weighted average} = \frac{O + 4M + P}{6} \quad (12)$$

However, the equations used to perform the calculations of this section and to couple both sustainably and resilience are an expansion of equations (3) and (4).

$$NPV_{with \ faults} = A_{net,with \ faults} \left[ \frac{(1+i)^N - 1}{i(1+i)^N} \right] - C_0 \quad (13)$$

$$A_{net,with\ faults} = \underbrace{A_i + A_e + A_w + A_f - A_m + A_s}_{\text{Sustainability only}} - \underbrace{A_{fc}}_{\text{No Resilience}} \quad (14)$$

To calculate the new NPV that would result from not integrating resilience with sustainability, equations (13) and (14) were used, where  $A_{fc}$  represents the annual fault cost. As for the last part of the analysis, equations (15) and (16) were used to calculate the new NPV that would result after integrating resilience tools within the smart systems of the sustainable building. The calculations of this part were done twice, once without considering the potential energy saving that the resilience tools might provide (Part A) and another time considering the potential energy saving (Part B).

$$NPV_{s,r} = A_{net,s,r} \left[ \frac{(1+i)^N - 1}{i(1+i)^N} \right] - C_{0,s} - C_{0,r} \quad (15)$$

$$A_{net,s,r} = \underbrace{A_i + A_e + A_w + A_f - A_m + A_s}_{\text{Sustainability}} - \underbrace{A_{m,r} + A_{e,r}}_{\text{Resilience}} \quad (16)$$

$NPV_{s,r}$  : is the calculated NPV after coupling sustainability and resilience.

$A_{net,s,r}$  : is the net annual savings after coupling sustainability and resilience.

$i$  : is the discount rate.

$N$  : is the time horizon.

$C_{0,s}$  : is the initial cost of installing the smart system.

$C_{0,r}$  : is the initial cost of installing resilience tools.

$A_i$  : is the environmental incentive.

$A_e$  : is the energy cost saving.

$A_w$  : is the workers cost saving.

$A_f$  : is the fire insurance cost saving.

$A_m$  : is the smart system maintenance cost.

$A_s$  : is the social savings.

$A_{m,r}$  : is the maintenance cost of the used resilience tools

$A_{e,r}$  : is the energy saving that would result from using the resilience tools.

## Chapter 4. Results and Analysis

In this chapter, the calculations used in the model will be presented and a thorough analysis of the results will be conducted, in order to get to the ultimate conclusion of the importance of coupling sustainability and resilience in smart buildings.

### 4.1. Sustainability Calculations

After formulating the model, gathering all the information needed and quantifying the used attributes, the model was applied on four smart buildings in Dubai, to test the feasibility of the concept of coupling sustainability and resilience in smart buildings. Table 4.1 demonstrates the data used to perform the calculations of the model.

Table 4.1: Cost and benefit analysis for four smart buildings in Dubai.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
$A_i$	Environmental incentives (AED/Year)	435,500	318,000	226,000	945,000
$A_e$	Energy cost saving (AED/Year)	116,250	51,800	26,200	128,250
$A_w$	Workers cost saving (AED/Year)	42,000	14,500	18,000	51,300
$A_f$	Fire insurance cost saving (AED/Year)	6,500	3,750	8,900	9,000
$A_m$	System maintenance cost (AED/Year)	60,000	30,000	50,250	72,000
$P$	Rental profit (AED/Year)	10,575,000	3,950,000	15,000,000	20,900,000
$\delta$	Social benefit coefficient	0.17	0.17	0.17	0.17
$A_s$	Social savings (AED/Year)	1,797,750	671,500	2,550,000	3,553,000
$A_{net}$	<b>Net annual savings (AED/Year)</b>	<b>2,338,000</b>	<b>1,029,550</b>	<b>2,778,850</b>	<b>4,614,550</b>
$C_0$	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000

N 10 i 2.25% Environmental savings Economic savings Social savings

The buildings used in this study were: a high-rise residential building, a low-rise residential building, a labor camp, and a high-rise office building. The case of the high-rise residential building will be used to clarify the steps of the calculations performed in this model, as the same calculations were applied to the other three buildings.

**4.1.1. Environmental aspect calculations.** For this part of the analysis, the total energy expenditure cost was provided alongside the energy cost savings due to

using smart systems. As for the environmental incentives, as mentioned in section 2.6.1, a 10% reduction in the energy consumption was used to account for the benefits provided by Dubai government, which results in a 435,500 AED savings.

**4.1.2. Social aspect calculations.** The social aspect of sustainability was the hardest to quantify, as it depends on the preferences of people to quantify some attributes that are hard to measure. As mentioned in section 2.6.2, in order to quantify this aspect of sustainability, the evaluating values and the weights of the 6 selected indices were calculated using a survey, RII, a non-pairwise weighting method and the mentioned equations in that section. First, two of the survey questions were used to get the evaluating vector of the 6 indices  $E = [0.16, 0.17, 0.17, 0.15, 0.19, 0.17]$ , Table 4.2. For example, for the productivity index, the numbers 4, 3, 3 and 0 represent the number of people who chose the contribution level of smart systems in improving productivity to be high, relatively high, moderate or low. Each one of those numbers was multiplied by the assigned weight and then the results were summed to get the evaluating score.

Table 4.2: Indices quantification.

		High (0.20)	Relatively high (0.15)	Moderate (0.10)	Low (0.05)	Evaluating score ( $E_j$ )
$I_1$	Productivity	4	3	3	0	0.16
$I_2$	Indoor environment quality	6	2	1	1	0.17
$I_3$	Reputation	6	2	1	1	0.17
$I_4$	Extra Profit	3	5	1	1	0.15
$I_5$	Services	7	3	0	0	0.19
$I_6$	Safety	8	0	0	2	0.17

N	10
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Second, one of the survey questions, the RII method and three non-pairwise weighting methods were used to determine the weights of the 6 indices, Tables 4.3 and 4.4. Using the RII method allowed for identifying the direct rank of each one of the 6 indices, while using the Rank sum, Reciprocal rank and Rank exponent methods allowed for converting the direct ranks into weights. However, the steps used to perform this part of the calculations were mentioned in section 3.4.1.2.

Table 4.3: RII calculations.

		Frequency of "5"	Frequency of "4"	Frequency of "3"	Frequency of "2"	Frequency of "1"	Weighted sum ( $\sum w$ )	RII
$I_1$	Productivity	4	4	2	0	0	42	0.84
$I_2$	Indoor environment quality	3	5	1	1	0	40	0.80
$I_3$	Reputation	5	0	3	1	1	37	0.74
$I_4$	Extra Profit	4	3	2	1	0	40	0.80
$I_5$	Services	4	4	2	0	0	42	0.84
$I_6$	Safety	6	1	1	2	0	41	0.82

A	5
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N	10
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Table 4.4: The three used non-pairwise weighting methods.

		RII	Rank	Rank Sum		Reciprocal Rank		Rank Exponent	
				$n - r_j + 1$	$W_j$	$1/r_j$	$W_j$	$(n - r_j + 1)^p$	$W_j$
$I_1$	Productivity	0.84	1	6	0.29	1.00	0.41	36	0.40
$I_5$	Services	0.84	2	5	0.24	0.50	0.20	25	0.27
$I_6$	Safety	0.82	3	4	0.19	0.33	0.14	16	0.18
$I_2$	Indoor environment quality	0.80	4	3	0.14	0.25	0.10	9	0.10
$I_4$	Extra Profit	0.80	5	2	0.10	0.20	0.08	4	0.04
$I_3$	Reputation	0.74	6	1	0.05	0.17	0.07	1	0.01
	Sum			21		2.45		91	

As Table 4.4 demonstrates, three different methods to get the weights of the indices and the results of the reciprocal rank method were used in this study. And that is because this method has the highest weights, while rank exponent and rank sum comes second and third [84]. Therefore, the weight vector and the evaluating score vector, after ranking the 6 indices, are  $W = [0.41, 0.20, 0.14, 0.10, 0.08, 0.07]$  and  $E = [0.16, 0.19, 0.17, 0.17, 0.15, 0.17]$ , Table 4.5.

Table 4.5: Social benefit coefficient.

		$W_j$	$E_j$	$\delta$
$I_1$	Productivity	0.41	0.16	0.07
$I_5$	Services	0.20	0.19	0.04
$I_6$	Safety	0.14	0.17	0.02
$I_2$	Indoor environment quality	0.10	0.17	0.02
$I_4$	Extra Profit	0.08	0.15	0.01
$I_3$	Reputation	0.07	0.17	0.01
				<b>0.17</b>

For the case of the high-rise residential building, using equations (5) and (6), the social benefit was calculated by multiplying the social benefit coefficient (0.17) by

the rental profit of the building (10,575,000 AED), to get a 1,797,750 AED worth of savings. The social savings of the other three buildings were calculated the same way.

**4.1.3. Economic aspect calculations.** For the economic aspect of sustainability, all of the values required to perform its calculations were provided. And those included the workers cost savings, fire insurance cost saving and an additional maintenance cost for the smart systems, as can be seen in Table 4.6.

Thereafter, equation (4) was used to get the net annual savings, while equation (3) was used to convert these annual savings and the initial cost into a net present value.

Table 4.6: The results of the cost and benefit analysis.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
$A_i$	Environmental incentives (AED/Year)	435,500	318,000	226,000	945,000
$A_e$	Energy cost saving (AED/Year)	116,250	51,800	26,200	128,250
$A_w$	Workers cost saving (AED/Year)	42,000	14,500	18,000	51,300
$A_f$	Fire insurance cost saving (AED/Year)	6,500	3,750	8,900	9,000
$A_m$	System maintenance cost (AED/Year)	60,000	30,000	50,250	72,000
$P$	Rental profit (AED/Year)	10,575,000	3,950,000	15,000,000	20,900,000
$\delta$	Social benefit coefficient	0.17	0.17	0.17	0.17
$A_s$	Social savings (AED/Year)	1,797,750	671,500	2,550,000	3,553,000
$A_{net}$	<b>Net annual savings (AED/Year)</b>	<b>2,338,000</b>	<b>1,029,550</b>	<b>2,778,850</b>	<b>4,614,550</b>
$C_0$	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	<b>NPV per unit floor area (AED/m<sup>2</sup>)</b>	<b>20,789</b>	<b>12,504</b>	<b>18,032</b>	<b>32,388</b>

N 10 i 2.25% Environmental savings Economic savings Social savings

According to Table 4.6, the NPV for the four buildings seem to be a positive value, which means that the smart systems are worth investing in. The high-rise office building seems to have the highest NPV and that is due to the high floor numbers and the floor area. However, the labor camp has a very high NPV due to its spacious floors and the high rental profit of the building. This indicates the impact of smart systems in the case of having high-rise buildings or even low-rise buildings with a high floor area.

## 4.2. Resilience Calculations

After performing the calculations to get the NPV in the case of having the smart systems working properly, in order to compare the results and study the importance of

maintaining these systems' resilience, Table 4.7 was constructed. Using the high-rise residential building case, the Table below demonstrates the difference between four NPVs, where the first one is the NPV obtained considering all systems working properly with no interruptions and is equal to 19,749,214 AED. While for the second part, in order to get a more realistic NPV, a rough estimation of 150 faults yearly with a cost of 5000 AED each was assumed. Then those two numbers were multiplied, and the result was substituted in equation (13), to have a new NPV that is equal to 13,099,552 AED. As for the third part of the Table, a scenario where FDD tools were equipped was assumed, the initial installation cost for such systems would be around 10% of the total energy expenditure of the building, and in this case it would be 435,500 AED. In addition, such systems might require an additional 180,000 AED yearly for maintenance. However, this part of the Table consists of parts A and B, where part A considers the initial cost and the maintenance cost of the added system, while part B considers the same costs but assumes an added benefit, which is a 15% saving in the total energy expenditure once implementing the FDD system. Therefore, using equations (14) and (15) the NPV for part A is 17,717,795 AED and for part B is 23,509,651 AED.

Table 4.7: Testing for smart systems resilience using hypothetical data.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Number of faults	150	20	30	200
	Cost of a single fault (AED)	5,000	5,000	5,000	5,000
	Fault cost (AED)	750,000	100,000	150,000	1,000,000
	Net annual savings (AED/Year)	1,588,000	929,550	2,628,850	3,614,550
	<b>NPV (AED)</b>	<b>13,099,552</b>	<b>8,116,591</b>	<b>23,012,953</b>	<b>30,647,382</b>
With FDD	NPV per unit floor area (AED/m <sup>2</sup> )	13,789	11,273	17,047	25,121
	Initial cost of FDD system (AED)	435,500	318,000	226,000	945,000
	Maintenance (AED/Year)	180,000	180,000	180,000	180,000
	Net annual savings (AED/Year)	2,158,000	849,550	2,598,850	4,434,550
	<b>NPV (AED)</b>	<b>17,717,795</b>	<b>7,089,294</b>	<b>22,520,966</b>	<b>36,972,680</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	18,650	9,846	16,682	30,305
	Energy savings (AED/Year)	653,250	477,000	339,000	1,417,500
	Net annual savings (AED/Year)	2,811,250	1,326,550	2,937,850	5,852,050
	<b>NPV (AED)</b>	<b>23,509,651</b>	<b>11,318,479</b>	<b>25,526,614</b>	<b>49,540,541</b>
NPV per unit floor area (AED/m <sup>2</sup> )	24,747	15,720	18,909	40,607	

N	10	i	2.25%
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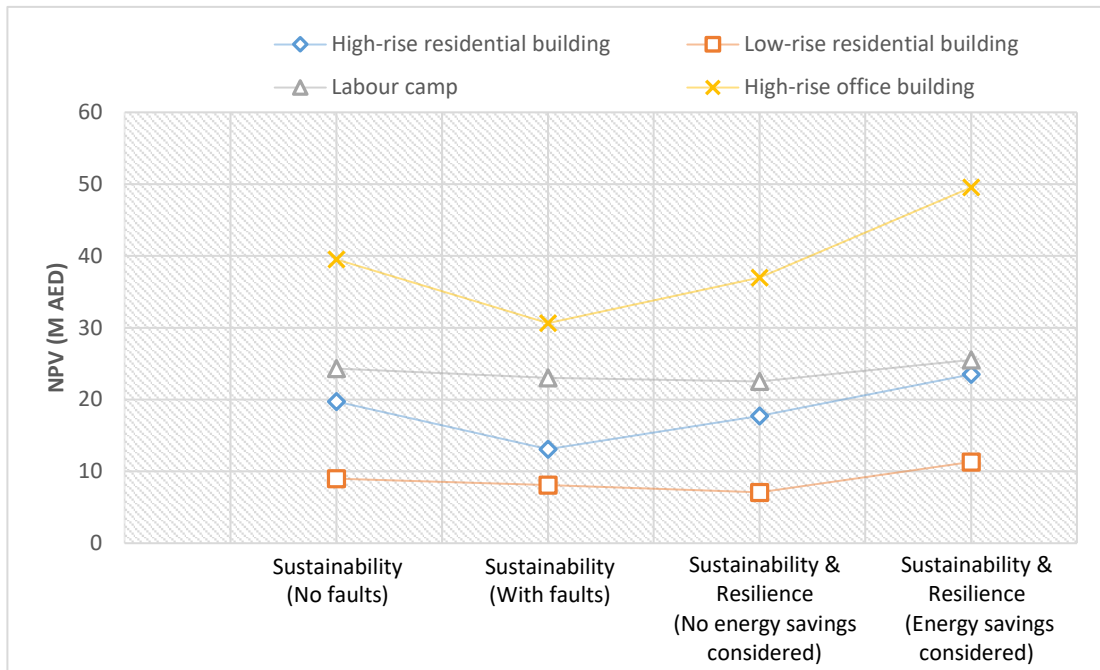


Figure 4.1: The impact of having FDD on NPV.

Table 4.7 and Figure 4.1 illustrate the impact of installing FDD tools on the NPV value for smart buildings. It can be concluded that having smart systems in buildings would definitely increase the profit of the building, producing a high NPV. While in the case of having undetected faults, the NPV value seems to decline significantly. In order to stop that from happening, the best solution would be implementing FDD tools. However, as mentioned before, using this method won't give accurate results as it is not dependent on the number of floors in the building, assuming a fixed number of faults and considers a fixed cost from within the range of costs found in the literature. Therefore, the approach used to get a better estimation for the fault cost considered a range of percentages that would tie up to the total energy consumption of the building, as well as the PERT method. Using the three scenarios that the PERT method assumes and their weighted average, four values for the NPV were calculated.

- First case: a pessimistic scenario (P) where the fault cost is equal to a 30% waste of the total energy of the building. Table 4.8 illustrates the effect of this scenario on the NPV.

Table 4.8: Testing for smart systems resilience considering a pessimistic scenario.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Pessimistic fault cost (30% of energy) (AED)	1,306,500	954,000	678,000	2,835,000
	Net annual savings (AED/Year)	1,031,500	75,550	2,100,850	1,779,550
	<b>NPV (AED)</b>	<b>8,165,502</b>	<b>544,843</b>	<b>18,331,591</b>	<b>14,377,875</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	8,595	757	13,579	11,785

- Second case: an optimistic scenario (O) where the fault cost is equal to 15% waste of the total energy of the building. Table 4.9 illustrates the effect of this scenario on the NPV.

Table 4.9: Testing for smart systems resilience considering an optimistic scenario.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Optimistic fault cost (15% of energy) (AED)	653,250	477,000	339,000	1,417,500
	Net annual savings (AED/Year)	1,684,750	552,550	2,439,850	3,197,050
	<b>NPV (AED)</b>	<b>13,957,358</b>	<b>4,774,028</b>	<b>21,337,238</b>	<b>26,945,737</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	14,692	6,631	15,805	22,087

- Third case: a most likely scenario (M) where the fault cost is equal to 20% waste of the total energy of the building, Table 4.10 illustrates the effect of this scenario on the NPV.

Table 4.10: Testing for smart systems resilience considering a most likely scenario.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Most likely fault cost (20% of energy) (AED)	871,000	636,000	452,000	1,890,000
	Net annual savings (AED/Year)	1,467,000	393,550	2,326,850	2,724,550
	<b>NPV (AED)</b>	<b>12,026,739</b>	<b>3,364,299</b>	<b>20,335,356</b>	<b>22,756,450</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	12,660	4,673	15,063	18,653

- Fourth case: using the three values of the previously mentioned scenarios and equation (12) to get the weighted average, Table 4.11 illustrates the effect of this scenario on the NPV.

Table 4.11: Testing for smart systems resilience considering PERT weighted average.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Pessimistic scenario (30% of energy) (AED)	1,306,500	954,000	678,000	2,835,000
	Optimistic scenario (15% of energy) (AED)	653,250	477,000	339,000	1,417,500
	Most likely scenario (20% of energy) (AED)	871,000	636,000	452,000	1,890,000
	PERT weighted average (Fault cost) (AED)	907,292	662,500	470,833	1,968,750
	Net annual savings (AED/Year)	1,430,708	367,050	2,308,017	2,645,800
	<b>NPV (AED)</b>	<b>11,704,970</b>	<b>3,129,345</b>	<b>20,168,375</b>	<b>22,058,235</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	12,321	4,346	14,940	18,081

Table 4.12: A comparison between the results of the four cases.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Pessimistic scenario NPV (AED)	8,165,502	544,843	18,331,591	14,377,875
	Optimistic scenario NPV (AED)	13,957,358	4,774,028	21,337,238	26,945,737
	Most likely scenario NPV (AED)	12,026,739	3,364,299	20,335,356	22,756,450
	PERT weighted average NPV (AED)	11,704,970	3,129,345	20,168,375	22,058,235

Table 4.12 summarizes and compares the NPV of the four cases. As it can be seen the pessimistic and the optimistic scenarios reflect the two extremes that the NPV can get to. While using the weighted average results in a better NPV estimate that lies between the two extremes and depends on the three values. Therefore, moving forward with the calculations, the weighted average NPV was the one used to perform the last part of the analysis, Table 4.13.

Table 4.13: Testing for smart systems resilience using the PERT method.

		High-rise residential building	Low-rise residential building	Labour Camp	High-rise office building
	Number of floors	28	4	4	30
	Building floor area (m <sup>2</sup> )	950	720	1,350	1,220
	Total energy cost (AED/Year)	4,355,000	3,180,000	2,260,000	9,450,000
	Capital investment of smart system (AED)	980,000	125,000	295,000	1,400,000
No faults	Net annual savings (AED/Year)	2,338,000	1,029,550	2,778,850	4,614,550
	<b>NPV (AED)</b>	<b>19,749,214</b>	<b>9,003,213</b>	<b>24,342,885</b>	<b>39,513,599</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	20,789	12,504	18,032	32,388
With faults	Pessimistic scenario (30% of energy) (AED)	1,306,500	954,000	678,000	2,835,000
	Optimistic scenario (15% of energy) (AED)	653,250	477,000	339,000	1,417,500
	Most likely scenario (20% of energy) (AED)	871,000	636,000	452,000	1,890,000
	PERT weighted average (Fault cost) (AED)	907,292	662,500	470,833	1,968,750
	Net annual savings (AED/Year)	1,430,708	367,050	2,308,017	2,645,800
	<b>NPV (AED)</b>	<b>11,704,970</b>	<b>3,129,345</b>	<b>20,168,375</b>	<b>22,058,235</b>
With FDD	NPV per unit floor area (AED/m <sup>2</sup> )	12,321	4,346	14,940	18,081
	Initial cost of FDD system (AED)	435,500	318,000	226,000	945,000
	Maintenance (AED/Year)	180,000	180,000	180,000	180,000
	Net annual savings (AED/Year)	2,158,000	849,550	2,598,850	4,434,550
	<b>NPV (AED)</b>	<b>17,717,795</b>	<b>7,089,294</b>	<b>22,520,966</b>	<b>36,972,680</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	18,650	9,846	16,682	30,305
	Energy savings (AED/Year)	653,250	477,000	339,000	1,417,500
	Net annual savings (AED/Year)	2,811,250	1,326,550	2,937,850	5,852,050
	<b>NPV (AED)</b>	<b>23,509,651</b>	<b>11,318,479</b>	<b>25,526,614</b>	<b>49,540,541</b>
	NPV per unit floor area (AED/m <sup>2</sup> )	24,747	15,720	18,909	40,607

N	10	i	2.25%
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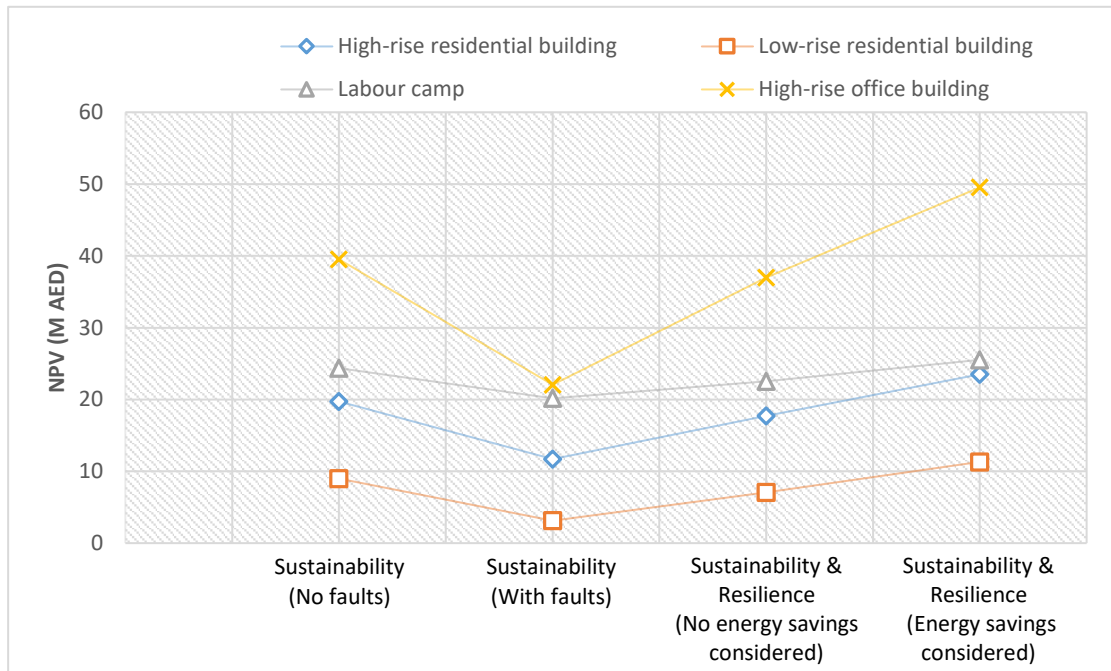


Figure 4.2: The impact of having FDD on NPV, using the PERT method.

Although the results of the  $NPV_{with\ faults}$  using the PERT method seem to be more realistic compared to the method that uses hypothetical data, the overall conclusion remains the same. Investing in smart systems in buildings increases the profit of the building, producing a high NPV, while ignoring the need to use fault detection and diagnostic tools affects the NPV negatively. Investing in such tools could significantly reduce the potential losses and might even turn them into savings. As can be seen in both Table 4.13 and Figure 4.2, adding the FDD tools to the four buildings created a very small drop in the NPV. Taking the high-rise residential building as an example, before considering the occurrence faults the NPV was 19,749,214 AED, while after considering the occurrence of faults the NPV dropped down to 11,704,970 AED. Although investing in resilience tools might add an additional cost (initial cost of installation and a maintenance cost). The fact that having such implementation reduces the drop in the NPV to 17,717,795 AED instead of 11,704,970 AED, promotes the importance of investing in resilience tools. And even if the selected time horizon was less than 10 years, the benefits of such investment would still be harvested, as the chances of failure would always be minimized due to the possibility of early fault detection. However, if the energy savings that result from using these tools were considered, the NPV would be 23,509,651 AED, which concludes that investing in fault

detection and diagnostic tools might not only reduce the potential losses but might contribute to enhancing the performance of the smart systems and increase the total profit. Therefore, this study proves that implementing smart/sustainable systems in buildings would definitely be profitable, while maintaining the resilience and the functionality of these systems will guarantee the continuous success and profitability of such implementation.

## Chapter 5. Conclusion and Future Work

### 5.1. Conclusion

In this thesis, the two concepts of sustainability and resilience in smart buildings were further explored and the possibility of coupling and quantifying the two together was tested. An intensive literature review was conducted to understand the aspects of the two concepts, quantifying methods and the required data. Thereafter, a model was formulated to couple both sustainability and resilience and measure them in monetary values, and smart buildings were chosen to apply this model on. In order to perform the calculations, both sustainability and resilience had to be dismantled into small manageable components. As sustainability was broken into its three aspects: environmental, social and economic, resilience was simplified to resemble the endurance level of the smart systems. The model feasibility was tested on four smart buildings in the UAE by which their data were provided.

The proposed model was based on a cash flow analysis where the NPV was used to weigh the benefits against the costs of having smart systems in buildings. Measuring sustainability using NPV required quantifying the effects of having smart systems on the environment, society and economy. While the environmental and economic calculations were almost straightforward, the social calculations required a special approach, and that included conducting a survey, using the RII method and weighting methods. As for resilience, the resulting NPV was compared with three recalculated NPVs based on different scenarios. The first scenario assumed a certain number of faults in the smart systems of the building. The second scenario assumed that an FDD system was installed to detect and prevent failure of the smart systems. The NPV for this scenario was calculated twice, one time considering the energy savings that installing FDD tools would provide, and another time ignoring them.

The results of this study conclude that using smart systems increases the profit of the building, generating a higher NPV. While once some faults start to emerge prior to detection, the NPV shall demonstrate a steep drop. This drop in NPV could be minimized or even turned into a profit by installing FDD tools that would predict failure before it happens. Adding the FDD tools to the four buildings created a very small drop in the NPV, and even increased the NPV slightly when considering the energy savings

that comes with installing these systems. Therefore, this study proves that implementing smart technologies in buildings creates sustainable structures with high profit yet integrating resilience within these structures minimizes the potential losses in case of failure and improves their financial performance.

## **5.2. Recommendations for future work**

The concept of coupling and quantifying sustainability and resilience seems to be the focus of many new studies, but it was not widely tackled in buildings, especially the smart ones. Therefore, since this research focuses on this area and seems to reflect the importance of coupling resilience with sustainability in smart buildings to get the best financial performance, further research could be conducted in order to broaden knowledge in this area and to provide more accurate results. Recommendations that could be taken into consideration to improve this research and eliminate its limitations are as follows:

- Data about the levels of greenhouse gas emissions could be added to the environmental aspect calculations.
- More people/experts could be involved in taking the survey in order to get more accurate results.
- More indices could be used to quantify the social aspect of sustainability, as for the sake of simplicity only six indices were used in this study.
- Other methods could be used to analyse the results of the survey, such as AHP, etc.
- Other costs and benefits could be added to the calculations.
- Many other fault detection systems with different capital and maintenance costs could be used, also these systems might have many benefits that could improve the performance of the smart systems.
- Further research on the decommissioning cost of the resilience tools could be conducted.
- Having certain studies that would set a baseline for the NPV of the smart buildings would create a better understanding of the impact on the NPV.

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## Appendix A

A sample of the survey questions for the six indices of the social aspect of sustainability.

### Index 1: Productivity

1. Do you think that installing smart systems in buildings would improve people's productivity level? (Example: Automatic lighting/temperature adjustment).

- Yes
- No
- Irrelevant

2. In your opinion, how important do you think this index (Productivity) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

3. To what extent do you think having smart systems would improve the productivity level of employees compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

## Index 2: Indoor environment quality

4. Do you think that installing smart systems in buildings would improve the indoor environment quality?

- Yes
- No
- Irrelevant

5. In your opinion, how important do you think this index (Indoor environment quality) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

6. To what extent do you think having smart systems would improve the indoor environment quality compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

### Index 3: Reputation

7. Do you think that installing smart systems would contribute to creating a good reputation for the building?

- Yes
- No
- Irrelevant

8. In your opinion, how important do you think this index (Reputation) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

9. To what extent do you think having smart systems would boost the reputation of a building compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

#### Index 4: Extra profit

1. Do you think that installing smart systems in buildings would contribute to increasing their rental profit?

- Yes
- No
- Irrelevant

2. In your opinion, how important do you think this index (Extra profit) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

3. To what extent do you think having smart systems would contribute to increasing the profit compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

## Index 5: Services

4. Do you think that installing smart systems in buildings would increase the quality of the services and reduce people's waiting time? (Example: Getting an elevator to be ready for the user once sensors detect the possibility of them leaving their apartments/offices)

- Yes
- No
- Irrelevant

5. In your opinion, how important do you think this index (Services) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

6. To what extent do you think having smart systems would contribute to enhancing the level of services compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

## Index 6: Safety

7. Do you think that installing smart systems in buildings would increase the level of safety?

- Yes
- No
- Irrelevant

8. In your opinion, how important do you think this index (Safety) is to quantify the social benefits of sustainability?

- Extremely important
- Very important
- Somewhat important
- Not so important
- Not at all important

9. To what extent do you think having smart systems would contribute to enhancing the level of safety compared to not having smart systems?

- High
- Relatively high
- Moderate
- Low

## Appendix B

Summary of the survey results is shown in the tables below.

First question: Do you think that installing smart systems in buildings would improve (the measured index)?

	Yes	No	Irrelevant	Total
Productivity	10	0	0	10
Indoor environment quality	10	0	0	10
Reputation	10	0	0	10
Extra Profit	10	0	0	10
Services	10	0	0	10
Safety	10	0	0	10

Second question: In your opinion, how important do you think this index is to quantify the social benefits of sustainability?

	Extremely important	Very important	Somewhat important	Not so important	Not at all important	Total
Productivity	4	4	2	0	0	10
Indoor environment quality	3	5	1	1	0	10
Reputation	5	0	3	1	1	10
Extra Profit	4	3	2	1	0	10
Services	4	4	2	0	0	10
Safety	6	1	1	2	0	10

Third question: To what extent do you think having smart systems would improve (the measured index) compared to not having smart systems?

	High	Relatively high	Moderate	Low	Total
Productivity	4	3	3	0	10
Indoor environment quality	6	2	1	1	10
Reputation	6	2	1	1	10
Extra Profit	3	5	1	1	10
Services	7	3	0	0	10
Safety	8	0	0	2	10

## **Vita**

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