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TOWARDS EVOLUTIONARY RESILIENCE IN THE HOUSE-BUILDING SECTOR: A FRAMEWORK PROPOSAL AND AN APPLICATION TO BUILDING SKIN

Morgane Bigolin

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2018

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Thesis submitted in partial satisfaction of the requirements for the degree of Doctor in Engineering awarded by the Postgraduate Program in Construction and Infrastructure of the Federal University do Rio Grande do Sul.

Porto Alegre, 13nd of December 2018

Prof. Luiz Carlos Pinto da Silva Filho
PhD., University of Leeds / United Kingdom
Supervisor

Prof. Carlos Torres Formoso
PPGCI/UFRGS Coordinator

EXAMINERS

Prof. José Luis Duarte Ribeiro (UFRGS)
Dr., Federal University of Rio Grande do Sul, Brazil

Prof. Luiz Antonio Bressani (UFRGS)
PhD. University of London, United Kingdom

Prof. Maria Angélica Covelo da Silva
Dr. São Paulo University, Brazil

To my parents_ Irno e Maria Salete _ each of whom taught me to value perseverance and curiosity in all that I strive to accomplish.

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“It is not the strongest of the species that survives, or the most intelligent that survives. It is the one that is most adaptable to change.

Charles Darwin

ABSTRACT

BIGOLIN, Morgane. **Towards evolutionary resilience in the house-building sector: a framework proposal and application to building skin**. 2018. Tese de Doutorado – Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura, UFRGS, Porto Alegre.

There has been an increase in the number of studies and research groups looking into questions about resilient cities around the world. The aim is to build initiatives focusing on enabling decision makers to tackle many ecological and social challenges that contemporary urban centres face, mainly caused by climate change. The building sector also has to be prepared to face those challenges. The construction industry, however, has yet to embrace a holistic concept of resilience. The strategies based on prediction and control approach often does not effectively reduce risks. By applying the resilience theory, this investigation aims to examine the applicability of the evolutionary resilient approach and develop an alternative framework that might be used to the housing sector, to finally address a model to assess building skin resilience. First, this study explores the conceptualisation of risks, looks at the role the performance-based approach in this scenario and also what resilience means in relation to spatial developments and buildings. Based on the literature review it was developed a theoretical framework for evolutionary resilience approach in the housing sector, extending this view with a building as a complex socio-ecological system. Based on this theoretical framework, the outline for the empirical research was further specified. The aim was to gain insights through a series of interviews and a focus group in order to assign a set of requirements and indicators for resilient buildings skin. Finally, those indicators were used to create an appraisal model to assess social housing building skin. The analysis showed that the holistic framework based on evolutionary resilience could constitute a comprehensive and innovative resilience approach in the housing sector. The main contribution of the appraisal model was to adapt theoretical concepts by proposing operational surrogates, enabling such knowledge to be more applicable in devising resilience strategies. This model can be used to assess resilience strategies, identifying gaps and opportunities, and to help the design and implementation of comprehensive projects.

Keywords: resilient building, housing sector; building skin, climate change, evolutionary resilience

RESUMO

BIGOLIN, Morgane. **Towards evolutionary resilience in the house-building sector: a framework proposal and application to building skins**. 2018. Tese de Doutorado – Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura, UFRGS, Porto Alegre.

Houve um aumento no número de estudos e grupos de pesquisa que investigam questões sobre cidades resilientes em todo o mundo. O objetivo é construir iniciativas com foco em capacitar os tomadores de decisão a enfrentar os vários desafios ambientais e sociais enfrentados pelos centros urbanos contemporâneos, causados principalmente pelas mudanças climáticas. O setor da construção também precisa estar preparado para enfrentar esses desafios. A indústria da construção, no entanto, ainda precisa adotar um conceito mais holístico de resiliência. As estratégias de projeto baseadas na abordagem de previsão geralmente não reduzem efetivamente os riscos. Aplicando a teoria da resiliência, esta investigação visa examinar a aplicabilidade da abordagem de resiliência evolutiva e desenvolver uma estrutura alternativa que possa ser usada para o setor de habitação, para finalmente abordar um modelo para avaliar a resiliência da pele do edifício. Primeiramente, este estudo explora a conceituação dos riscos, analisa o papel da abordagem baseada no desempenho neste cenário e também o que significa resiliência em relação aos desenvolvimentos urbanos e edificações. Com base na revisão da literatura, foi desenvolvido um modelo teórico para a abordagem da resiliência evolutiva no setor habitacional, ampliando a visão de edificação como sendo um complexo sistema sócio ecológico. Com base nessa estrutura teórica, o esboço da pesquisa empírica foi delineado. O objetivo foi obter insights através de uma série de entrevistas e um grupo focal, a fim de atribuir um conjunto de requisitos e indicadores para a pele de edifícios resilientes. Finalmente, esses indicadores foram usados para criar um método de avaliação para a construção de habitações de interesse social. A análise mostrou que a estrutura holística baseada na teoria de resiliência evolucionária poderia constituir uma abordagem de resiliência abrangente e inovadora no setor de habitação. A principal contribuição do modelo de avaliação foi adaptar conceitos teóricos, propondo substitutos operacionais, possibilitando que tais conhecimentos fossem mais aplicáveis na elaboração de estratégias de resiliência. Esse modelo pode ser usado para avaliar estratégias de resiliência, identificar lacunas e oportunidades e ajudar a projetar e implementar projetos mais abrangentes no setor habitacional.

Palavras-chaves: edificação resiliente, setor habitacional; envelopamento, mudança climática, resiliência evolutiva

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LIST OF ACRONYMS

ABRAINC: Associação Brasileira de Incorporadoras Imobiliárias

ABNT: Associação Brasileira de Normas Técnicas

BIM: Building Information Modelling

BS: Building Skin

CEPED/RS-UFRGS: Centro Universitário de Estudos e Pesquisas Sobre Desastres da Universidade Federal Do Rio Grande Do Sul

CEPED UFSC: Centro Universitário de Estudos e Pesquisas sobre Desastres da Universidade Federal de Santa Catarina GRID: Grupo de Gestão de Risco de Desastre

CRED: Centre for Research on the Epidemiology of Disasters

EM-DAT: Emergency Events Database

EN: European Standard

ERB: Evolutionary Resilient Building

EWE: Extreme Weather Event

FEMA: Federal Emergency Management Agency

FINEP: Financiadora de Estudos e Projetos

IoT: Internet of Things

ISO: International Organisation for Standards

IPCC: Intergovernmental Panel on Climate Change

LEED: Leadership in Energy and Environmental Design

MHML: My House My Life programme

M2M: Machine-to-Machine

NBR: Norma Brasileira

QFD: Quality Function Deployment

ST: Social Technology

UN: United Nations

UNISDR: United Nations Office for Disaster Risk Reduction

1 INTRODUTION

This chapter presents the research problem, the questions and objectives that guided this investigation. The first section introduces the research background about the environmental extreme weather events caused by climate change and highlights the importance of the concept of resilience in this context, addressing the house-building sector. The second section summarises the research problem, which is translated into a set of questions and objectives, presented in the third and fourth section. In the fifth section, the scope limitations of this investigation are outlined. The sixth provides a brief overview of the research methodology adopted in this work. The seventh summarises the content of this thesis.

1.1 BACKGROUND

1.1.1 The climate change and EWEs

Climate change is a significant challenge for all countries. Temperatures are breaking records around the world, and the number of extreme weather events is increasing. Global annual average temperature has risen by more than 0.7ºC from 1986 until 2016, and analysis suggests that for the end of the 21st century could increase 1.5ºC (WUEBBLES et al., 2017). Also, it has been argued that the frequency and intensity of extreme weather events, including floods, droughts and storms are increasing during the last years, and this is due to the intensified of climate change (IPCC, 2014). The annual global cost with disaster due to extreme weather was estimated at over $314 billion in just 2017 (EM_DAT, 2018). There is a consensus that the intensity of heavy precipitations is increasing due to increasing temperatures (WASKO; SHARMA, 2017). Ultimately, all countries and their population will be affected. However, mainly the most vulnerable, the poorest countries, are where the cost of extreme weather can cause a complete disruption in the system.

The assessment of climate change impacts at the human society and in the built environment is the focus of many authors around the world. However, the literature from developing countries still represents a small fraction (BURKETT et al., 2014), indicating challenges, but also opportunities for scientific research. Although the contrast on literature numbers and uncertainties about the future climate, it is safe to affirm that government of both developing and developed countries, it will face more frequently challenges relate to extreme weather events, as high temperature, precipitation (storm, flood) and windstorm on everyday scenarios.

Global average temperatures are expected to rise during this century. One of the main concerns about the hot temperatures is related to elderly illness and mortality. The 2003 heat wave was responsible for around 70 000 deaths across Europe (ROBINE et al., 2007) and was estimated that in the UK the number of fatalities increases 16% (JOHNSON et al., 2005). Additionally, Wolf & McGregor (2013) suggest that the poor house quality represents one of the principal components for heat vulnerability.

Storms and floods are equally problematic. According to the UN Office for Disaster Risk Reduction, 250 million people have been affected annually by flood events over the last ten years. In England, there are over than 5.2 million properties at risk of flooding, which means one in six properties (ENVIRONMENTAL AGENCY, 2009). The Brazilian Atlas of Natural Disasters suggests that more than 4.500 situations of flood have been registered between 1991 and 2012. In Porto Alegre, just in 2015, more than 5.000 people were affected and needed to leave their houses[1].

Urbanisation, increased human population, growing cities are challenges for the functioning of all ecosystems (ALBERTI, 2010) aside from increase problems for the built environment. As more people inhabit the urban areas more, workplaces, services and, mainly, homes are necessary. The difficulties for the housing sector with the urgency for new buildings is a pressing challenge primarily in developing countries (TAM, 2011). However, it is also in developed countries where the current infrastructure has been built without predicting the difficulties caused by the climate change (CHAMPAGNE; AKTAS, 2016).

In the last decades, many countries had suffered essential transformations in the organisation of the territory. The population of the cities has grown from 746 million in 1950 to 3.9 billion in 2014, as shown in Word Urbanization Prospects, published by the United Nations. In Brazil, 84% of the total population live in urban areas. The migration to cities in most of the cases does not increase the life quality of this population, since this fast urbanisation had created many instances of agglomeration and urban settlement in risk areas, as flood areas or in danger of a landslide, for example. In the context of climate change and the city's population growing, the numbers

[1] Report for the Porto Alegre Resilient Challenge, 100 Resilient Cities, by Rockefeller Foundation

and severity will increase inflating problems and demanding solutions for infrastructures and buildings.

The 2005 United Nations World Conference on Disaster Reduction called for improving the safety of buildings as a priority for global disaster reduction efforts, including through a "building disaster reduction network". These unresolved issues are likely to come to the forefront in the near future. The imperative is to provide affordable, appropriate performance, energy efficiency and sustainable dwellings. In theory, houses with proper performance do exist. However, with the threat of climate change and increased uncertainty about the future of the building environment (MWASHA; WILLIAMS; IWARO, 2011), new concerns starts to show up, and the term resilience becomes a central concept in policy and practice in many countries (DAVOUDI; BROOKS; MEHMOOD, 2013).

1.1.2 The resilience approach

Considering the complex nature of extreme weather uncertainties, a range of proposals related to cities and buildings has been developed in recent years to understand and address the problem of the effects of climate change in the built environment. Over the last decade, the concept of resilience had continuously been the focus of many studies and governmental reports that discuss the implications of climate change. However, the extensive use of the term had been creating some divergences and misunderstandings.

Resilience has become an important concept in a range of disciplines, and because of this multi-function has remained a fuzzy concept (DAVOUDI; BROOKS; MEHMOOD, 2013). The practical relevance and conceptual meaning are in danger due to the term is used ambiguously and wide extension (BRAND; JAX, 2007). However, nowadays, it is becoming an essential paradigm in the context of how disasters affect the society (COETZEE; NIEKERK; RAJU, 2016). Several policy documents, as such as the Sendai Framework for Disaster Risk Reduction 2015-2030, highlights the importance of building resilience capacity in communities and society.

However, despite the academic, policies and practitioners discussions, there are still conflicts and controversies when the term resilience has been used (LIZARRALDE et al., 2015). Recently, new approaches in dealing with extreme weathers events in the building environment, have been discussed in literature (FOLKE, 2006; HOLLNAGEL, 2014; LIAO, 2012) Currently, three main, distinct perspectives about resilience have been developed since the term had been used in 1973, by C.S Holling for ecological systems approach (DAVOUDI; BROOKS; MEHMOOD, 2013). These perspectives have been called engineering resilience, ecological resilience and more recently the evolutionary resilience. Although resilience approach can have a positive advantage being a multidisciplinary concept, the adoption by the built environment as a design principle had created a series of misunderstandings and competing frameworks. Besides the long history of those approaches, the use of the term in natural hazards management is relatively recent (BERKES, 2007).

What defines resilience in urban scenarios remains ambiguous, and the critical examination and understanding of the term are paramount to propose, measure and planning practices for the different scales of the built environment. Resilience must be present in all scales. The strategies should address the regional scale, the communities and the building site. However, there is a lack of studies on how the new buildings, especially those to accommodate the expanding population can endure through time and extreme events. As such, this scenario gives rise to an array of questions on how a building can be designed to be resilient

1.1.3 The importance of resilient buildings

Buildings are among the most complex objects designed and built by humans. Housing is crucial, once shelter the occupants from a number of Extreme Weather Events (EWEs), such as windstorms, rainstorms and have a close relation in significance with the users. For the construction and operation of those buildings, a high amount of energy, water and material resources is consumed. Nevertheless, it is paramount that those building could withstand stresses and improve performance, increasing their lifespan.

The impacts of the construction and maintenance of buildings are frequently related to environmental effects, human health, and the global climate, and several research groups are dealing with those impacts. Also, researchers are attempting to organise and define resilience for buildings (CHAMPAGNE; AKTAS, 2016; GOLZ, 2016). However, current research and design approaches do not deal with how the risks from EWEs affect the buildings uniformly or even including the unpredictable effects. Most critically, these approaches do not systematically integrate performance and resilience over the lifespan of the various building systems.

Houses are expected to have a long life cycle, and the construction exploits a large number of resources and any improvement to take longer the building life will significantly reduce the environmental impact. The challenge is to incorporate resilience into the design and construction of buildings. Especially social (public) housing, since the primary purpose is to provide affordable, decent and safe dwellings for the most vulnerable and poor part of the population. In the UK, the social house represents 18% of the housing stock, with approximately 4.7 million homes (SMITH, SWAN, 2012). In Brazil, throughout the governmental program “my house, my life” around 3 million homes for low-income people had been built since 2009.

Recently, the discussion about resilience has also become present in the assessment, design and selection of materials for buildings (CHAMPAGNE; AKTAS, 2016; WHOLEY, 2015). However, most of these building resilience principles developed do not cover all the characteristics of the resilience concept, focusing mainly on resistance and robustness, while some of the strategies are confused with sustainability approach. Furthermore, the principles present in the built environment resilience literature (HASSLER; KOHLER, 2014a; HOLLNAGEL, 2014) are theoretical and do not present practical implementation for buildings design.

The use of resilience as a building design principle appeared in recent years to reduce the risks and withstand the extreme events (CHAMPAGNE; AKTAS, 2016; NAUMANN; NIKOLOWSKI; GOLZ, 2009). Previous studies point out the use of future climate projections during the design phase (CHAMPAGNE; AKTAS, 2016), or emphasise just the ability of building withstand its damaging effects (GOLZ, 2016). However, it is imperative, for a holistic approach to building resilience, to consider the inherent uncertainties of weather events and the climate change and a more flexible approach.

Laboy and Fannon (2015) affirm that there are two goals by which is essential to develop resilient building frameworks. The first is the ambition of sustainable buildings since they should last time enough to justify the investment of ecological resources. The second is the risk that overly optimised buildings leave people vulnerable. In this point of view, the balance of these contradictory goals are fundamental to reach resilient buildings.

Considering the complex scenario of creating a building in an unpredictable environment, strategies can no longer be based on the conventional method of risk assessment. However, it is useful to know the effect and develop and implement optimal measures, based on risk assessment and management; it is also fundamental to deal with uncertainty. Resilience here could be viewed as a performance-based approach to deal with the associated uncertainties of the extreme weather events.

1.2 RESEARCH PROBLEM

Brazil had presented a rapid an intense urbanisation process, added to all the problems that came with this situation. In fifty years, the country transformed from an agrarian-based population into an urban society (1950-2000). The process of urbanisation increased the growth of precarious and informal settlements, and several times, located in risk areas. Additionally, the rapid urbanisation also increased significantly the housing deficit in the country (LONARDONI; CLAUDIO; FRENCH, 2013). The ABRAINC, through its recent report concluded that Brazil will need 12 million new homes until 2027, or 1, 2 million each year[1]. To deal with this situation, since 2009, Brazil has been implementing a national social housing programme call “My House, My Life” (Programa Minha Casa Minha Vida - MHML). For its magnitude the program is considered an important milestone. However, some critics about the poor infrastructure and the low-quality houses also have been raising since then.

In this context, the Brazilian Standard NBR 15.575 (ABNT, 2013) was implemented in 2013 for the housing sector. The NBR 15.575 was the first performance-based standard to define requirements and criteria for safety, habitability and sustainability issues, intending to increase the housing sector quality in the country. However, although the standard was considered as a paradigm shift, it does not deal with requirements to improve the extreme weather resilience. Nevertheless, practice and assessment of performance building lifecycle have recognised the risk of extreme weather events as a critical component of building performance and sustainability, however, the resilience approach is not a reality. Building resilience is becoming increasingly important since the earth’s climate continues to change and diverge from historical data (CHAMPAGNE; AKTAS, 2016), however there are still a gap in practical approach.

There is also the need to understand how to apply resilience to design process in a practical way. The stakeholders engaged on housing sector are not aware of how to deal with uncertainties related to EWEs. Besides environmental risk are stated on the standard the design team not rarely neglect those requirements, over economic reasons. For this reason, design to uncertainties is far more distant. Whereas part of the problem may reside in the fact that there are not a structured requirements to achieve resilient buildings, the lack of a risk culture in academia where the architects and engineers have their education could be also a constrain.

[1] Available at https://www.abrainc.org.br/wp-content/uploads/2018/10/ANEHAB-Estudo-completo.pdf. Accessed in 28 Oct 2018.

Some questions are arising from this background. One of them is how to adapt the conceptual underpinnings of the resilience approach into the housing sector in order to understand how the physical building should behave to become more resilient. Understanding this issue is essential to define which surrogates may be used to assess design strategies that can enhance the building resilience.

This investigation refers to a problem with practical importance and theoretical relevance to envisioning contributions to the real world and also to the literature about resilience in the built environment. Buildings should be able to respond to performance requirements even when under regular stress or extreme shocks. Also, the importance of the resilience approach should be considered as a goal and architecture practice, and a design principle to buildings is indicated by several authors (CHAMPAGNE; AKTAS, 2016; HASSLER; KOHLER, 2014a; LABOY; FANNON, 2016) a key concept to deal with the uncertainties of the climate change.

From a theoretical perspective, the question remains about the design of buildings that are prepared to cope and adapt to stresses and shocks of the extreme natural events. The problem is how to deliver a framework to a physical building system that are based on socio-ecological systems. In light of this situation, further development of the resilience concept for buildings and their systems is paramount. In doing so, this understanding could provide a holistic and useful framework to assess the resilience of buildings. However, resilience theory has been criticised by becoming a buzzword with no practical utility (DAVOUDI et al., 2012). Therefore, it is also necessary to operationalise the framework, in order to bring resilience to real life and a practical approach to orient architects, engineers and other stakeholders to look for the best solutions for resilient buildings.

As a practical relevance of the research problem, it is necessary to develop a model to support decision makers by drawing together some interdisciplinary knowledge to assess the functional performance of buildings in the face of adverse events. Given the risks due to EWEs, that the housing sector is not entirely aware of the response as part of this process, resilience will be assessed for EWEs of buildings designed according to current codes. Especial attention should be given to the building skin since it is the system that separates the interior against the environment and the extreme weather events.

This brief literature review indicates that there is a lack of existing studies concerning a holistic view of the resilient building, and hardly any in an evolutionary perpective. Also, a gap was founded related to studies that appropriately assess the nature of house building resilience, in support of the real-world decision making for an extending building lifespan.

1.3 RESEARCH QUESTIONS

Based on the research problem summarised in the previous section, four main questions are formulated:

a) How to define resilience requirements for the house-building sector?
b) How to adapt the conceptual underpinnings of the resilience approach into the house buildings?
c) Which requirements should have a house building skin for defining comprehensive and coherent strategies for resilience?
d) How can an appraisal rating system model be used to help the stakeholders to assess the resilience of buildings to EWEs?
e) How can an appraisal rating system model be used to evaluate innovative building systems and technologies?

1.4 RESEARCH AIM AND OBJECTIVES

This research aims to devise a model to assess the resilience of building skin systems in the housing sector to the impacts of the extreme weather events based on an evolutionary resilience framework.

In order to achieve the research aim, a number of objectives are proposed for this investigation:

a) Propose a theoretical framework based on a comprehensive literature review to adapt the conceptual underpinnings of the evolutionary resilience approach into the house buildings;
b) Propose the operationalisation of the evolutionary resilience framework through a set of core requirements for the building skin;
c) Devise a set of surrogates (indicators) to assess the requirements; and
d) Implement the proposed model in a real case, aiming to assess its utility;

1.5 RESEARCH SCOPE AND LIMITATIONS

The goal of this research is to develop a model to assess the resilience to the impacts of the extreme weather events based on an evolutionary resilience framework. In doing so, this investigation also develops a theoretical framework, based on the evolutionary approach, for housing resilience to extreme weather events increased by climate change.

Man-made disasters were excluded from this research. This choice was made because the frequency of the severe weather events has been increasing globally, and especially in South America countries, still there is a lack of studies in this area. The man-made is quite complex, and were excluded from this research.

The scope of the framework is limited to the housing building, once the world population are increasing and a number of new homes need to be provided, and those places need to be secure and prepared for the implications for impacts of the future weather conditions. Increasing resilience of houses to climate change and the severe weather conditions have positive societal and economic effects, and the consequences of the natural disasters can be mitigated.

Finally, the model is based on the knowledge and reality of the Brazilian context. The interviews and expert's focus group were drawn focusing on this reality. The application was implemented using project design from Porto Alegre (BR) as study analysis.

1.6 CONTENT OF THE THESIS

The remaining part of this document is divided into eight chapters. After this introduction, Chapter 2 present the theoretical background of the research. The review synthesises the literature in three broad themes of the research subject. Firstly, the risk management as a traditional view to deal with extreme weather events and disasters in the urban development. Secondly, the building performance-based approach is explored, using the perspective of a definition that is appropriate in the new context of the housing sector. Thirdly, the resilience term is investigated on its multidisciplinary perspective, the three approaches of ecological, engineering and socio-technical or evolutionary approach are examined.

The findings from the literature review are the basing point for the development of the theoretical framework. Chapter 3 is concerned with a merge of the preview chapter. It discusses the concepts of systems to understand a building as a fluid and socio-ecological system and connected withthe evolutionary resilience approach. The resilience underpinnings for building system are described, and the Evolutionary resilience framework is outlined.

Having established the theoretical background of the thesis, Chapter 4 presents the research method; outline the reasoning behind the research methodology undertaken in this investigation, its approach, strategies and methods. This chapter presents the steps carried out in the development of the empirical phase: semi-structured interviews and focus group.

Chapter 5 details the semi-structured interviews and the focus group. Present the analyses and discusses the qualitative data gathered during this investigation, which served two purposes: to explore the view from the experts on the subject and validate framework requirements. The first section is focused on the semi-structured interviews as a mean to outline the main contributions. Their content analysis is presented along with the main ideas that derived from it. The second section shows the model validation through the focus group. This chapter of the qualitative data collection is part of the exploratory phase of the study.

Chapter 6 presents the culmination and application of the work undertaken. The Evolutionary Resilience building model for the development of housing building skin is presented. It details its guidelines; the appraisal structure and its application are presented through a case example.

Chapter 7 relates the empirical findings (Chapter 5 and 6) to the theoretical framework developed in Chapter 3. The evolutionary framework is refined after the empirical contributions to understand how is the buildings in relation to resilience today, but also a framework for those buildings in the future. The chapter discusses the challenges of the interaction of the flexibility and robustness needs on building development.

The eighth and final chapter presents the overall conclusions from this research on an evolutionary approach to resilient buildings and discusses questions for further research. In the pursuit of this aim, this followed the structure framework presented in Figure 1. The structure present the interactions between the theoretical framework and empirical work that had been carried out in this thesis.

This research, on one hand, advances both the theoretical and practical development on the resilience principle in the housing-sector. It adds the evolutionary perspective, which is then applied to building skin system. On the other hand, it contributes to the discussion on the inclusion of the user's knowledge on housing-development, assuming a shared responsibility on the resilient buildings. As such, it focuses on the interactions between flexible/evolvable system, and the need of robustness.

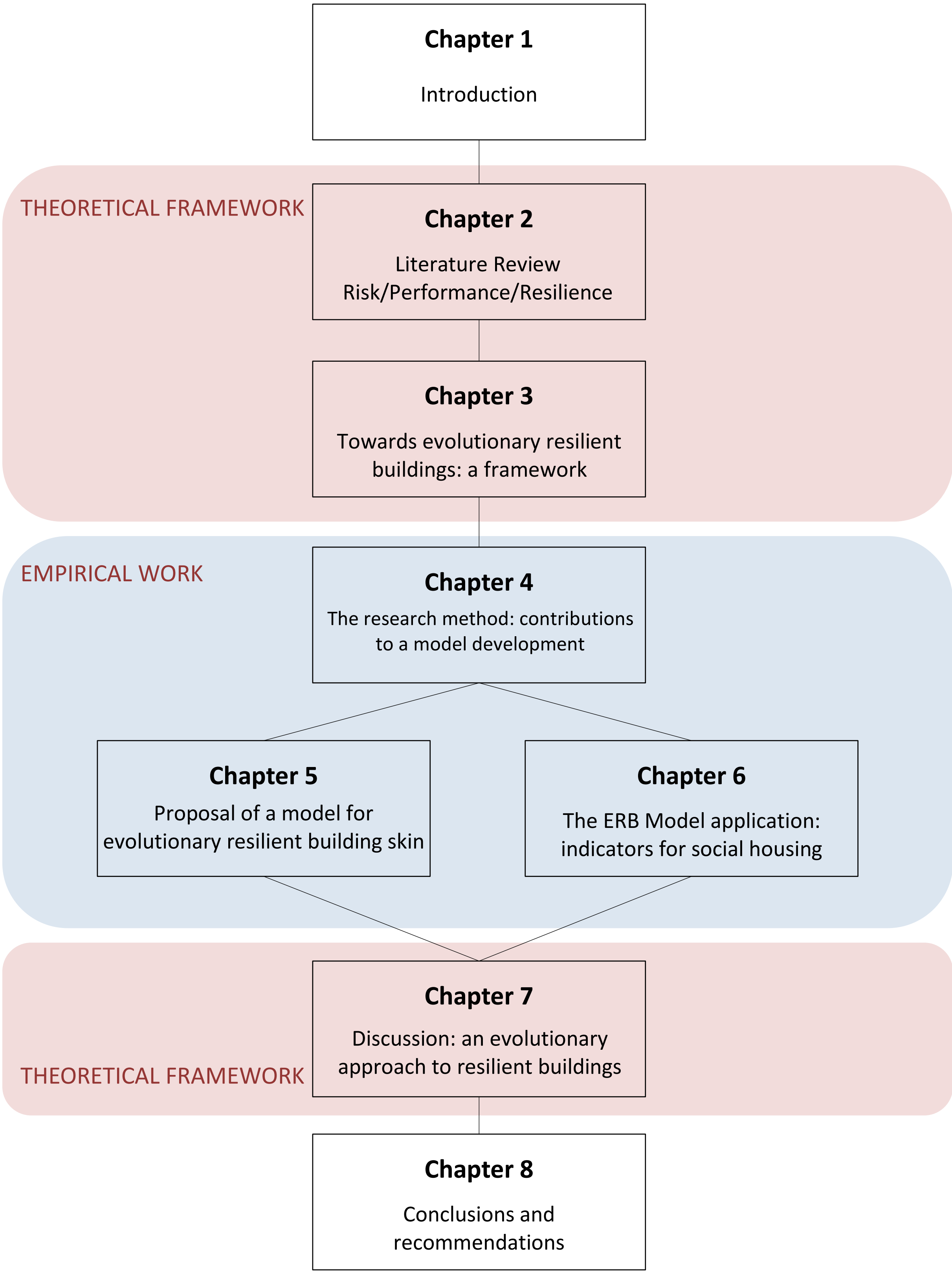

Figure 1: Structure of the thesis

2 LITERATURE REVIEW: RISK MANAGEMENT, PERFORMANCE-BASED APPROACH AND RESILIENCE

This chapter contains a review of the general knowledge about three broad themes of the research subject: risk management, performance-based approach and resilience concepts. The literature is written by the academy, industry and government, particularly housing construction. Firstly, the literature about the risk and related concepts are discussed, and some types of natural events in the Brazil context are explored. Secondly, the building performance approach and the standards and regulations are considered. Thirdly, resilience and the multiple approaches and definitions about the term is presented and discussed. Finally, the three elements are linked and their themes synthesised to justify and validate the research problem.

2.1 RISKS: UNDERSTANDING THE BASIC CONCEPTS

In a general form, risk can be described as "the possibility that something unpleasant or unwelcome will happen" (Oxford Dictionary). The recent large-scale events, such as the Indian Ocean earthquake and tsunami of 2004, the hurricane Katrina in the United States (2005), Tohoku earthquake in Japan (2011), Hurricane Sandy also in the United States (2012) brought up the importance of risk and disaster theme. Man-made, extreme weather events represent extreme risks the society and population must face. The definition of risk is the most important concept in disaster risk management; however, the meaning still requires more clarification. In the publication United Nations Strategy for Disaster Reduction Terminology[1] (UNISDR, 2009), the risk is considered as "The combination of the probability of an event and its negative consequences".

In a broad view, ISO Guide 73:2009 defines risk as "effect of uncertainty on objectives" wherein 'effect' is a deviation from the expected, 'objective' can have different aspects and levels, and 'uncertainty' is the state of deficiency of information (ISO, 2009). Additionally, the guide also considers that risk is often expressed as a possibility of events and/or consequences. Safety researchers traditionally use this view, and the traditional risk matrix is represented as shown in Figure 2. As seen in the figure, risk assessment is the relationship beyond the severity of the

[1] Available at: https://www.unisdr.org/we/inform/terminology#letter-r

consequences, and their probability (HOLLNAGEL et al., 2011). Based on that, the safety efforts and traditional risk management thinking had traditionally worked. (STEEN; AVEN, 2011).

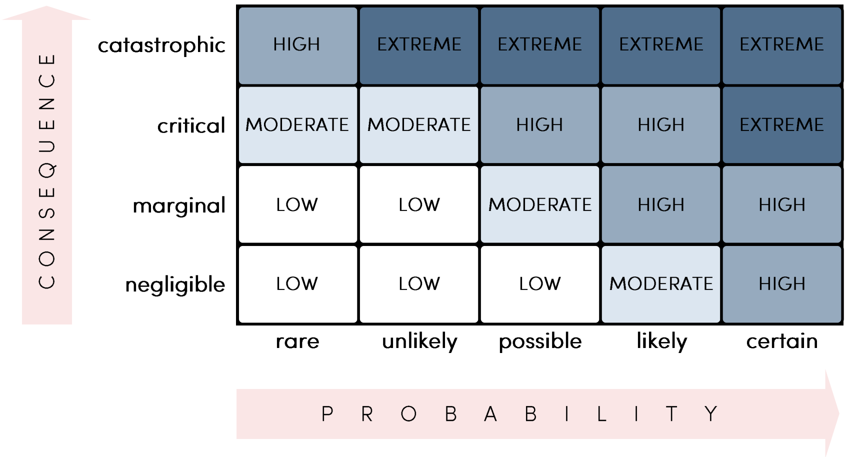

Figure 2: Traditional risk matrix (HOLLNAGEL et al., 2011)

Aven and Renn (2009) distinguish between two categories of risks. In the first category, the main component of risk is a probability. The traditional risk perspective follows this approach. In the second category, the central element is uncertainty, and here probability is considered a knowledge tool for expressing the uncertainties. In this perspective, the probabilities definition is carried out by a knowledge-based approach, (degree of belief) about the occurrence. When analysing both categories, the authors claim that risk refers to the uncertainty of the consequences and the severity of then. This perspective does not discuss the role of the system vulnerability, which can be an indicator to minimise uncertainty.

Risk can be described as potential damage (ROAF et al., 2009). For risk management approach, risk can measure probability or deal with uncertainties and adverse effects on people, properties or environment. By estimating the probability of a phenomenon of given magnitude times the consequences which are related to vulnerabilities (FELL et al., 2008). This is a critical factor in the literature review, as it recognises that for risk assessment it is necessary to define which hazards could impact a specific place and how (SHAWAB et al., 2007). Following this, risk can be assessed using the equation illustrated in Figure 3.

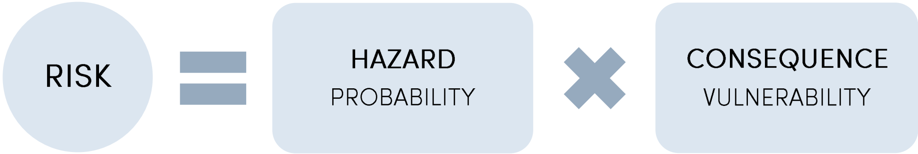

Figure 3: Risk assessment equation (CEPED/RS-UFRGS, 2016)

The risk assessment can be done by identifying the probability that a hazard (natural or man-made) could happen and the consequences on people, properties and environment. The effects can be assessed by the degree of loss, the value of damage or number of people lives. The result is closely linked with vulnerability (CEPED/RS-UFRGS, 2016). Therefore, it can be said that the severity of the consequence is higher when the vulnerability is considered high. A similar stance is adopted in this research, where all of those interplays are embraced in the risk's assessment. However, it is appreciated that uncertainty plays an essential role in hazard intensity as in the severity of the consequences.

2.1.1 Risk assessment and management

The multidisciplinarity inherent in risk management conduct to diverse conceptualization. Literature on risk management covers a broad spectrum of disciplines including, engineering, economics, geography, social sciences and sociology, for instance. The approaches are multiples and there is not a consolidated terminology.

The richness and complexity of the research on the varied aspects of risk assessment and management extend also to others terms that compound this research subject, as vulnerability, hazard and adverse extreme events. Given this context, the Figure 4, shows how important terms on risk management are related between them. The flow chart suggests that there is a logical information flow that starts by recognizing the type of events, passing by understand the probabilities and consequences of those events in order to reach the risk assessment. The figure also indicates that resilience actions are part of risk management and are the way to deal and be prepare to those risks.

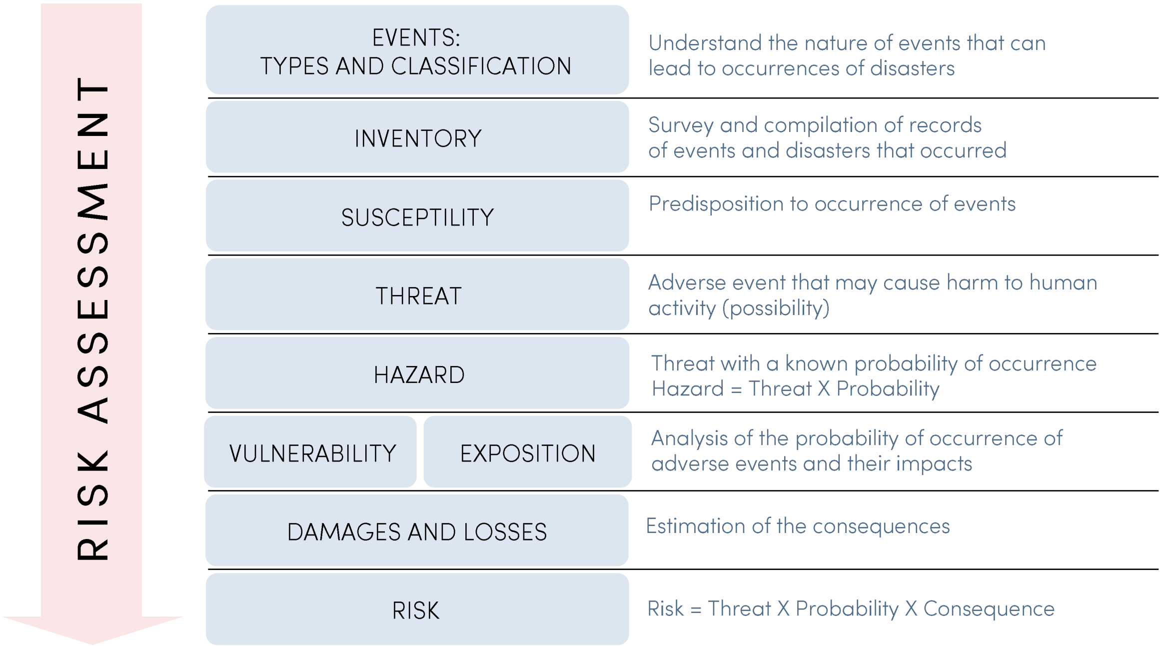

Figure 4: Conceptual flow chart of risk management (Based on CEPED/RS-UFRGS, 2016)

A useful starting point is to extract and define the key elements of this flow chart. The next sections of this chapter, explore in more detail the relevant definitions and understanding about the terms which are fundamental for this investigation.

2.1.2 Vulnerability

The vulnerability is the propensity to suffer some degree of loss, however not just expressed as exposure to hazard, but also by understanding holistically (human environment) the ability of how the system deals with hazard (BERKES, 2007). Proag (2014) defined vulnerability as the degree of how the system may react adversely during an event. The United Nations Strategy for Disaster Reduction Terminology brings the idea of susceptibility and defines vulnerability as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” (UNISDR, 2009). This conception implies a qualitative or quantitative measure of the physical or social resources that may not resist stressing.

The vulnerability could be analysed by an expected condition or degree of damage and cost to repair (CEPED/RS-UFRGS, 2016). In other words, vulnerability indicates a pre-existent state of a system exposed to a hazard. Those conditions could be analysed and expressed by the characteristics of the exposed system elements, by the environmental context and the type of hazard or event under appraisal. Figure 5 shows the interactions among the viewpoints that should be analysed.

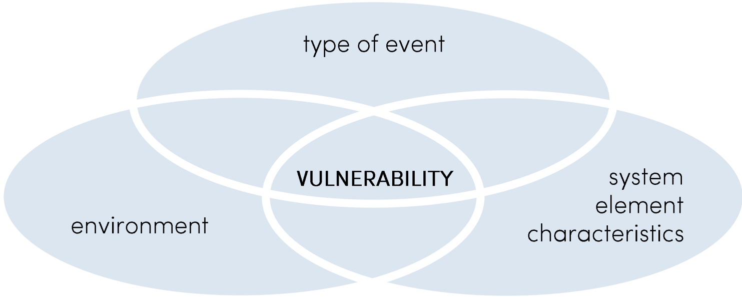

Figure 5: Vulnerability interactions (Based on CEPED/RS-UFRGS, 2016)

Those viewpoints suggest a holistically approach to define the vulnerabilities. For example, a house may be vulnerable or not to flood conditions depending on its position in the site or yet, this house may have low vulnerability to flooding but high vulnerability when considering storm condition, for instance. Proag, (2014) suggests three aspects to measure vulnerability:

a) Physical: vulnerability related to buildings, infrastructure and agriculture.
b) Social: vulnerable groups such as women, mentally and physically disabled people, children, and elderly and poor people, refugees and livestock.
c) Economic: losses to economic assets and processes that can be direct (physical and social infrastructure) and/or indirect (loss of production, employment, vital services, income disparities).

The vulnerability is inserted into many studies related to reducing vulnerability by building resilience (BERKES, 2007; MARIA PINTO et al., 2014; MOLES et al., 2014). For the point of view of reducing vulnerability to hazard, several aspects of resilience are brought into the discussion. However, resilience and vulnerable communities are not directly related. A vulnerable community is one which does not have the capability to preserve their own structure, while a resilient community can absorb the shock by adaptive capacity (MARIA PINTO et al., 2014). Nevertheless, building resilience into community systems is a way to cope with uncertainties and reduce vulnerabilities (BERKES, 2007).

2.1.3 Hazard, Extreme Weather Events and Disasters definitions

Hazard and Disaster do not have the same meaning. The Intergovernmental Panel on Climate Change (IPCC) definition mentioned that a hazard is “the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" (IPCC, 2012). A disaster in the other hand takes place when a hazard (natural or man-made) interacts with the human environment, especially in a vulnerable scenario (CEPED/RS-UFRGS 2016).

There are many descriptions of disaster as many authors writing about it. A definition widely accepted is presented by The United Nations Office for Risk Reduction that defines disaster as "a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" (UNISDR, 2009).

There is no common agreement regarding the classification of disasters and the subdivision typologies. Generally, researchers classify disasters in 5 categories: natural, unnatural or man-made, purely social, technological and hybrid (SHALUF, 2007a). The Centre for Research on Epidemiology of Disasters (CRED) classifies disasters in two groups: natural and technological. In (SHALUF, 2007b) opinion on natural disasters, those events are resulting from natural forces, where man has no control.

However, the terminology of "natural disaster" is continually used by some authors and by the media, it is not widely accepted. Nearly 40 years ago, O'Keefe; Westgate and Wisner, (1976) stated that the term 'natural disaster' was a misnomer, and questioned how 'natural' the so-called 'natural disasters' were. They highlighted that many disasters result from the combination of natural hazards and social and human vulnerability, including development activities that are ignorant of local hazardous conditions. Whilst earthquakes, droughts, floods, and storms are natural hazards; they may lead to deaths and damages (i.e. disasters) that result from human acts of omission rather than acts of nature (UNISDR, 2010). Therefore, it is more appropriate to use the term 'natural events' when talking about the events mentioned above, or 'disasters' when discussing a severe disruption of the functioning of a community or a society as a result of exposure to a hazard.

When consider natural events, they do not cause a serious disruption in society however, they may cause losses to the population, properties and environment (CEPED/RS-UFRGS 2016). Among natural events, the great concern due to the climate change is the so-called Extreme Weather Events (EWEs). EWEs are considered as "weather conditions that are rare for a particular place and/or time” (CREW Working Terminology) (HALLET, 2013). This definition recognises the particularity of being a “rare situation” in a determined place or time. However, the word “rare” is used in EWEs to refer an event with sufficient severity to generate a hazard (WEDAWATTA, 2013).

Examples of EWEs include extreme precipitation, floods, droughts, windstorms, extreme temperature landslides. The Intergovernmental Panel on Climate Change (IPCC) group these events in three categories:

a) Extremes of atmospheric weather: temperature, precipitation, wind;
b) Weather and climate phenomena: Monsoons, El Niño and other modes of variability, tropical and extratropical cyclones;
c) Impacts on the natural physical environment: droughts, floods, extreme sea level, waves, and coastal impacts, as well as other physical effects, including cryosphere-related impacts, landslides, and sand and dust storms.

It is important to note that the term EWE is often, as referred above, used to encompass events like flooding and landslide; which are more related to hazard than weather condition. A hazard, as mentioned, is a “potentially damaging phenomenon”. In this way, flooding and landslide, for instance, could occur due to a weather condition (heavy rainfall) although coupled with inadequate drainage and human modification of the land. However, the term EWE is often used as an umbrella term, to include weather-related hazards as well (WEDAWATTA, 2013). A similar stance to the IPCC definition and categorisation is adopted in this research, where the term EWE embraces both weather condition and hazard due to weather. The following section will briefly discuss some EWEs, which affect several countries as many Brazilians cities commonly.

2.1.4 Types of Extreme Weather Events

2.1.4.1 Flooding and flash flooding

The incidents of floods that frequently occur worldwide exposes vulnerabilities to flooding that can destroy homes, families, economies and businesses in an instant. In Brazil, the events related to floods and flash floods are the costliest to the country (CEPED/RS-UFRGS, 2016). Floods and flash floods have become more destructive, affecting more people in Brazil. In 2011 around 2 million people had been affected, in 2012 this number risen to 5, 2 million people (CENAD, 2012). Porto Alegre, is frequently affected by flooding. The Figure 6 show the 1941 unprecedented flooding (a) impacted more than 70.000 people, and was the motivation for the construction of a series of waterfront protection measures, that now is perceived as cutting the city from its lakefront (Guaiba Lake) (LOITZENBAUER et al., 2012). The Figure 6 also shows the 2015 flooding that affected mostly poor families living in the Porto Alegre islands on the Guaiba Lake.

(a) (Source: https://www.sul21.com.br/em-destaque/2015/10/historias-e-fotos-da-maior-enchente-de-porto-alegre/)

(b) (Source: http://g1.globo.com/rs/rio-grande-do-sul/noticia/2013/08/moradores-de-ilhas-deixam-casas-em-porto-alegre-prefeitura-pede-doacoes.html)

Figure 6: Pictures of the 1941 flooding in Porto Alegre (a) and 2015 flooding in Ilha do Pavão, Porto Alegre.

Similarly, the severity of floods in the United States is causing many losses, and it is the most common natural event in the country (SCHWAB et al., 2007). The National Flood Insurance Program (NFIP) is a program created by the Congress of the United States and aims to reduce the impact of flooding on private and public structures. They estimate that the average commercial flood claim was nearly $89,000 between the years 2010 and 2014 with nearly 25 percent of businesses closing permanently after a flood. In the context of the UK, the situation does not seem different. In England, the Environment Agency, informs that one into six properties is in risk of flooding. There are 5.9 million properties in risk areas of flooding, with 3.5 million of them being houses[1]). The flood risk in all countries is expected to increase due to climate change associated with expanding urban population (KOTZEE; REYERS, 2016).

It is important to mention that floods generally fall into two categories (SCHWAB et al., 2007):

a) General floods: are caused by precipitation over a long period and or over a given river basin. The riverine flooding it is due when precipitation and water runoff volume levels exceed the capacity of rivers or streams natural watercourse. The coastal flooding is usually the result of storm surges, wind-driven waves and heavy rainfall. Lastly, the urban

[1] Available at: https://www.gov.uk/government/organisations/environment-agency. Accessed in 03/10/2018.

flooding is due to the surface water, increased by impermeable surfaces. The speed of drainage collection, the reduced carrying capacity of the land and overwhelming sewer systems.

b) Flash flooding: occurs within a short period of heavy rainfall, and the flood water moves at a very fast speed. Its strength can roll boulders, tear out trees and destroy buildings and infrastructure.

The approach to flood risk management needs to change from resistance to resilience if the cities want to cope with floods (LIAO, 2012). The global increase in magnitude and damaging of flood events have shown that the traditional approach is not sufficient to deal with future uncertainties (KOTZEE; REYERS, 2016). And building for resilience has become important given the demand for new houses and the need to build in flood-prone areas (ESCARAMEIA; KARANXHA; TAGG, 2007). This new approach to deal with flood by the cities and buildings is particularly essential, as there is an increasing urgent to address flooding and the future uncertainties of the extreme weather events, rather than just relying on traditional approaches that are no longer adequate (TEMPELS, 2017).

2.1.4.2 Extreme precipitation and windstorm

Precipitation is the total quantity of water received at a specific place during a particular period of time. One significant impact of climate change is the higher precipitation, which results in more flooding on many sites (BLANCO et al., 2009). The IPCC report adds that these extreme precipitation events will become more intense and frequent in many regions, and these changes in precipitation will not be uniform (IPCC, 2014). All areas of the UK have experienced an increase over the past years to winter rainfall from heavy precipitation (JENKINS; PERRY; PRIOR, 2009). The UK Met Office affirms that the years of 2013 and 2015 was driven by large scale precipitation and made UK's record December rainfall[1].

In Brazil, precipitation varies widely. For instance, according to the Brazilian Atlas of Natural Disasters, while in the Southeast region can reach 4.500mm per year, part of Northeast the precipitations levels are 500mm per year. The South region is characterised by extreme precipitation events, causing flooding, flash floods, windstorm and tornados, with the possibility of snowfall between May and September. Hail is another hazard associated with precipitation that is a concern at the South and Southeast regions. In the last 22 years, at least 2 million people

[1] Available at: https://www.metoffice.gov.uk/climate/uk/summaries. Accessed in 02 Oct 2018)

were affected by hail events, having their houses damaged (CEPED/UFSC, 2012). Figure 7 show the impacts of the tornado that affected the Vila Oliva district, in Caxias do Sul city, in June of 2017.

(source: Paulo Pasa)

Figure 7: Pictures of the 2017 storms in Caxias do Sul

High intensity and long-lasting rainfall are associated with landslide triggering factors (ZÊZERE et al., 2008) and contribute to the increase of floods, being used to estimate the ensuing flood flows (PROAG; PROAG, 2014). Precipitations can be associated with windstorms. The high wind speed, increase the storm damages and may cause an outage of emergency, infrastructure and transportation services (BASYOUNI, 2017). In the South region of Brazil, tornados and windstorm are common cause of disasters. Those events are increasing in the last decade, with 364 windstorm events in 2009 compared with 75 in 1991.

The impacts of those extreme effects on buildings have particular relevance. The intense rainfall has an effect on the intensity of runoff and can create some issues regarding structural integrity, drainage. The hail events can cause significant damage to roofs, guttering and windows, the increased humidity cause mould, condensation and so on (BASYOUNI, 2017). Heavy rainfall in urban areas is often damaging. However, the public underestimates the consequences in infrastructures and building (GOLZ et al., 2016), and since the probability and magnitude of these events have been increasing, it is paramount the research in the field.

2.1.4.3 Extreme temperatures

The extreme temperatures can be characterised by the extremely cold winter and contrasting hot summer. Severe winter can produce some hazardous conditions, as freezing rain, wind chill, extreme cold and snowstorms (SCHWAB et al., 2007). A number of heavy snowfalls affected the UK in recent years, leading to a costly situation for business (WEDAWATTA, 2013). In

Brazil, especially in the South region, the cold weather can form frost. The event is particularly damaging to crops or future crop yields, what may cause many losses for farmers.

However, the emerging concern is about the high summer temperatures and the recent heat waves events. Global average temperature has increased by nearly 0.8ºC since the late 19th century (JENKINS; PERRY; PRIOR, 2009), and, according to the Intergovernmental Panel on Climate Change (IPCC), this happens due to anthropogenic gas concentration. It is well accepted that heat waves have severe impacts on human health, increasing mortality and morbidity (WOLF; MCGREGOR, 2013).

Miller (2015) states that the effects of heat waves on houses and users is a significant concern and proposes that more thought should be given to building regulations, air-conditioning standards and building design. The potential house overheating have particular interest for vulnerable social housing residents, and this issue is a more considerate concern when is occupied by vulnerable people such as elderly, and/or people suffering for ill-health or mobility impairment (MAVROGIANNI et al., 2015). The impact of high temperatures, heat waves and consequent overheating inside houses will become more frequent with the evidence of the global warming; thereby, more attention should be demanded in this subject.

2.1.4.4 Droughts

Droughts are characterised by prolonged periods of no rain or small quantity of rain in a specific region, causing a severe problem in the hydrological cycle (CENAD, 2012). Droughts are a common weather extreme experienced by Brazil, and in some parts of the world is a common experience. In the Brazilian Northeast, the droughts are the cause of population displacement, and the water availability is constrained.

Furthermore, severe droughts can cause many losses in crops and familiar agriculture, also affecting energy production (CENAD, 2012). Additionally, a long period with no rain can increase the susceptibility to fire on the dry vegetative groundcover, been particularly dangerous for wildfires (SCHWAB, 2007)

2.1.4.5 Mass movement and Soil Erosion

Mass movement and soil erosion are global problems, and human activity plays an important role (GUERRA et al., 2017). A mass movement, as Selby (1993) synthesised, is the movement of soil and/or rock downslope, under gravity driving force, without being assisted by water or ice. However, the water and ice can decrease the soil shear and turn the event catastrophic (GUERRA et al., 2017). Land subsidence and collapse are mass movements that can cause severe damages in building structures. They are problems throughout the word and can be caused by a loss of support below the ground (SCHWAB, 2007).

The most common and damaging of mass movement events are landslides. Landslides can vary from size and speed of soil and debris downhill and can cause serious disruptions on agriculture, infrastructures and all community life (SCHAWB, 2007). Clague and Roberts (2012) argue that each year, landslides can be responsible for over 1.000 deaths and hundreds of millions of dollars in losses around the world.

In Brazil, especially in recent years, the construction of houses on steep slopes has been responsible for many landslides. Over 40 people died in Angra dos Reis Municipality, São Paulo State, due to landslides associated with about 200mm of rain in 24 hours in December 2009. In 2011, one of the most severe tragedies occurred in a region known as Região Serrana Fluminense, where more than 900 people were killed (GRAEFF; GUERRA; JORGE, 2011). There is still much to be understood about those tragedies, and a more significant effort must be made to avoid urban development in steep slopes and rivers banks.

Selby (1993) classified soil erosion as a process that occurs on hill slopes, carried out by flowing water and splash process. Outlining the difference between natural and accelerated soil erosion is important. The first is where the water is flowing on the soil surface, reducing soil thickness over a long period, the second usually happens on agricultural fields and bare soils (GUERRA et al., 2017). These events are becoming a recurrent problem in the UK, and the cost is high. Boardman and Vandaele (2010) argues that besides erosion, runoff and resulting muddy flood are related to the weather. However, the land use and management decisions are in fact, the main causes.

2.2 BUILDING SYSTEMS PERFORMANCE

The building performance-based approach is especially important to be discussed in the literature review for this research, once, the building functions, that is a fundamental part of resilience, are closely related to how the building systems perform. The performance-based approach is a viewpoint where the building is considered as a whole, and it is allowed trade-offs between different parts of the building's systems to achieve the objectives (BARLOW, 2012).

A key element here is the consideration of the emergence of performance-based regulation and in particular Brazilian case, the standards (NRB 15.575_ Performance-based building Standard) besides the earlier prescriptive regulations, criticised by their rigidity in materials and configurations specifications. The performance-based approach tend to stimulate innovation, a systemic view in the building sector, information sharing and cooperation between public and private sectors.

This approach should comply with the environmental and social aspects of the building. Due to this view, it seems that the building performance requirements and how they can be measured during the building lifecycle are closely related to the environmental risks and with if the resilience itself.

2.2.1 Evolution of the performance-based approach

For thousands of years, the concept of the performance of buildings, and the idea of considering a house as a whole that should be able to provide acceptable comfort levels and follow some requirements is part of architecture and civilisations. Lorenzi (2013) mentions the Hammurabi code, from 1900 B.C. as an example of a document that establishes several rules that punish the builder in case of building failure during the years. A well-known quote from the Hammurabi Code mentions the following:

> "Article 229: If the builder has built a house for a man, and his work is not strong, and if the house he has built falls in and kills a householder, that builder shall be slain."

It is important to highlight that the code does not mention the ways and means, but instead states the required result (the building should not collapse) (FOLIENTE, 2000). The performance approach started to receive attention with the concrete steel structures applied to buildings and the concern around performance began to be more evident (LORENZI, 2013). In 1925, the US National Bureau of Standards published a report with orientations for the arrangement of building codes and setting that whenever possible, requirements should be stated regarding performance rather than prescriptions.

The evolution of the performance-based approach is connected with the development of innovative building systems (LORENZI, 2013). In 1947, France developed an institute called *Centre Scientifique et Technique du Batiment*, (CSTB) to evaluate the performance of these innovative systems. Still in Europe, in 1960 was created the *Union Européenne pour Agrément*

Technique de La Construction, (UEAtc), for the consolidation of the performance concept and evaluation of the building systems. In the same decade, the Department of Housing and Urban Development in the U.S also promoted a program to develop criteria for the design and evaluation of innovative systems.

During the years, some reports and proceedings of a series of conferences had been developed around the subject. The International Council for Research and Innovation in Building and Construction (CIB), the American Society for Testing and Materials (ASTM), and the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) had been developing a series of conferences and progress in this area in the last decades. An important milestone was the ISO 6241 – Performance Standards in Building: Principles for their Preparation and Factors to be considered, in 1984. This standard describes a general principle for the preparation of performance-based regulation assisting standards committees concerned with the subject. This standard had been recently revised by ISO 19208: Framework for specifying performance in buildings (ISO, 2016).

During 1990, there was an emphasis towards performance-based construction regulation in an international level stimulating high-performance emerging technologies (BARLOW, 2012). In 2001, the Performance-Based Building Thematic Network (PeBBu network) was created, funded by the EU 5th Framework Research Programme and managed by CIBdf. The program's main goal was the stimulation and dissemination of Performance-Based Building ideas. One of the objectives was to reach a consensus document called the conceptual framework on Performance Based Building. This program ran until 2005 and came up with a final report that compiled the achievements of the network.

In Brazil, the first studies started around 1970 and 1980, led by Instituto de Pesquisas Tecnológicas (IPT) and supported by Banco Nacional de Habitação (BNH). The studies, following international concern, focusing on investigating the performance of innovative systems (LORENZI, 2013). Later, in 2008 the first version of the Brazilian Building Performance Standard, NBR15575 was published. However, the standard was only officially published in 2013. This standard is explored and, in the section 2.5.4, Brazilian Performance-based Building Standard – NBR 15575 (2013).

2.2.2 Performance-based and prescriptive regulation

In essence, a prescriptive approach indicates a solution while a performance-based approach describes a required performance (FOLIENTE, 2000). The performance-based approach is basically, the practice of thinking in terms of ends rather than means (CIB, 1982). The ISO 6241(1982) add that performance approach is related to the behaviour when in use. In the final report of PeBBu network, to this concept was added the behaviour related to use during service life. The revised ISO 19208 (ISO, 2016) brings the concept of the standard ISO 6707-1:2014, 9.1.1 where performance is the “ability to fulfil required functions under intended use conditions, behaviour when in use or impact on economic conditions, the environment, society or quality of life”. The framework presented on this standard, reiterate that performance is the behaviour in use and is related to health, safety, convenience, comfort and protection of property, besides seeking sustainability. This performance of the building as a whole may vary from its parts, and on the other hand the subsystems, element or component may influence the performance of the building. Figure 8 shows the structure of the framework to define the relation of the performance of a whole building and its parts ISO 19208.

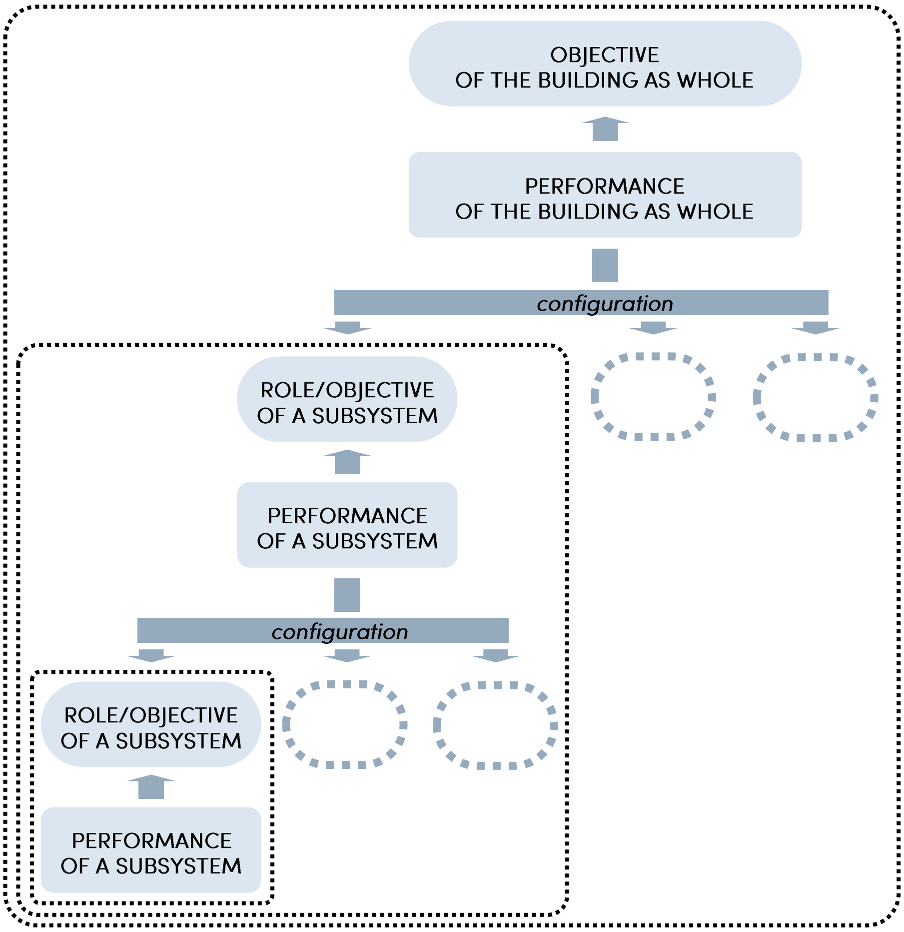

Figure 8: Hierarchical structure of the performance as a whole building and its parts (ISO 19208, 2016)

Performance-based approach plays an important role in the stimulation of innovation in the construction sector. The prescriptive approach, on another hand, had been criticised as a rigid mechanism where materials and configurations must meet regulatory goals reducing the opportunities for innovation (BARLOW, 2012). Foliente (2000) affirms that the more performance orientated is the specification the easier will be for the designer provide alternative solutions for a specific problem while enhancing innovation. The idea around performance-based approach is not to guide how to build the building, but how the building should behave after built, thus the technique and materials used to reach this goal become wide open. Similarly, Barlow (2012) points that in performance-based regulations, the building is consider as a whole and allowed trade-offs between the different building systems to achieve the objectives, which orients to a systemic innovation rather than just materials sub-systems.

The performance concept is largely embraced philosophically. However, its appliance is fundamentally associated with the building behaviour and context under certain conditions. (COVELO SILVA, 2010). The climate, legislation, and social factors are among those conditions. The social aspect challenges the focus on the performance level required for both needs of the users as well as construction business (SPEKKINK, 2005). Borges, 2008, also points out that the performance required should express the socioeconomic reality of each country or location.

The users' needs are the starting point for analysing the functions of a building, the performance requirements and also the engineering parameters. In this context, Gibson (1982) affirms that users are taken as a broad term to define not just the permanent occupants, visitors and maintenance team, but also interested parties such as owners, financiers, and neighbours. In fact, De Wilde (2018) corroborates with the users are the first step to performance-based design, however, the author call users as stakeholders. The Figure 9 presents the core steps to achieve a performance-based design, whose focus are the users.

CORE STEPS OF PERFORMANCE-BASED DESIGN	
STEP 1	Identify all stakeholders of the future building, their activities and the corresponding stakeholder needs
STEP 2	List all conditions and activities that might be a barrier to achieving the stakeholder needs; study these as generalized loads and, where needed, the combinations of loads that might occur
STEP 3	For each stakeholder need, identify performance indicators that allow to specify the performance requirements
STEP 4	For each performance indicator, define what it is that indicates stakeholder dissatisfaction or performance failure
STEP 5	Define accepted levels of failure, and acceptable percentages of dissatisfied stakeholders, for each stakeholder need while taking into account all stakeholder activities that have been identified
STEP 6	Define the loads that will be applied to the building in terms of checking performance
STEP 7	Set the threshold values (limits) for the performance indicators
STEP 8	Apply any safety factors to modify the threshold values into design targets
STEP 9	Identify which analysis tools can be used to study the performance of the building under the loads that need to be studied
STEP 10	Employ approaches that allow the analysis of the performance of all relevant design options

Figure 9: Steps of performance-based design (DE WILDE, 2018)

In order to meet the user’s needs, it is necessary first to make these requirements more explicit. At this stage, the user’s requirements should be translated in “performance language” (SPEKKINK, 2005), distinguishing the user's demand and how this is supplied. To represent this relation, Ghieling (1988) presents a model that is called “Hamburger Model”, seen in Figure 10.

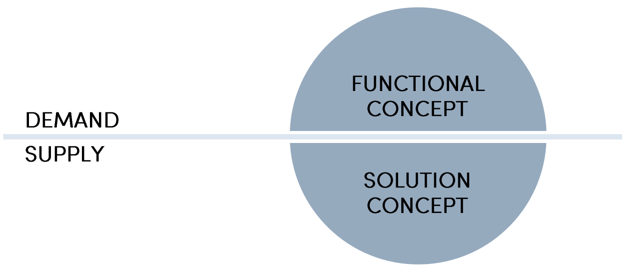

Figure 10: The Hamburger Model (SPEKKINK, 2005)

Figure 10 also represents the need for validation or verification of the building result against the performance targets. The performance verification can be made through: in situ testing, calculation/simulation and a combination of testing and calculation (FOLIENTE, 2000). Those verifications implies that the performance-based approach can be applied either in the production for building or as quality control.

Additionally, adequate methods of verification must be chosen to have a clear answer about a specific behaviour. Based on the performance approach for buildings several codes, regulations and standards have been developed over the years. Some of these will be discussed in the following section.

2.2.3 International Regulations

The protection of their citizens is the major reason for the government to draw up laws and regulations for the built environment. Governments, associations and representatives of organisations in the building sector are involved in the formulation and acceptance of these regulations and standards. The umbrella of the performance-based building standards is the recently revised ISO 19208:2016, which provides a framework to specify the performance of a building to achieve specified user requirements.

In addition to the technical standards, the construction sector must to comply with the building regulations. Those are legal documents that intended to ensure that buildings are constructed accordingly, provide a safe and healthy environment for the users. Performance-based building codes have been in use since 1985, with the publication of The Building Regulations in England and Wales.

In order to develop a building regulation, the performance-based code frameworks used had been variations of the Nordic Five Level System developed in 1976 (FOLIENTE, 2000). This system, developed by the Nordic Committee on Building Regulations and called NKB model have five levels. Level 1, addresses the goals and objectives of the user/consumer; Level 2, sets functional requirements for which parts of the building; Level 3, the translations to operative and performance requirements; Level 4, the verification methods and Level 5, the example of acceptable solutions (a prescriptive part of the system) (MEACHAM et al., 2005). This structure is behind many building codes currently in use, since this relation between top societal goals and bottom of verification levels seems to be very effective (MEACHAM, 2010).

Since the use of the performance-based codes grounded on the NKB models, it was noticed a need of gathering more detail to accomplish the top levels of the user's goals, as information about risk, in particular, building that should stand over hazard events (MEACHAM; VAN STRAALEN, 2017). In the 2000s, the level of risk was added to this model, and the eight-level model was developed by the Inter-Jurisdictional Regulatory Collaboration Committee (IRCC).

Figure 11 shows the two models described above: the NKB five levels model (left) and the eight-tier IRCC performance/risk system hierarchy for performance-based building regulation.

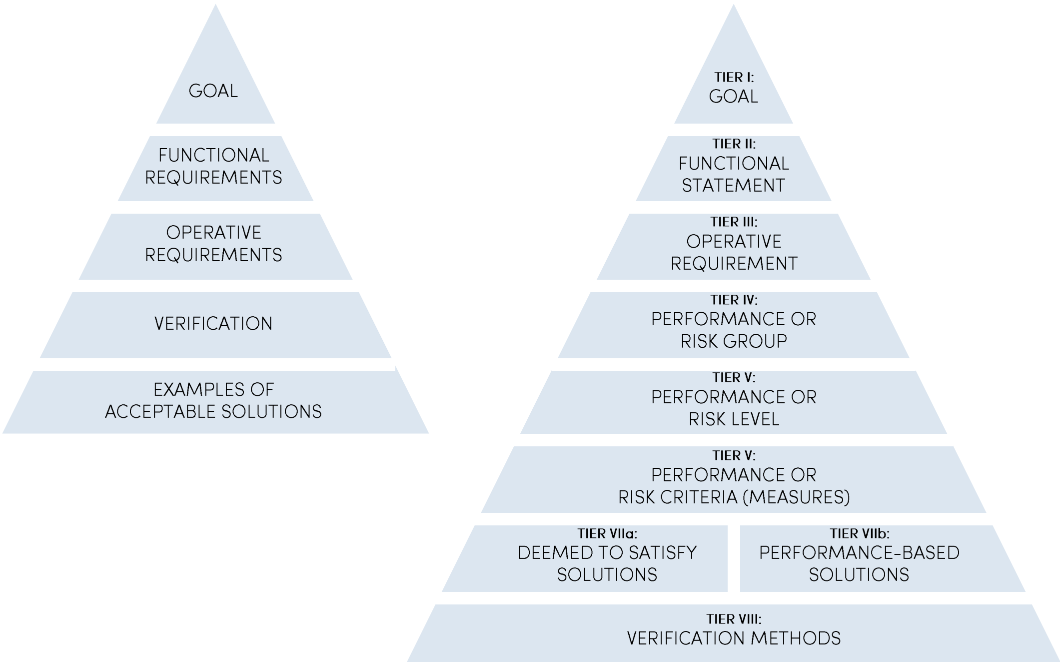

Figure 11: NKB hierarchy (NKB, 1976) and IRCC hierarchy performance-based building regulatory system (MEACHAM et al. 2016)

Since the beginning, the building codes have evolved, especially in the last decade. After the transition from prescriptive building codes to functional or performance-based, new societal needs had been included. Among these needs are the ones related to sustainability and climate change resilience (MEACHAM; VAN STRAALEN, 2017).

However, some significant advances are still in progress, and the societal expectation and environmental threats are continuously changing. The incorporation of risk into regulation is still a complex and challenging task. Meacham (2016) demonstrate through a comprehensive literature review that there is still a lack of clear performance criteria and verification methods. Although, the author affirmed that the most significant challenge would be to address sustainability and resilience objectives in building codes.

2.2.4 Brazilian Performance-based Building Standard – NBR 15.575

The Brazilian Performance-based Building Standard NBR 15.575 (ABNT, 2013), is a recent national voluntary standard developed with a performance-based approach for housing buildings, first released in 2008 and finally published in 2013, by the Brazilian Association of Technical Standards (ABNT). And, to date, there have been a few published academic work which evaluates the response and adequacy of the housing design, mainly in durability and maintainability requirements.

The standard establishes requirements, parameters and methods to specify, elaborate and assess the performance of housing projects. The standard proposes the minimum indicators needed to achieving security, habitability and sustainability requirements. In Brazil, the performance-based approach was introduced later in the construction sector. The NBR 15.575 standard had studies developed between 2009 and 2012, and the Performance-based Building standard is only applied to the housing sector.

The NBR 15.575 had a high impact on the construction sector. The standard is a major regulation which will have considerable impact on the planning, design, construction and occupations of new homes. The housing building sector strives to meet the new requirements introduced by the standard. However, all the construction sector stakeholders' responsibilities is settled by the standard, including for the first time in the Brazilian scenario, the user's responsibilities.

The NBR 15.557 is divided into six parts that represent building subsystems: Part 1 - General requirements; Part 2 - Structural requirements; Part 3 – Requirements for internal floors; Part 4 – Requirements for Internal and External walls; Part 5 – Roofing Systems requirements; Part 6 – Requirements hydrosanitary systems. In each one of those parts, the performance requirements and criteria are based on the three big objectives such as user Safety, Habitability and Sustainability, as shown in Figure 12.

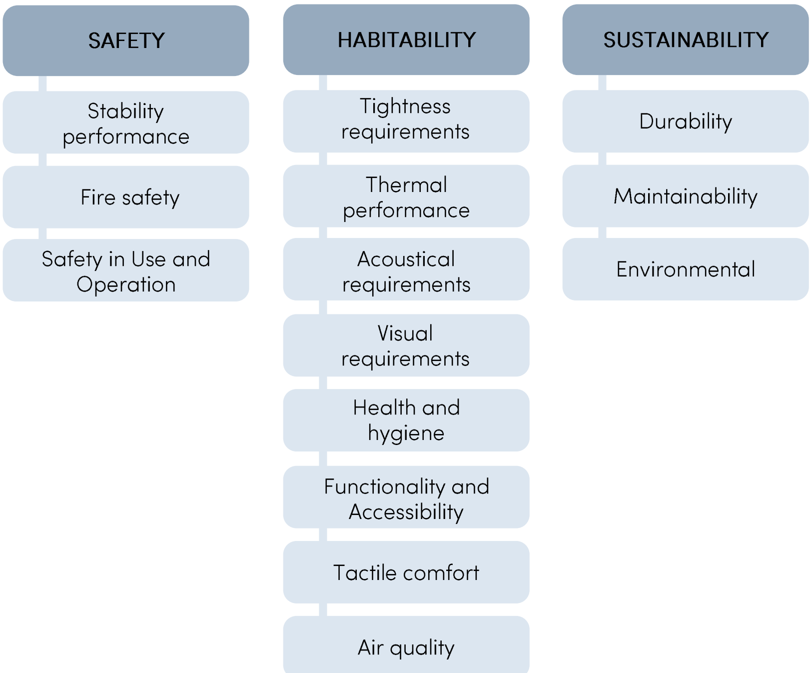

Figure 12: House Building Performance Requirements, NBR 15.575 (ABNT, 2013)

2.2.5 Building life cycle: Key concepts

This section of the literature review explores important definitions around building life cycle, including the design, construction, operation, maintenance and end of service life. This view is useful to understand the performance over time and to possibly increase resilience. Accordingly to the ISO 15.686-1 (ISO, 2011) "the life cycle, incorporates initiation, project definition, design, construction, commissioning, operation, maintenance, refurbishment, replacement, deconstruction and ultimate disposal, recycling or re-use of the asset (or parts thereof), including its components, systems and building services". As Figure 13 shows, the life-cycle stages for building assessment with life-cycle phases have been defined in standards such EN 15.978 (EN, 2011). These standardisation efforts are significant since there are very few studies that have assessed the described phases (OREGI; HERNANDEZ; HERNANDEZ, 2017)

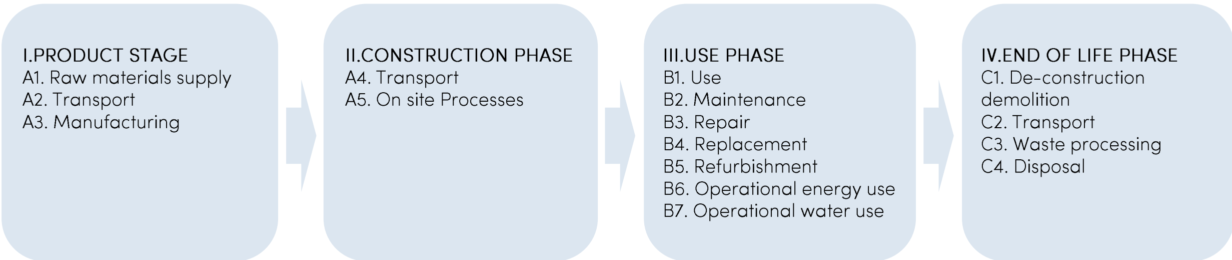

Figure 13: Different stages of the building life-cycle according to EN 15.978 standard (EN, 2011)

Following, some concepts and the issues that should be considered around of design life, service life, maintenance and obsolescence are clarified for this research.

2.2.5.1 Service life and design life

Service life is the "period of time after installation during which a facility or its component parts meet or exceed the performance requirements" ISO 15686-1 (ISO, 2011). During this period the building gradually deteriorated (if the building does not experience any acute shocks) and can become obsolete. Nireki (1996) argues that service life must be associated with proper maintenance of the item and is a synonym of durability. However, it is understood for this research that durability is related only to the components that compound the building (PRIETO IBÁÑEZ et al., 2016) and service life is more appropriate to apply to the buildings.

In order to achieve a design life, the service life planning should be established preferably in the early stages of the design phase, preparing the brief and design for the building to achieve or exceed its design life. The design life is the service life intended by the designer and should be planning aiming reliability and flexibility, increasing life-cycle and reducing early obsolescence. The ISO 15686-1 (2011) affirms that a service life planning must take into account life-cycle cost of the building and the life-cycle environmental impacts. A more accurate service life prediction can support the selection of materials and optimisation of a whole building and can be helpful to determine timing and schedule for inspections as well as providing a better measure to manage risks (EL-RAYES et al., 2016)

2.2.5.2 Maintenance, conservation and maintainability

The NBR 15575 (ABNT, 2013) define maintenance as the activities that conserve and recover the functions of the building and its systems, to attend the safety of the users. ISO 15686-1 (ISO, 2011) adds that maintenance is a combination of all technical and associated administrative actions during the service life to retain a building, or its parts, in a state in which it can perform its required functions.

Maintenance can be either preventive or corrective, whether preventive concerns about the routine maintenance plan and the corrective maintenance is the reactive maintenance in response to a failure or break down (MOTAWA; ALMARSHAD, 2013a). Conservation can also be understood as the preventive maintenance, for this research, maintenance will be used to define either conservation as corrective maintenance.

Maintainability can be defined as a degree to which a system, component or materials can be maintained when this activity is executed under procedures and pre-established protocols (ABNT, 2013). It is, finally a design parameter (DYK; KNOPJES, 2006).

2.2.5.3 Obsolescence

One of the contributions of maintenance is to delay or perhaps avoid obsolescence. Obsolescent buildings or components are those that are no longer able to be adapted to satisfy the requirements (ISO 15656-1, 2011). Rudbeck (1999), points that there are six “lives of buildings”: design life, economic life, functional life, social and legal life, technical life and technological life. The author affirms that the end of the building service life is the moment when one of this lives exceed the limits.

ISO 15656-1 (ISO, 2011) defines three types of obsolescence: Functional, which the function is no longer required, Technological, when better performance is available or changing pattern of building use, and Economic, when it is fully functional but less efficient and more expensive. An important aspect when dealing with buildings as part of a socio-ecological system is that factors such as cultural value, social acceptance and changing connections with the growing city can also ensure early obsolescence. However, in this thesis, the building will be analysed as an isolated peace, and just the functional, technological and economic obsolesce will be analysed.

The adaptation with refurbishments and upgrading are the major strategies to counter obsolescence, and for this flexibility of design and components, connections are a key factor. The material re-use and recycling or building repurposing are better alternatives to reduce waste, energy and resource consumption at the end of service life (ASSEFA; AMBLER, 2016).

2.3 THE NATURE OF THE TERM RESILIENCE

The resilience word as a scientific English term was used for the first time in 1625, by Sir Francis Bacon in the compendium of natural history (*Sylva Sylvarum*) to explain the strength of echoes (ALEXANDER, 2013). Afterwards, the concept has been used in several different spheres, such as mechanics, and subsequent psychology and ecology, (HOLLNAGEL, 2014), in recent years, in social, urbanistic and sustainability studies. The term came from *resilire, resilio,* the Latin term for bounce, justifying the concept of "bouncing back"(ALEXANDER, 2013). The first use of the term resilience in mechanics' approach was used to describe the strength and ductility of steel beams in 1858. In this context, the resilience of the steel is related to its resistance against application of force (rigidity) and to absorb deformations (ductility)(ALEXANDER, 2013).

In the psychological field, the term began to be used during 1970 in studies related to people that appeared to be functioning facing traumatic situations without adaptations problems (BORGE; MOTTI-STEFANIDI; MASTEN, 2016). Most recent perspectives include protective and risk factors as suggested by (ESHEL et al., 2017) where resilience should be defined "as the balance of individual strength (protective factors) and vulnerability (risk factors) following an adversity or a traumatic event".

Over the last years, a number of different disciplines adopted the term, such as ecological, social, socio-technical, organisational and socio-ecological systems, introducing several new definitions and transdisciplinary uses and adaptations (HASSLER; KOHLER, 2014a). In the organizational sector, the term resilience is relatively new to management thinking and has been introduced with an awareness increase about risks and vulnerability; reduced reserves create the scenario for resilience thinking (MCASLAN, 2011). The British Standard, BS 65000 (BS, 2014) defines "organisational resilience" as the "ability of an organisation to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions in order to survive and prosper." This definition leads to a broader and holistic view of how business deals with risk management.

Resilience Engineering is the current approach in safety management system, which explores the nature of complex socio-technical systems. The resilience thinking contrasts with risk management, a traditional approach in this field. While risk management is based on failure reporting, risk assessment to diminish things that goes wrong, resilience engineering focuses on the things that go right (HOLLNAGEL et al. 2011). The Resilience Engineering Association defines that "resilience engineering looks for ways to enhance the ability at all levels of organisations to create processes that are robust yet flexible, to monitor and revise risk models, and to use resources proactively in the face of disruptions or ongoing production and economic pressures". Similarly, Hollnagel (2011) argues that resilience engineering points out that four abilities are necessary for the system to be resilient: to respond to events, to monitor ongoing developments, to anticipate future threats and opportunities and to learn from past failures and successes. The engineering resilience approach pursuits the establishment and management of this interdependent abilities.

In the environmental policy-making arena and disaster management scopes, there are multiple definitions of resilience. Birkmann et al. (2010) identifies 21 definitions of resilience in the UK Civil Protection Guide. In another major study Lizarralde et al. (2015) analyse 43 policy documents and 21 practitioners interviews, and in both cases, the term still does not have a common sense. The practitioners interviewed describe that resilience does not mean much in a practical sense, although they try to implement. Despite the definition of resilience in disaster management being only a buzzword at first, some theoretical approaches highlight a series of abilities or capacities.

The term resilience has been largely used in policy and seems the answer to climate change adaptation, environmental management, economic development and strategic planning (DAVOUDI; BROOKS; MEHMOOD, 2013). In the prominent international policy documents such as Sendai Framework for Disaster Risk reduction 2015-2030 resilience is defined based on the document of the United Nations Office for Disaster Risk Reduction (UNISDR), "2009 UNISDR Terminology on Disaster Risk Reduction" as:

> The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (…).

This definition is relevant because the inclusion of community and society shows resilience in the camp of governance and policy, beyond the scientific discourse (DAVOUDI et al., 2012). According to the Intergovernmental Panel on Climate Change (2007) “the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change”. While the second definition highlights the ability to absorb and adapt, the first focus on recovery and resist.

In Paton (2007) work is argued that resilience has to cope with adaptive ability, since the idea of bounce back does not capture the reality of disaster situations, since the physical, social and psychological conditions are always changing. Here resilience is defined as the “capacity of a community, its members and the systems that facilitate its normal activities to adapt in ways that maintain functional relationships in the presence of significant disturbances”. Paton’s definition highlights the necessary ability of adaptation. This interpretation is similar to the evolutionary resilience approach that will be a focus on this study.

2.3.1 Interpretations of resilience

Based on a literature review from a wide range of disciplines Davoudi et al. (2012) identifies three different main conceptualisation dealing with resilience: engineering resilience, ecological resilience and evolutionary resilience. These three definitions or faces, as the author calls, contrasting in how to approach the equilibrium state and how to reach it. These three approaches will be elaborate in turn.

2.3.1.1 Engineering resilience

In Engineering, resilience is the ability to return to an equilibrium state after a disturbance (GUNDERSON, 2000). Therefore, in engineering for a system to be resilient, the definition “concentrates on stability at a presumed steady-state and stresses resistance to a disturbance and the speed of return to the equilibrium point” (BERKES; FOLKE 1998, p. 12). Such resilience concept consists of four properties: robustness related to strength and withstand a level of stress; redundancy, property of the system which the elements are capable of being substitutable; resourcefulness, the capacity to identify the priority problems and apply materials in order to achieve goals; and the rapidity to achieve the goals in a timely manner (BRUNEAU et al., 2003). Engineering resilience is, therefore, the ability to "to return to the steady-state following a perturbation"(HOLLNAGEL, 2014). This approach has been used mainly dealing with safety management in socio-technical systems (STEEN; AVEN, 2011)

Resilience in this field is a property of dynamic and intentional systems. In this type of system there are the people intentions, and besides this approach had been defined mainly for socio-technical systems and safety management, the conclusions about resilient systems abilities are close to social-ecological definitions (HASSLER; KOHLER, 2014a). However, for resilience engineering is accepted the idea to return to an equilibrium state contrasting with the new ideas in socio-ecological systems.

2.3.1.2 Ecological resilience

The pioneering work to refer resilience to ecosystems was Holling, 1973 paper that contrasted resilience and stability. Holling suggested that "Resilience ... is a measure of the ability of these systems to absorb changes [...] and still persist" and Stability as the ability to return to an equilibrium state after a temporary disturbance" (HOLLING, 1973). This definition is important because it challenges the ecological paradigm of equilibrium (LIAO, 2012), and introduces the idea of multi-equilibrium and rejecting the idea of a single equilibrium (DAVOUDI; BROOKS; MEHMOOD, 2013). Additionally, led to a distinction between engineering resilience and ecological resilience (HOLLNAGEL, 2014).

In the ecological approach, resilience is the result of tolerance and reorganisation contrasting with engineering which the interpretation is related to resistance and recovery (LIAO, 2012). The idea in the ecological approach is that exist more than one equilibrium state, contrasting with engineering interpretation, it is suggested that resilience is a returning to a pre-disturbance state, which the system *bounces back* to a pre-existing state, while in ecology the system *bounces forth* to a new state and can continue between states (DAVOUDI et al., 2012).

This interpretation of multiple equilibrium states is argued to be more appropriate to social-ecological systems since it does not exist an optimal reference state in coupled human-natural systems (BERKES, 2007). Additionally, as some authors affirm (Maria Pinto et al., 2014; Elkadi, 2015), that communities that suffered from disaster do not want to come back to previous situations, but they look for new steady states. Engineering resilience approach, with this point of view, seems, therefore, inadequate to apply in social recovery (ELKADI, 2015). Nevertheless, resilience in ecological approach still persist the idea of equilibrium state. However, this state is understood as an adaptation to a new situation that can also be an improvement of the previous state, contrasting with the evolutionary approach that is explained in the next section.

2.3.1.3 Evolutionary resilience as the theoretical framework

Recently, the idea of equilibrium perspective began to be discussed in the view of the socio-ecological systems. This approach has been called evolutionary resilience (DAVOUDI et al., 2012) and this framework contrast with engineering and ecological, mainly because the evolutionary approach does not accept the idea of stable equilibrium. Instead, this approach interprets the resilience of social-ecological systems as the ability to change, self-organisation and the capacity to learn and adapt in response to stress (CARPENTER et al., 2001).

From this perspective Holling and Gunderson (2002) suggest that the system have different phases: exploitation phase (growth), rapid accumulation and colonization, in this phase the resilience is considered high; conservation phase (stability), present rigidity and the resilience is low, release phase (creative destruction, collapse) characterised by uncertainty and the resilience is low but increasing and; reorganization phase (innovation and restructuring) greatest uncertainty and also high resilience (PENDALL; FOSTER; COWELL, 2010). These phases occur in “panarchical” rather than hierarchical, thus, not necessarily sequential or fixed. (HOLLING AND GUNDERSON 2002). The cycles does not offer a possibility to measure resilience but configure a holistic framework to understand adaptations and changes (DAVOUDI; BROOKS; MEHMOOD, 2013). However, it is important to highlight that this framework allows the conclusion that the highest resilience level belongs to the phases that are the biggest potential for change and innovation.

Walker et al. (2004) try to define resilience in an evolutionary approach as “the capacity of a system to absorb disturbance and reorganise while undergoing change to still retain essentially the same function, structure, identity, and feedbacks”. This work also presents the relationship among resilience, adaptability and transformability, that has different concepts, caused misunderstandings in the field. Some years after, the work of Folke et al. (2010) pointed that this definitions and distinction between the concepts were a cause of confusion and argued that resilience related to social-ecological systems is focused on the three aspects, and incorporates the concept of “resilience as persistence, adaptability and transformability”. This concept is more accepted and nowadays applied in socio-ecological systems.

Davoudi et al. (2013) also suggested that for a social-ecological system, the component preparedness should be added, since should be expected that the human has a background that allows interfere and change the scenario. These four-dimensional aspects suggest, therefore, that a socio-ecological system can be more or less resilient depending on these capacities (persistence, adaptability, transformability and preparedness). As a result, for a social system, the resilience will depend on the social learning capacity to be persistent, flexible and innovative (DAVOUDI; BROOKS; MEHMOOD, 2013). The four abilities can be described as follows:

Persistence

The first dimension of the resilient socio-ecological system is Persistence – being robust, resistant to disturbances. It is the physical property that withstands disturbances without functional degradation (BRUNEAU et al. 2003). Persistence is the main component of the engineering resilience, although the idea of persistence is essential even for the evolutionary resilience, which accepts in the adaptive and transformative cycles some elements will persist in the next phases (DAVOUDI et al. 2016).

Adaptability

The analysis of the second dimension – Adaptability – is the capacity of the system of absorbing the disturbance. This ability aims to adjust responses to external stresses and allows development (FOLKE et al., 2010). This dimension has two main characteristics: flexibility and resourcefulness, (DAVOUDI et al., 2016). It can be understood as an efficient and effective way to choose between the alternatives.

Transformability

The third dimension – Transformability - relates to being innovative. Transformability is the capacity to create a new system (WALKER et al., 2004) and implies a positive trajectory, which includes innovation and knowledge around that innovation (DAVOUDI et al., 2016). It is a movement that the systems need to do when just the adaptation inside their characteristics is not sufficient, and a deep reconfiguration is necessary. Being innovative and promoting easy future transformations to cope with the uncertain nature of climate projection in a design phase, is a challenge to assess this resilience dimension.

Preparedness

And, finally, the fourth resilient socio-ecological system dimension – Preparedness – relates to the "learning capacity". This dimension was introduced by Davoudi et al. (2013) and suggests the preparation and intentionality of human activity. This dimension is related to the learning capacity and unites the other three dimensions: persistence, adaptability and transformability. This analysis suggests that a system can be more or less resilient, depending on the learning capacity (preparedness) to being persistent, adaptable, and transformative.

The three resilience conceptualisations presented above differ mainly on how to approach with the notion of equilibrium after a disturbance. The discussion goes beyond the systems abilities to better react to stresses and disturbances and still persists over time. Many disciplines can apply these theories, and each one defines surrogates to assess or measure resilience.

A brief analysis of the engineering, ecological and evolutionary resilience approaches is provided in Figure 14. Summarizing, the paradigmatic difference between the two first approaches can be illustrated by the ball and cup heuristic. The ball represents the state of the system while the cup embodies the attraction or state of equilibrium (LIAO, 2012). The evolutionary resilience can be represented as Holling (1986) calls as, adaptive cycle, and is visualising as a series of infinity curves, representing the system in different scales (DAVOUDI; BROOKS; MEHMOOD, 2013).

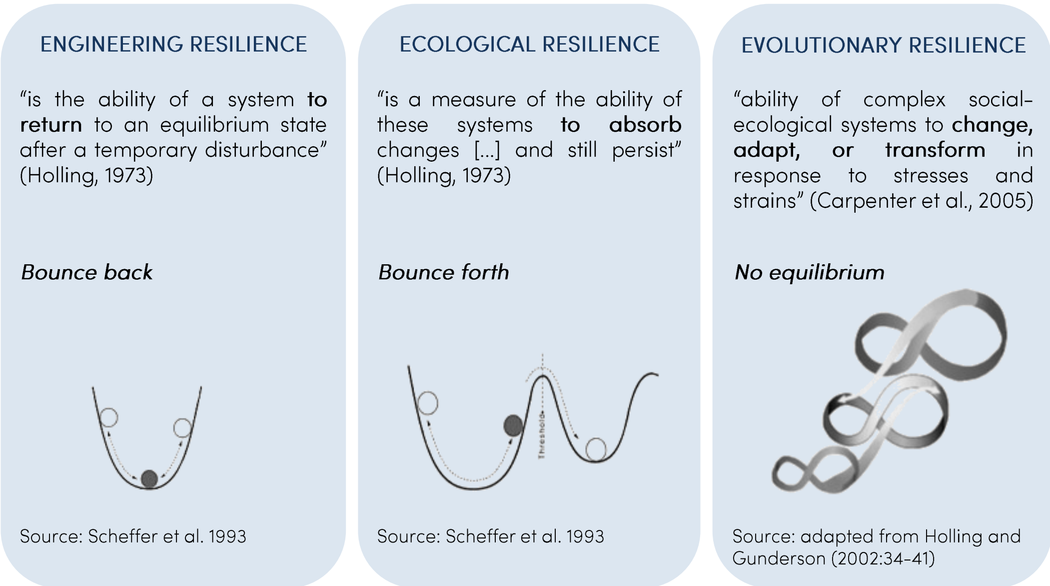

Figure 14: Resilience approaches summary

2.3.2 Resilience in the built environment

Hassler; Kohler (2014a) define built environments as a complex socio-technical system that contains man-made building and infrastructure stock that constitutes part of the physical, natural, economic, social and cultural capital. Therefore, built environment frameworks can be differentiated in two types: hard and soft built infrastructure: the first includes the building fabrication, networks and physical support systems, etc. The second are the institutions, rules, governance, knowledge, value, etc.

The urban landscape or built environment also has been discussed as a social-ecological system and can be understood as a physical manifestation of human activities (BHARATHI, 2014). Folke et al. (2010) define that socio-ecological systems are related to the interdependence between people and nature. In conceptualising the built environment as a socio-ecological system, the principles of resilience can be applied in its development, but ultimately, the socio-technical and socio-political processes that are intrinsic and less direct with resilience thinking must be considered (BHARATHI, 2014).

In this context, the resilience debate came up in sustainability discussion. Both paradigms still lead stakeholders and practitioners to misunderstanding and to creating their values and definitions of the terms (LIZARRALDE et al., 2015). There is an agreement between researchers that both concepts are linked but not equals or replaceable (HASSLER; KOHLER, 2014a). For Pickett et al. (2014), resilience is the key to operationalising sustainability. The authors show how the urban system can be more adaptive in the ability to satisfy social and sustainability indicators.

Resilience and sustainability are closely related to climate change. Here, sustainability aims to reduce the negative environmental, social and economic impacts that is one of the causes of climate change and resilience reducing the effects on the built environment of climate change. However, the interdisciplinary field of resilience remains a challenge, and the links and boundaries reveal existing gaps in knowledge (LADIPO; REICHARD, 2015).

The use of resilience related to climate change adaptation has gained prominence in the policy domain. Looking for framing urban planning, the use of resilience at an International level has become evident. The American government and other organisations started an effort to define and measure resilience. The Rockefeller Foundation (2016) that aims to help cities around the world to become more resilient with the project “100 resilient cities” adopted a concept defining urban resilience as "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience."

The Ten Essentials for Making Cities Resilient of UNISDR was developed to help the implementation of the Sendai Framework for Disaster Risk Reduction (2015-2030) at the local level. One of the Ten Essentials identified is "Pursue resilient Urban Development and Design". This topic indicates the importance of raising awareness about hazard-resistant building practices in all construction sector actors.

In the academic debate, there has been a recent focus on the built environment, and some definitions and frameworks have been developed. In this context, Hollnagel (2014), defines "resilience engineering" being different of "engineering resilience" and defines that a resilient built system comprises four main abilities: ability to respond to disturbances; knowing how to monitor the events in the environment and the performance of the system itself; knowing how to learn from the experience and ability to anticipate threats and opportunities. In this approach, a built system should be able to control itself, applying the four mentioned abilities as a closed system, but not able to control the environment, as represented in Figure 15.

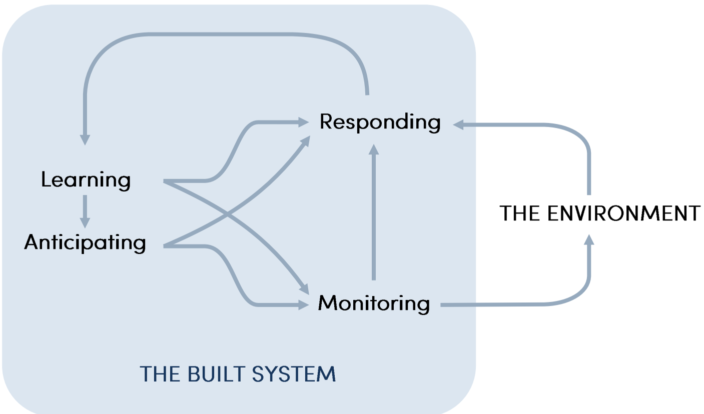

Figure 15: Dependencies among built system resilient abilities (HOLLNAGEL, 2014)

Resilience and adaptability became key concepts in contemporary approaches to urbanism (PICKETT; CADENASSO; MCGRATH, 2013). Contrasting with engineering resilience, the authors, affirm that ecological resilience is appropriate to urban systems, given the changes and challenges that the urban system face which need the capacity of a site to adjust to external shocks. They use the adaptive cycle model of resilience as contributions to the achievement and promotion of sustainable development. In this conception, key tools are identified in the ecological thinking about urban resilience: landscape, metacity, assessment of ecological and design models, and the use of design as experiments.

Hassler; Kohler (2014b) consider resilience as long-term management of built environment. Here the built environment has a series of capitals, as natural, physical, economic, social and cultural. For the authors, resilience is related to sustainability and shares some concepts as continuity, stability and equilibrium, duration and durability, robustness and vulnerability. They argue that the built environment is a "live document of the impacts and adaptations to catastrophes in history", but these historical conditions cannot be reproducible since there are now new conditions and vulnerabilities combining with new risk profiles.

Liao (2012) uses the ecological approach to develop a theory of urban resilience to flooding. The theory suggests flood adaptation instead of the usual approach of resistance. The author, affirm that cities and flood can coexist. Urban resilience here, is defined as the "city's capacity to tolerate flooding and to reorganise should physical damage and socioeconomic disruption occurs, so as to prevent deaths and injuries and maintain current socioeconomic identity" (LIAO, 2012 p1). In order to allow the transition from theory to practice, the author defines a surrogate measure, the per cent floodable area. He proposed floodable lands, areas in the city capable of storing flood water and sediments, not just green areas. The idea contests the paradigm of safety against flood and, instead, make the city living with uncertainties and disturbances.

Besides the theories and models, the process of making a resilient built environment is a complex process. The challenge grows depending on how vulnerable are the city, and the population. Around 1600 cities with a population with more than 300.000 were analysed, and the most urban vulnerable population were located mainly in developing countries (BIRKMANN et al., 2016). Clearly, this is an issue because, besides the vulnerabilities, these countries also have limited knowledge about the past and future impacts of extreme weather. Malalgoda; Amaratunga; Haigh (2014) shows some findings of the challenges in creating a disaster resilient building environment in Siri Lankan cities. The results revealed a lack of regulatory frameworks; unplanned cities and urbanisation; old building stocks and at-risk infrastructure; unauthorised structures; lack of funding; inadequacy of qualified human resources; among other challenges.

Resilience in a built environment is also discussed regarding nature: a model or a design principle. In order to solve this question, Wildavsky (1988) investigated strategies for anticipation and resilience. He argues that the anticipation approach is just possible with sufficient information and has a lack of flexibility and capacity to learn. In this research, the resilient concept is similar and is considered the evolutionary approach. A resilient system is that, therefore, in the face of disturbances the system capable of learning, persisting, adapting, and transforming (DAVOUDI; BROOKS; MEHMOOD, 2013), to maintain the essential functions and performance.

The “resilience thinking” interacts with the built environment in different scales. More recently the interest of researches has addressed an individual building context. For the purpose of this research, an individual building scale will be used.

2.4 SUMMARY: INTEGRATING RISK, PERFORMANCE AND RESILIENCE CONCEPTS

The building performance-based approach is essential in the context of building resilience for two main reasons: this approach maps the critical functions of the building systems and promotes great opportunities for innovation. The essential functions of a house are: to provide shelter that should encompass safety, habitability, sustainability, health and well-being are the ones that should be preserved through time. Health is broadly defined as a “state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity” (WHO, 1946). Moreover, well-being is considered within the spectrum of health and is defined as a person’s cognitive and affective evaluations that include experiencing pleasant emotions, low levels of negative moods, and high life satisfaction. (DIENER et al., 2002). Well-being is steadily gaining importance, however, can be difficult to assess. Although important, wellbeing is not considering in the Brazilian performance-based standard, as a specific requirement, for instance.

The role of performance-based approaches for buildings systems in a context of disaster mitigation raises interest in the inherent permanent character, or at least long-term of buildings, meanwhile, should resist and provide shelter on an EWE. To understand how building performance characteristics can endure through time and EWEs the knowledge of the environment constrains plays an important role. Therefore, the environmental risks should be correctly considered in the previous phases of design and decision-making. For example, Porto Alegre has a wet climate, and water is part of its environmental challenges and should be considered and the earlier phases of the building design. In Brazil, the most common and likely EWEs involve water: urban flooding, storm surges and windstorms. The building design, use, and maintenance should consider those events, and in fact, they are already commonplace in codes and regulations of the construction sector.

The design of a building should consider in depth this constrains and create different strategies to deal with them. For instance, the work of Pushpalal and Ogata (2014) mentions the special situation of Japan, in the coastal Tohoku area, where 126,000 buildings were destroyed by the unprecedented and unexpected tsunami which happened in March 2011. By analysing 11 survived buildings, the authors drew some important conclusions, one of them regarding the opening ratio (area of windows and door in relation with walls). The buildings that presented high opening ratio have the low possibility of moving and or toppling. The importance of this type of study is paramount for a precise understanding of building damages in order to establish and determine future guidelines and requirements.

The different approaches to risk and uncertainty lead to different decision-making frameworks and tools to deal with the adaptation (DESSAI; VAN DER SLUIJS, 2007). It is fundamental to assessing and mapping the local environmental risks, vulnerabilities and hazards. These maps can lead to minimise, and possibly eliminate the vulnerabilities in the building environment. Additionally, in spatial developments, the presence or absence of buildings and infrastructures in flood-prone areas can be decisive in managing flood risks (TEMPELS, 2016).

The environmental risks identification and mapping are currently considered critically important to understand which performance requirement will be directly affected by those EWEs. These relations can suggest, as the building codes also do, that the focus is on structural and safety, and suggesting that resilient buildings are those exceeding minimum code requirements, so the key building systems can continue to function (JENNINGS; VUGRIN; BELASICH, 2013).

In Carpenter et al., (2001) work “From Metaphor to Measurement: Resilience of What to What?”, the authors propose that to understand the resilience of a system properly, the research must clearly define resilience in terms “of what to what”. This sentence shows the importance of the context of analyses to define properly the indicators that can measure the resilience of a system.

However, it is imperative to highlight that those threats and vulnerabilities are associated with a great deal of uncertainty, and the very principle is that their tendency cannot be quantified (DESSAI; VAN DER SLUIJS, 2007). Park et al., (2011) affirm in their work, that risk analysis and management alone are insufficient. The authors affirm that risk and resilience strategies are not equaled. Risk-based strategies are effective when hazard probabilities are known or can be estimated. Where the risks are unknown or unexpected, the resilience approach suggests strategies through adaptation, flexibility, diversity and innovation (KLEIN; NICHOLLS; THOMALLA, 2003; ZHOU et al., 2010).

Although the resilience term is a frequently discussed concept in academia and policies documentation, it has been noticed that the term is unfamiliar to many and inconsistently defined across the construction industries (JENNINGS; VUGRIN; BELASICH, 2013). Few works discuss the term resilience to study the design and concept of buildings. Some researchers are critical to apply the concept to a narrow building approach since; a building should not be considered in isolation from their urban context (LABOY; FANNON, 2016). However, considering a building as a fundamental element of a social-ecological system that should be resilient to a changing world and understand these relations is paramount to increases an urban system resilience.

In addition, a number of researchers have considered the close relationship between resilience and sustainable performance. Phillips et al. (2017) works analyse the possible conflicts between resilience and sustainability. They qualitatively evaluated resilience strategies on an environmental life-cycle basis. The 88 strategies were evaluated as positive, negative or conditional. The work concludes that many more resilience strategies are supporting sustainable design than being contradictory. However, the strategies that focused on durability and longevity as well as redundant systems tended to have divergent resilience and sustainability performance. The explanation is that these strategies run the risk of overbuilding and increasing upstream emissions rather than be helpful.

Other studies had considered including the resilience design principles in green building certifications program (CHAMPAGNE; AKTAS, 2016). The general idea of this work is that a resilient building should be able to adapt and remain functional under pressure from severe climatic events. However, it is a valid discussion; the resilient principles assigned to a projected regional climate change trends are not flexible and are more related to already widespread sustainable requirements rather than resilient aspects (besides contributing also for resilient buildings). In addition, it is still ignoring the deeper dimension of uncertainty as a principle that cannot be quantified.

Lately, Laboy and Fannon (2016) discuss a critical resilience framework for architecture. Their approach moves beyond the functionalist perspective, towards a framework of social-ecological architecture practice. The authors contrast the “long-term resilience – ability to get to a new normal in a changing context” against “short-term resilience – time to get back to normal after a system disturbed”. They conclude that a resilient architecture, should look to endure a long time, however, not as an immutable standard, but “by humbly serving the future” (p. 50). They also consider the relationships among technology, human use and natural environment.

The analysis of the literature also revealed, other studies with more narrow approaches related to resilient buildings. Golz (2016) explores the flood-resilient building materials and constructions. Those alternatives and strategies were evaluated about the performance to reduce flood risks on building scale. The work set eleven evaluation criteria organised on sub-objectives: retention of the statical-constructive integrity, the resistance of building-physical characteristics, suitability of the construction design, and permanence of the component part. This work is important since indicating a form of resilience evaluation of construction alternatives in a comprehensive manner and reducing the bias of decision-making process.

Housing developments ought to meet the performance requirements of structural and safety imposed by the identified environmental risks. These trends are met when the current building design emphasises long-life buildings with robustness and durability. These characteristics are especially true in sustainable buildings. Long lasting buildings reduce the necessity of new materials and energy to rebuild and avoid a considerable amount of waste generated by the demolition(LABOY; FANNON, 2015). However, the challenge is to balance robustness with reconfigurability and durability with adaptability to provoke a renewed focus on sustainable development connecting with evolutionary socio-technical resilience

This literature review presented a discussion about the perspectives of risks, performance-based approach and resilience. The aim is based on this discussion, suggest some surrogates for more resilient buildings by applying the evolutionary resilience approach with four dimensions: persistence, adaptability, transformability and preparedness. These surrogates had been developed in order to provide a more operational point of view and bring theoretical resilience into the building design practice. The theoretical framework based on the literature review is presented in chapter 3: Towards evolutionary resilience buildings.

This framework suggests that for a building to be resilient is necessary a holistic and innovative way of thinking the design and maintenance of the building. It is proposed the BIM integration to manage information and increase stakeholders learning capacity to control and maintain all the required performance parameters, assess the technological features for adaptation and facilitate transformation through modular and disassembled elements. These four abilities should be related to the environmental conditions of a particular location since a building required performance and the exposed risks will change accordingly with addressing geographically specific priorities. However, it is understood that in resilience management the unpredictable events must be considered. For this framework, special attention has been paid on this subject with the compound the innovative character of this framework.

3 TOWARDS EVOLUTIONARY RESILIENT BUILDINGS: A FRAMEWORK

Given the momentum for change discussed in Chapter 2, especially in section 2.4, this thesis sustains the idea that there is a clear opportunity for the creation of a new resilient building approach. Addressing the need for enhancing the EWE resilience of building systems and the need for a conceptual understanding in this regard, research was undertaken to address the problem of "how to adapt the conceptual underpinnings of the resilience approach into the house buildings". Following the review of existing literature, a conceptual framework was developed for the research study. This chapter firstly presents the concepts around how to understand a building as a living and socio-ecological system, in order to justify the choice of the evolutionary resilience approach. Following, it is described how the resilience underpinnings can adapt for the building systems, and the Evolutionary Resilient Building (ERB) framework is delineated. The consolidation of concepts carried out in the initials chapter provided the background for the critical evaluation of the status quo that will be carried out in this thesis.

3.1 BUILDING SYSTEM AND THE BODY SYSTEM: AN ANALOGY

It was considered that for this research would be necessary to expand the idea of a building rigid system and comparing to an organic body system. This comparison is not a completely new idea, and it is frequently in the smart building and smart cities approaches. For instance, Ahuja (2016) investigate the comparison among the building and the body system when involves energy, temperature control and air quality mainly. The author compares human circulatory versus building hydraulic system, human respiratory versus building air system, human logic versus building control system. It is an interesting example to understand energy flows and system integration on smart buildings. The Figure 16 show the integration and the systems that can be compared in the author's model.

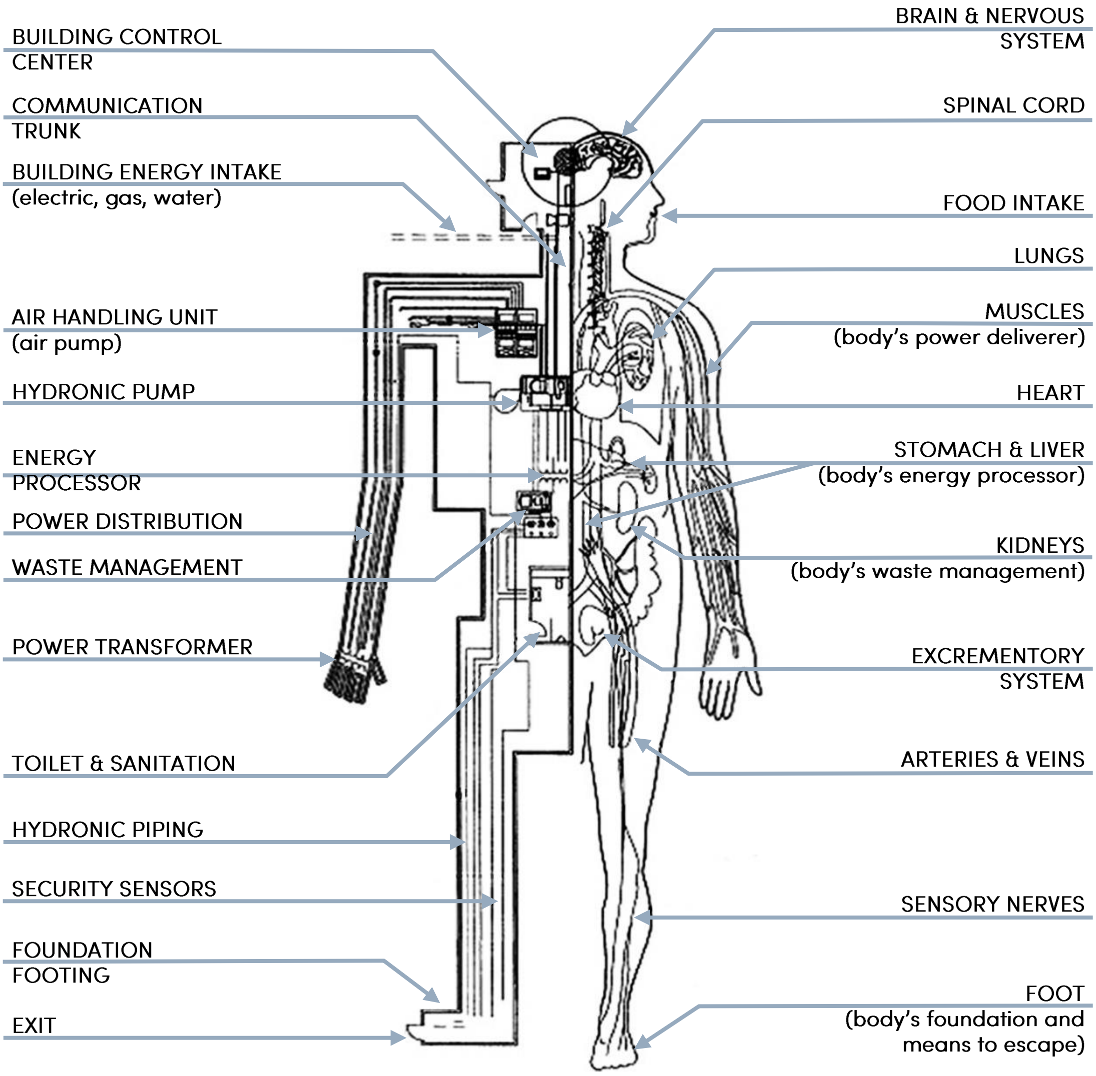

Figure 16: Body building system integration (AHUJA, 2016)

The idea of biomimicry that generates innovation inspired by nature is a solid concept in architecture aiming sustainability and recently to find resilient solutions. The novelty here is how to precede this analogy to understand how a body works and how should be a building get inspiration to be resilient. The concept is explore nature's solutions and learn by them to create solutions to deal with problems. For instance, the current Brazilian panorama on the building house sector shows a scenario where the sensors and building control system is not a common reality. However, a simplistic comparison between the body and buildings system still can be made. Therefore, for this research which aim applying evolutionary resilience underpinning to buildings, the relation of building system and body system can be a fruitful analysis.

Therefore, here it was considered crucial to expand the rigid building system and think as a sophisticated and organised body system. The approach used in this research regarded some relations between the building system and the human body as shown in Figure 17. The figure represents a more straightforward relationship between each system, and do not intend to compare the building with all the complexity of the human body. However, the comparison is helpful to understand some functional concepts related to building system as well how these systems can be resilient. Additionally, the comprehension about the relationship between body and building can provide valuable insights into new opportunities to generate innovative, resilient building systems. The aim is to provide a novel form to understand an EWE building resilience inspired by some of the human body systems that were considered associated with resilience.

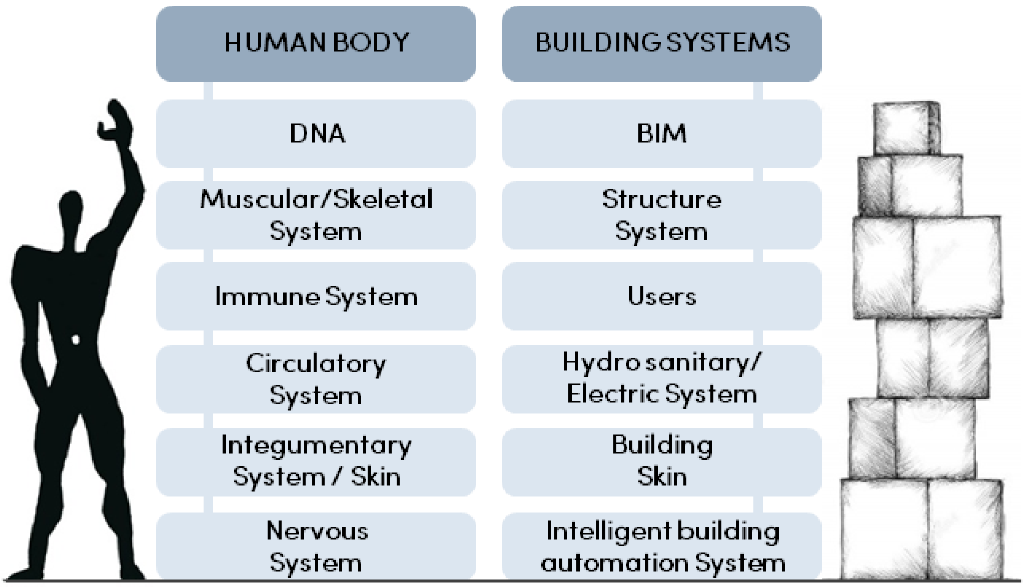

Figure 17: Human body and building system relation

The Figure 17 shows possible elements that can be compared with body systems and building systems, starting with the body DNA and the Building Information Modelling. DNA is the molecule that carries all the genetic information and instructions about the development of the living body. Similarly, this level of information on buildings approaches can be addressed through the BIM methodology. BIM is a methodology that can be used to improve and manage information over the building design, construction, operation and maintenance process. The information needs to be stored securely to be used over a buildings life-cycle, to track energy savings, maintenance performance effectively (AHUJA, 2016). Through the use of BIM technology, a Virtual model of a building is constructed, containing the geometry, the relevant data and all the functions to model the construction and the lifecycle of a building (EASTMAN et al., 2011). Information management is one of the central ideas from which the whole concept of resilience buildings will stem.

A closer parallel can be represented by the Muscular/Skeletal system analogous to the Structural system. This relation is not only comparable as structural rigid and stable system but also can include pre-designed movements based on the behaviour of vertebrate animals that instinctive reacts to maintain the balance under external shocks (VÁZQUEZ, 2015). These conceptions could be a new way to design a building structure system that traditionally relies on the robustness of the system. Taking advantage of flexibility to maintain structural equilibrium is part of a new resilience approach for these systems.

The circulatory system is responsible for the distribution of blood, oxygen and nutrition to every part of the human body. Similarly, the hydraulic/electric system is responsible for the circulation (water and energy) and frequently requires energy to operate. Both human body and buildings are highly dependents of these systems. During the years, some problems may happen, high pressure versus corrosion on older copper or galvanised steel piping or lack of sufficient electric conductors. A require maintenance during the lifespan and the supply of more energy with the years is a common situation on buildings. A building system that facilitates these maintenances and renovations could be more reliable, besides more resilient. These systems should be protected to deal with extreme weather situations, to not create a chaotic environment.

The building skin can be easily compared with the human skin, once fulfils similar tasks. The façade and could be add the roofing system is the interplay between indoors and outdoors. The system determines the appearance of the building, and has influence on the internal comfort, as the body skin. Some authors define the envelope as the human third skin (HAUSLADEN; SALDANHA; LIEDL, 2008) what create an interior and exterior.

Additionally, the main purpose of buildings is to satisfy the human need of protection from external environment and his threats. In response to that, several techniques had been used in order to provide shelter against different climatic conditions and weather events. With people spending more time inside buildings, besides provide healthy and comfortable conditions for the human activities, the buildings are also, most of the time the first shelter and protection against the extreme weather events.

Building skin systems play a key role for building withstand stresses imposed by the uncertainties of natural disasters, and the projected climate change challenges. This is the reason why this particular system had been selected for the further analysis. In this research, house building skin is interpreted as the area where different internal and external forces are interplay to maintain a constant internal comfortable condition. Therefore, the building skin includes both opaque and transparent wall elements as well as the roof.

Finally, the Nervous System is responsible for receive messages from the external world. The normal functioning of the body as well the survival in some measure depends on this communication. The body perceives the temperature, the pressure, the humidity, among other sensations. More than that, the body activate other systems to react and protect instinctively. On buildings, smart technologies, weather sensible systems are current emergent technologies. The impacts of daylighting performance, artificial lightning systems (GERBER, 2011), the temperature control, among other sensors for security, fire are being studied and developed for buildings. Although these technologies are not yet common in current scenarios, the future projections shall embrace these demands.

Both, human body system and building system has to deal with a series of uncertainties during the whole lifetime. The short or long life-cycle of both systems is reflected by the quality or health of the systems, by the impacts of the environment, and the routine of maintenance. The routine of maintenance of the human body involves including in the routine regular physical activities, healthy eating habits, regular night sleeps among others habits. For instance, Rennie (2005) discusses the importance of body maintenance and repair in order to modify protein metabolism of human skeletal muscle keeping then in good shape.

Similarly, a building also needs constantly maintenance, in order to retain systems and restore them in a functioning state. Therefore, easy maintenance should be pursued during the development of a building design. Maintenance plays a large role to keep the building well performing as well on improving the EWEs resilience. Maintenance will often be the controlling factor in making a preparation action to keep the system functions as expected on stress situation. Both scenarios, body and building, maintenance is not a system part or a system property, but in fact, it is accomplished by external activities. In building systems, the design and management of the maintenance is important to improve life-cycle.

In the human body, the Immune system is the body defence against infections organism. In building systems, if considered that the building alone is not fulfilling its function, the users could be the interplay that protects the building. In this scenario, the building is more than a just a physical element rather is permeated and changed by the users. These parallels between body systems and a broad view of building system can consequently be considered as a mean to understand and to deal with the uncertainties of the EWEs. These ideas will be explored in the next section.

3.2 RESILIENT BUILDINGS IN A VUCA WORLD

Volatility, Uncertainty, Complexity and Ambiguity: the acronym VUCA is used to describe an environment, mainly organisations that are ever-changing, whose confident diagnosis are challenging and confuses executives (BENNETT; LEMOINE, 2014). Even though the acronym is broadly used in organisations and leadership, the meaning of each element serves to explain the real word of housing when dealing with the natural environment and users. Each element can be briefly explained as:

a) Volatility. The dynamics of change that could be reflected on the nature and speed of change forces in the environment.
b) Uncertainty. The lack of predictability, the prospects for surprise; and this term is also constantly used in resilience literature that deals with the unpredictability of the events.
c) Complexity. The multiplex of forces, no clear cause-and-effect chain and confusion that surrounds the relations in a built environment, mainly in periods of stresses.
d) Ambiguity. The haziness of reality, the potential for misreads intentions, and the mixed meanings between the stakeholders.

To deal with the VUCA world, a building should be considered more than a single three-dimensional stable object. The building is a system, and it is a part of a more complex system. A system can be generally defined as a complex set of interacting elements and parts that are connected. The system theory started to become necessary mainly in the development of complex engineering systems that have to be assembled from components of different technologies (VON BERTALANFFY, 1968). A building, besides does not presenting the same complexity of space vehicles, for example, is not likely to be resolved with a single technology. Thus, a system approach became necessary. It is important to highlight also that “the whole is more than a sum of its parts” (VON BERTALANFFY, 1968, pp.18). In other words, system thinking means to have a holistic view relative to an issue whilst pay attention on the details (parts) and the relation between them, recognising how one action taken in a part can affect the others or the whole system. Systems can also be conceived as “complex, non-linear, and self-organising, permeated by uncertainty and discontinuities” (BERKES; FOLKE, 1998, p. 12).

In order to understand the behaviour of the building is useful to consider them as complex systems. The principle of the system thinking needs the ability to seeing that everything is connected to everything else. In this context, system dynamics helps to enhance learning about complex systems, since it is a method to developing models to help to understand dynamic complexity (STERMAN, 2000). Traditionally, in the construction sector, the buildings are considering as a fixed/single state. The lifespan of each building part is defined in the project, and once the regular maintenance is carried on, the system will have the same behaviour during all service life. The measurement of the environmental impacts of buildings and the quantification of the functional performance is not a common practice during their lifespan. Complex dynamic systems require more than a technical tool, rather it is fundamentally interdisciplinary and the understanding that they are in disequilibrium and evolving (STERMAN, 2000).

Hollnagel (2014) affirms that buildings are part of what constitutes the physical, natural, economic social and cultural asset of the society, and arguments that the built environment should be called instead, “built system”, and the environment is considered outside of this system and something to deal. The concerning about this assumption is that in this scenario a building should always be in conflict with the environment. The idea of resilience, in this sense, is a system capable of responding, monitoring, learning and anticipating. This notion means that the idea of been flexible and adaptable to the challenges is not the central concern and main issue.

Sterman (2000) also affirms that dynamic complexity arises because the systems are (besides others) history-dependent, change in time, and adaptive, and yet the decision makers often continue to intervene to correct the differences between the desired and the actual state, trying to restore the system to an equilibrium state. These complex system characteristics cope with building and environment relations where everything is relative and constantly changing.

The insights gained during the literature review sustain the idea of interaction among the building, the environment (risks), and finally, the users, represented by the performance requirements to hold in place functionally. These relations provides the basis for the discussion of a building that can be both network and fluid. Contrasting with the Euclidean view of the objects in terms of three orthogonal dimensions, the network description of object and spaces sustain the idea of a network of relations, and the stability of these relations makes a properly working object. This view reflects the classical actor-network theory (ANT) point of view, which objects do not exist ‘in themselves’ but are the effect of relational networks (LAW, 2002).

In the end, the building can also be a fluid object, since their boundaries are not solid and sharp and their performance is no a binary matter. Laet and Mol, (2000) discuss the idea of fluid objects using as a case, the Zimbabwe Bush Pumps and their relationships with the social and environment, bringing out the adaptability of the pumps. They conclude:

> "Something similar might be true for other technologies that transport well. Therefore, we mobilise the metaphor of the fluid here to talk of the Bush Pump. In doing so, we hope to contribute to an understanding of technology that may be of help in other contexts where artefacts and procedures are being developed for intractable settings which urgently need working tools. Because in travelling to 'unpredictable' places, an object that isn't too rigorously bounded, that doesn't impose itself but tries to serve, that is adaptable, flexible and responsive - in short, a fluid object - (Laet and Mol, 2000, p 226)

Bussular (2017), also point out that the actor-network theory can also discuss the disaster concept. This approach argues that disaster is the disruptive effects in a heterogeneous, unequal, timeless and multi-territorial relational network, and the vulnerabilities and hazards arising from these relations. Such a view of objects and disaster assumes the relational point of view that this thesis wants to carry on. The resilient buildings are effects of relational networks and, they can adapt, survive, evolve and learn.

It is important to emphasise this concept since it is how a building can remain in a network space and finally recreating the network links, the principle behind the resilience-building concept. The built (technical), the users (socio) and the natural environment (ecological) are part of the same system and have intrinsic relations. For this reason, the idea of the evolutionary resilience, where the human intentionality is associated with the unstable environment; where a system is not stable and in an equilibrium state, instead it is changing and transforming and finally; where the boundaries and meanings are fluids, was considered the best approach to understand building resilience. This chapter aims to investigate the process to deal with uncertainties and the building characteristics necessary to improve resilience in an evolutionary approach. Next section, starts this task by illustrating the relations of risk, performance building and resilience, the key concepts in the definition of the building resilience strategy.

3.3 OUTLINING A FRAMEWORK FOR RESILIENT BUILDINGS

In this section, the conceptual evolutionary resilient building (ERB) framework, based on a holistic academic and professional literature of resilience beyond the limits of architecture and engineering disciplines will be presented. The conceptual framework, developed for the research study, represents the theoretical basis for the focus proposed to address in the research problem defined for the study. The literature review covered the themes for the development of this framework and were presented in the previous chapter. The approaches of Risk Assessment, Performance-based building approach and Resilience, (especially evolutionary resilience) were integrated to propose this first framework. A conceptual framework was considered fundamental since this provides a sense of direction and focus for the study. Miles and Huberman (1994) mention that “a conceptual framework explains, either graphically or in narrative form, the main things to be studied – the key factors, constructs or variables – and the presumed relationships among them”.

The framework encompassed the relations between the constructs while conduct to a building evolutionary resilience concept. A complete framework should contain objects representing all the relations in a built environment analysis; since to make a fully building resilience model, it would be necessary to develop all these components. Figure 18 presents the conceptual framework proposed for this research.

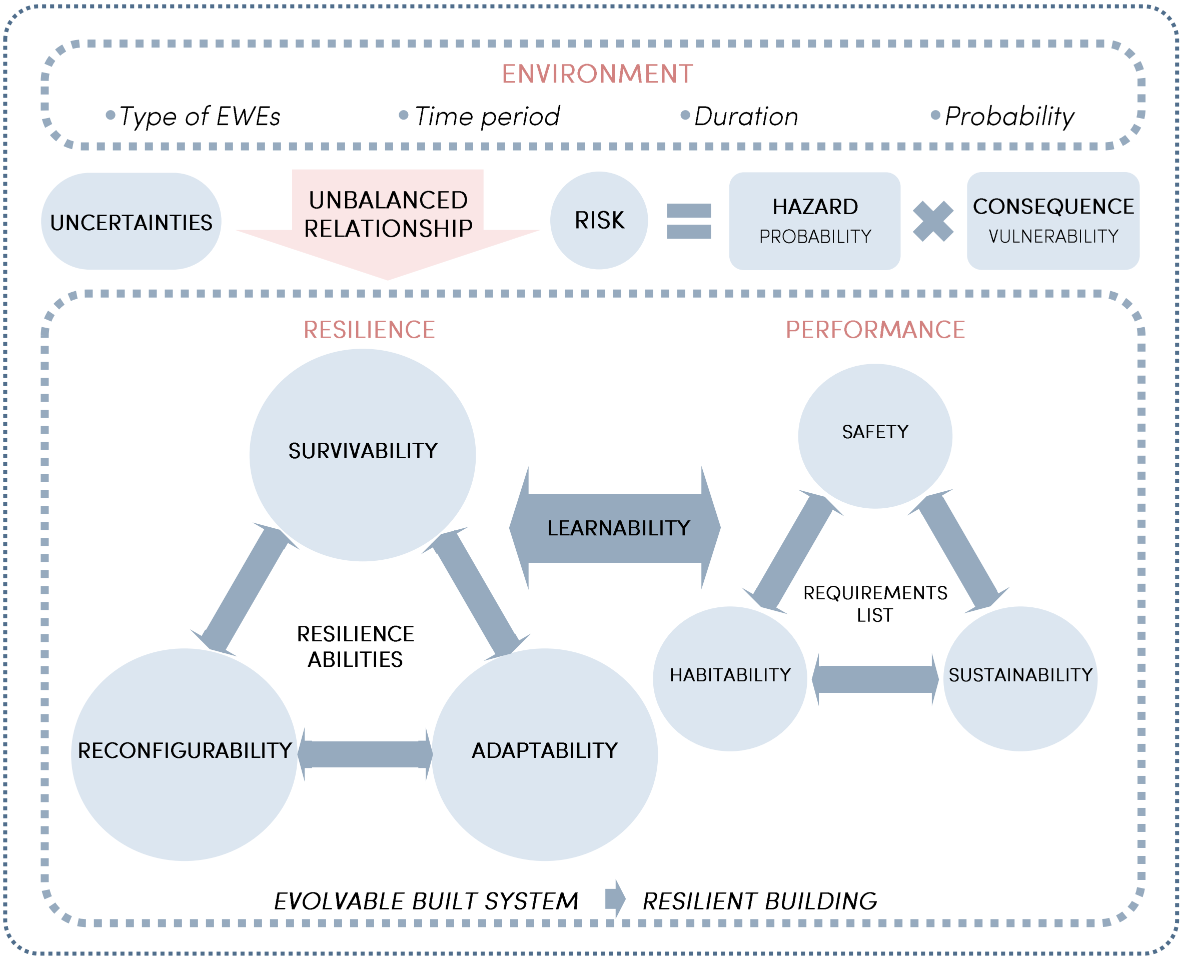

Figure 18: Conceptual Framework for Building Resilience

It is understood that the building must be designed as a whole ensuring a holistic view and considering the city resilience, to not create an island of resilience in a catastrophic city. However, since the focus of this thesis has been the housing sector, mainly the building itself, (further for a deeper analysis just the skin system) the characteristics and abilities presented in the diagram, represent just the relation of a building in a challenging environment.

From the preview chapter the concepts of risk, and as had been shown in Figure 18, arise from an unbalanced relationship between the environment and the building. Although the uncertainties is also component of this relationship. As complex and uncertain, the impacts of the environmental behaviour can be, in some form, summarised by the risks probabilities and the uncertainties including the possible trends due to global warming. There is, for instance, a considerable consensus that the intensity of the rainfall events is increasing according to the temperature rise. However, some hydrologic flows are not expected as seems to be.

The work of Wasko and Sharma (2017) shows that there is little evidence to suggest that the same occurs about floods. While the precipitation-temperature sensitivity is positive, the same is not applied to streamflow-temperature sensitivity. However, the authors still admit that there are additional factors that disrupt those results, as the urbanisation that in recent years had increased streamflow due to a larger proportion of impermeable surfaces. Critically, while smaller catchments coupled with a drier countryside, the cities suffer from more intense flooding. However, the prevision of a change in climate is accepted, the precise prediction of quantities, duration and frequency of the rainfall-causing flood is still an enormous challenge.

Heavy rainfall and floods are a particular issue on environmental hazards, once unlike overheating (that is a commonplace talking on climate change subject), those are an emotive subject due to the possible devastation that they can cause, besides put lives on danger. A flooded house may have fixtures that could be impossible to fix or sometimes can be inhabitable for weeks or maybe months. Critically, overheating can possible reduce the building energy efficiency, besides there are a number of passive strategies that are broadly studied. The risks associated with extremes rainfall, on the other hand, are still far from satisfying entirely the complex and evolving users need and environmental hazards.

In this way, as suggested in Figure 18, the relation between the environment and the building, a common disaster risk assessment template can be assumed. Although the evolutionary approach of resilience engages with an unpredictable and uncertain changing environment, some assumptions can be made to understand the risks probabilities in a given context. In some measure, it is necessary to answer which types of risks the building should perform. Therefore, in this framework, for a given site, some environment characteristics can be pointed as a key influence on the building resilience. For instance, the type of EWEs (hazards) and the possible consequence of these events should be analysed. In addition, the analysis of the probabilities of certain EWEs can be helpful for further categorise and incorporate resilience strategies into building design, mainly due when taking into account costs and sustainability. In this sense, the importance of assessing the risk probabilities is desirable to achieve a non-over built building, taking to account the real practical world.

In this context, the building vulnerability is an important characteristic, since determine how susceptible each system is to the impact of EW hazards. Those vulnerabilities should be identified since they are the key elements that need attention during EWEs. It is important to highlight, that the vulnerable parts of the building can be identified just about some determined risk. For instance, the roof can be a vulnerable system considering windstorms but not when considering floods. The vulnerable systems are the ones that should be firstly improved to achieve a more resilient building.

However, in contrast, associated with the relatively risks, the unbalanced and disruptive relations between the environment and the buildings is also plagued with randomness and uncertainty. There is a multitude of non-controllable factors that affect the outcome of each EWEs. It is widely accepted that there is very high variability of the natural events, but associated there is also the uncertainty of the human actions. These unpredictable social interactions happen in either construction, use or maintenance. Fine, 1982 argued that since the building is infrastructures of the society, the dynamic process and the changes are non-linear. In this context, it is important to assume that uncertainty is not ignorance, but an essential content of this system, that present some level of chaotic behaviour.

As illustrated in Figure 18, the performance requirements can be subcategorized on three groups: Habitability, Safety and Sustainability. Since the Brazilian Performance standard divide on these three groups should be easier to incorporated and addressed by the building resilience to EWE. The habitability performance indicators list, as had been discussed in the literature review, is local and cultural driven. Accordingly, to the climate behaviour and the cultural acceptance, some requirements can change in a place to another, without prejudice for the users. On the other hand, for both, Safety and Sustainability should be the same list for all countries; although it is common have differences. Some countries have rules more restrictive than others, usually due to past accidents and concerns.

The performance approach corroborates with the idea of a building as an open system and fluid object, allowing the assumptions of the complex and dynamic interactions between the building with users and environment. Traditional practice has designed (or should have) buildings to respond for each performance requirements and the risks of EWEs. The move towards performance-based approach including risks conducts to a holistic way to see the building, beside that, there is the challenge factor to consider uncertainty.

The uncertainty factor corroborates to break the paradigm of the man controlling nature. Additionally, focus the attention on mitigation and do not rely on false security that structural measures can reflect. For instance, investments on dams and channelisation for resistant flood control infrastructures enabled citizens to build in floodplains, which resulted in a need for continuous investment in flood defence (TEMPELS, 2016).

As a fluid object, buildings interact with the environment and cannot change the frequency or intensity of EWEs impacts. The way this building interacts with the environment, for this thesis mainly with the EWEs, will characterise how much resilient this building can be. The EWEs resilience for this framework will be characterised as a building systems ability, which a building lasts a long-term life, maintaining the system's performance, and facing events in a dynamic process of transformation to a more desirable trajectory. Davoudi; Brooks and Mehmood (2013) also corroborate with this idea when they affirm that fostering resilience involves not only recovery from shocks, but also looking for preparedness and transformative opportunities in which facing challenge.

In this sense, a resilient building in this research framework should present some characteristics or abilities. These abilities, as a fundamental part of the framework, and must be connected and supported with the performance requirements by a constant structured information flow (learnability). The learnability is paramount and imperative to be the interplay between the resilient abilities and the performance requirements, dynamically and holistically. This information flow needs to provide the necessary data in a timely manner for each one of the resilience abilities perform their functions. The data can be used as a tool for the designers and users in decision-making about which ability need to be activated in a EWEs. Additionally, the data about how should the building perform (performance requirements) is also required as a practical way to perform quality control.

In broad terms, the risk assessment allows information for decision-making in the performance-based approach design process. In the same time, the building resilience abilities should able to deal with the uncertainties of the unbalanced and disruptive relations with the environment.

The central point in Figure 18 is the evolutionary building resilience abilities. In this research, building resilience to EWE is viewed as a combination of the building abilities of Survivability, Reconfigurability and Adaptability, with an imperative incorporation of Learnability. This reduced diagram and the discussion of this is presented on the next sections.

3.4 CONCEPTUAL CHANGES PROPOSED TO DESIGN EVOLUTIONARY RESILIENT BUILDINGS

Recently, due to the increasing occurrence of disasters in the built environment added to the effects of climate change, the discussion about resilience began to be recurrently also for the design of resilient buildings. However, most of such building resilience principles developed, do not cover all the concept that characterise the resilience approach, focusing mainly on resistance and robustness. Furthermore, some of the principles carried out in the built environment resilience literature (HASSLER; KOHLER, 2014a; HOLLNAGEL, 2014) are theoretical and do not present practical implementation for design and material assessment for buildings.

Besides the improvement and increasing awareness about high performance, sustainability and green buildings in the constructions sector, still, there is a lack of concern about one of the essential functions of the buildings: providing shelter and protection against the hazards. Designing healthier, more efficient, adaptable, and flexible buildings benefit the construction sector and as well as the user welfare.

However, designing, constructing and operating resilient buildings requires interdisciplinary expertise from the fields of architecture, engineering, economics, social and environmental science to carefully weigh various options and make informed decisions. The first step in the process of outlining a framework for resilient buildings involves the discussion about the balancing between robustness and reconfiguration on buildings schemes.

The most obvious definitions and methods of evaluating resilient buildings to EWEs, are conceiving those are resistant, better protected and prepared to deal with these events, aiming to minimise the impacts. A common tendency perhaps of the ideal safe building dealing with EWEs are thinking as durable and strong buildings. Although important, these characteristics cannot be the only requirement explored in design buildings. Buildings, especially house buildings, require a design approach based on resilience to EWEs rather than on resistance. Resisting floods or windstorms for example, using thicker walls, stronger structures, neglects inherent uncertainties arising, from social behaviour and fails to address the EWEs that are expected to increase with climate change. Thereby, it is not a reliable approach to long-term resilient buildings.

By applying evolutionary resilience theory to address building system persistence through Survivability, Adaptability, Reconfigurability and Learnability, this thesis developed an alternative framework focusing on the evolvable buildings rather than just robustness. For this reason, *Evolutionary resilient buildings are those able to maintain the performance by reconfiguring dynamically and holistically to a more desirable trajectory while facing an unpredictable and unbalanced relation with the environment. It derives from sustaining with a stable network of relations with other entities through survivability, adaptability, reconfigurability and learnability*.

The theory of EWEs resilient buildings challenges the traditional structural engineering approach of rigidity and robustness, but not ignoring it. To enable resilience, building reconfiguration is advocated not to replace, but to complement robustness and resistance through mitigating EWEs hazard. In fact, the objective of resilient buildings is to create a long lasting building with easy and costly repair in case of acute shocks. As instance, the BS 855000: 2015, the current British flood performance standard “Flood resistant and resilient construction – Guide to improving the flood performance of buildings” also join the ideas of resistance and resilience. The publication defines flood resilience as measures that can help to reduce the consequences of flood water entering the property and emphasize particularly the speed of recovery for the building can be reoccupied.

To operationalise the theory for planning practice, the surrogates’ assessment (Survivability, Adaptability, Reconfigurability and Learnability) is further developed for assessing building resilience to EWEs. However, architects and engineers are typically involved at the concept to construction phases they have little or no influence after when occupied. Ultimately, the dwellers take the decisions that will determine the long will be the building lifespan. Based on this assumption, the resilience abilities of this framework try to encompass the phase of use, operation and maintenance, in addition to design and construction phases.

Based on this discussion, the next step is the definition of resilient abilities, which consist of building design principles that will be further validated and defining requirements and indicators to accomplish each one of the abilities. The definition of indicators and validation process will be discussed in the further chapters. The next section presents a discussion about the socio-technical abilities for buildings that are resilient to preserve their function in the face of multiple EWEs.

3.5 RESILIENCE ABILITIES

Turning evolutionary theory into building sector practice requires assessing and evaluating building resilience to EWEs. Because resilience is not directly observable and easy to measure, it must be inferred from surrogates, although it is not possible to represent resilience with just one surrogate (CARPENTER; WESTLEY; TURNER, 2005). From this perspective, it was developed surrogates based on the understanding, interpretation and translation of evolutionary resilience in socio-ecological systems and the four dimensions defined by Davoudi; Brooks and Mehmood (2013) framework to a building system approach.

Applying the evolutionary resilience concepts to buildings are challenging because of the need of understanding the evolutionary resilience components to a complex, however, rigid system. Abdulkareem and Elkadi (2018) affirm that the inflexibility and durability of the constructions are also a barrier to resilience policy be applied to cities. In light of this situation, this conceptual framework focuses mainly on the physical dimension of the building, however, considering the complex relational network that includes social and environment relations. In this work, the building is considered a socio-ecological system, sharing some characteristics as "(…) non-linear and multiscale dynamics, (…), their sensitivity to external perturbations, and the reflexivity of human action" (BENNETT; CUMMING; PETERSON, 2005).

Assessing the building resilience to EWEs requires surrogates for socio-ecological characteristics, since contrasting with a just ecological system, in the built environment there is human design, action and intervention. The buildings are part of the built environment complex system, where physical, natural, economic, social and cultural capital are included (HASSLER; KOHLER, 2014a). With this idea in mind, it was decided to examine the evolutionary resilience components (DAVOUDI; BROOKS; MEHMOOD, 2013) and to compare them with features in required performance of building adding the concept of reconfigurable systems (SIDDIQI; DE WECK, 2008). The results of this investigation were as follows, presented in Figure 19, whose diagram represents the relations between the evolutionary building resilience abilities. Each one of the proposed abilities is further discussed.

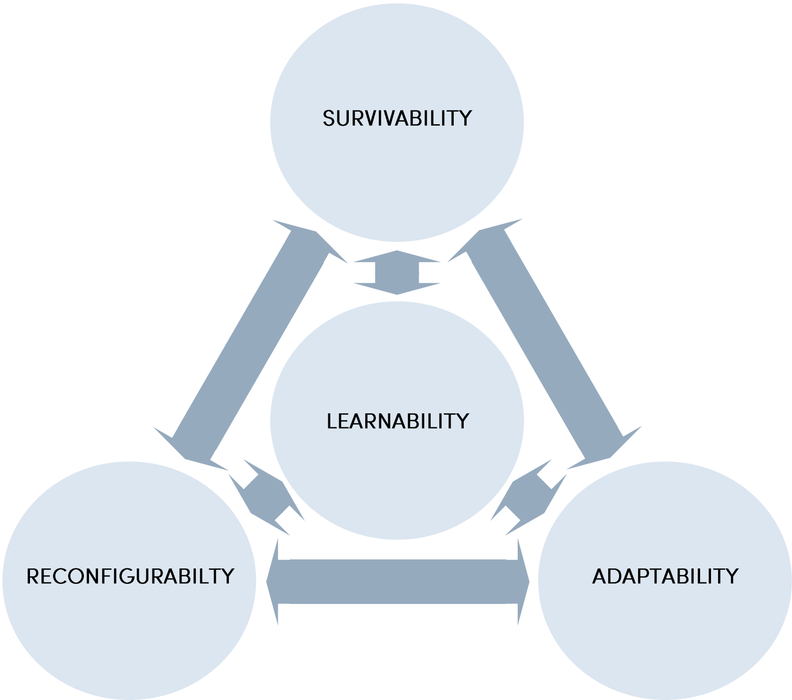

Figure 19: The relation between the building resilience abilities

3.5.1 Survivability: persistence dimension

The first dimension of the resilient socio-ecological system is Persistence – being robust, resisting to disturbances. It is the physical property to withstand a disturbance without functional degradation (BRUNEAU et al., 2003). Persistence indicates permanence, and more then consider that some elements will persist in the next phases, the necessity of the building remains functional conduct to understand this ability as Survivability.

In buildings systems, survivability is fundamental, and is related to continuity, resistance and to keep attending the building performance requirements facing the environmental risks, including those uncertainties caused by climate change. The survivability factor drives a system, when “the system remains functional, possibly in a degraded state despite a few failures” (SIDDIQI; DE WECK, 2008)pp.1. Persistence in building starts with durability to standard conditions and resistance from the extreme events, and to keep these characteristics, maintenance and conservation are fundamental.

As construction cost increase and the effect of the extreme weather events in buildings are more intense it is fundamental increase the resilience and as consequence the building lifespan. During service-life, buildings deteriorate, and mainly the skin system shows the marks of the environmental aggressions. This process is inevitable but can be controlled and the service life extended when a proper maintenance is performed (Chew et al. 2004).

Survivability is, perhaps, the most well know resilience dimension by designers, and there are a number of building regulations, standards, test methods and specification to deal with the extreme natural hazards. There are, however, three challenges in this dimension: design based in performance (no specifications), design based on the future predictions and design for maintainability. The target is to understand and to predict the future conditions in order to design addressing resilience as a requirement to keep the required performance (CHAMPAGNE; AKTAS, 2016).

The idea of survivability is design based on maintaining required performance for future conditions, and fundamentally by design for maintainability. Maintainability is defined in BS 3811(BSI, 1984) as “the ability of an item, under conditions of use, to be retained in or restored to a state in which it can perform its required functions when maintenance is performed under stated conditions and using prescribed procedures and resources”. The importance of the maintainability is that the designer should think in the lifecycle of the building, not just about inevitable deterioration of the system. Although, he should also address the impacts and stress that the building can be exposed, based in future conditions. The challenge is during the design phase think to enhance maintainability.

However, besides the efforts to predict the future climate, natural disasters and risk, is still necessary deal with the uncertainty, once it is an irreducible condition in complex systems (BERKES, 2007). The acceptance of this conditions means that the resilient building needs adaptation strategies that may be more appropriate to deal with not predict or changing scenarios.

3.5.2 Adaptability: being flexible

The analysis of the second dimension – Adaptability – is capacity of the system absorbs the disturbance. This ability aims to adjust responses to external stresses and allow development

(FOLKE et al., 2010). This dimension has two main characteristics, flexibility and resourcefulness (DAVOUDI; ZAUCHA; BROOKS, 2016). Which can be understood as an efficient and effective way to choose between the alternatives.

Flexible system design can be used to achieve adaptability in a changing environment. Flexible systems can be defined as systems designed to maintain the performance through real-time adaptations in configuration when operating conditions or requirements change in a predictable or unpredictable way (OLEWNIK et al., 2004). The concept of adaptive system is fundamental in resilient building approach, since nonflexible and robust system typically does not have the capacity to respond to changing and unexpected conditions. So, while robust building systems try to neutralise the external impacts, adaptable and flexible systems use the changes in the environment intentionally to create better and safer conditions inside.

Intelligent building technologies and multi-ability features may help to address this dimension as well. A number of authors define the intelligent buildings to "performance adjustment from its occupancy and the environment"(WONG; LI; WANG, 2005). The idea is the development of innovative and technological devices for building that can be adaptable and dynamic, in a way that allows keeping the internal conditions and the performance requirements in a changing condition or extreme stress.

These technologies are largely developed for solar control, as for instance, the Rolf Disch`s the experimental rotating houses Heliotrop, in Freiburg, the houses can rotate according to the sun` s position, with maximise warmth and natural sunlight as possible. Other studies go towards thermal comfort and energy efficiency (JOHNSEN; WINTHER, 2015; LOONEN et al., 2013; SHAIKH et al., 2013). However, less technologies are developed and applied for other natural events, as severe winds, flooding.

Multiability is when the systems have some features that can perform multiple functions at a different time (SIDDIQI; DE WECK, 2008). For instance, for the flood issues, the population of the North of Brazil, in the Amazonia region, presents a simple solution, where they build their houses under "palafitas" that are high wooden stakes that avoid that the level of the flood reaches the interior of the house. These solutions work as a foundation, ventilation under the houses and flood protection. Another example, can be the balconies that can be folded (GE; MCCLUNG; ZHANG, 2013).

The adaptability dimension is not yet completely explored, mainly for intelligent and multi-ability features. There are a lack of studies and a number of opportunities to develop new features and technologies to adapt to extreme weather events. This dimension is particularly important for building because since they can absorb the stresses, giving a degree of security against the uncertainty.

3.5.3 Reconfigurability: transformability dimension

The third dimension – Transformability - related to being innovative. In socio-ecological systems, transformability is the capacity to create a new system (WALKER et al., 2004) and implies a positive trajectory that includes innovation and knowledge around that innovation (DAVOUDI; ZAUCHA; BROOKS, 2016). It is a measure that a socio-ecological system needs to incorporate when just the adaptation is not anymore sufficient, and reconfiguration is necessary.

Reconfigurability is the way that building can achieve the transformability dimension. This ability may be the most important factor for the system to respond for future changing needs. In this type, the "system changes easily over time by removing, substituting and adding new elements and functions" (SIDDIQI; DE WECK, 2008) pp.1. Being innovative and promote easy future transformations to cope with the uncertain nature of climate projection in a design phase is a challenge to assess this resilience dimension.

Retrofit and refurbishment are a common task, but to design an innovative and transforming building, is a challenge. The lack of flexibility in the conventional building design does not enable transformation. The common attitude in these cases is the demolition of the entire, or parts of the building. Assembled and disassembly strategies for building systems are design approaches that can address the reconfigurability target.

Design to disassembly demonstrates great benefits from recycling and energy saving (GAO et al., 2001) being a better alternative comparing to demolition. Disassembly approach also could be a better alternative to easy recovery and conservation, addressing the transformability dimension. If the building is design to de easily disassembled, it will be easy to replace, add or subtract elements of the system. This dimension will be a particular challenge for the conventional housing construction industry that mainly works with masonry, for example.

Modular systems also facilitate Reconfigurability. Modular system present potential to shorten the time and reduce costs in design and construction (GENERALOVA; GENERALOV; KUZNETSOVA, 2016). In order to be affordable these substitutions, all building materials must use modular units. Modular components and elements can be replaced by similar in new conditions or also, for a new technological and innovative product.

The idea around reconfigurability is to ensure that all the elements of the building can be easily replaced. This dimension deal with uncertainty in the most flexible approach, once the unpredictability about future weather conditions and future technologies can be managed. In Frank Lloyd Wright's Johnson office building, each column was provided with four utility chases. They were designated for electricity, plumbing, telephone and "future", years after this chase could be used for data cables. Ensuring that these strategies are adopted into the design of the new buildings, will improve the building ability not just to cope with severe events but also be able to be adequate and update to the future technologies and innovations.

3.5.4 Learnability: preparedness

Finally, the fourth resilient socio-ecological system dimension – Preparedness – related with the “learning capacity”. This dimension was introduced by (DAVOUDI; BROOKS; MEHMOOD, 2013) and suggest the preparation and intentionality of the human activity. It is related to the learning capacity and unites the three others dimension: persistence, adaptability and transformability. This idea suggests that a system can be more or less resilience depending on the learnability (preparedness) to increase survivability, adaptability and reconfigurability. Reason why this ability is the central elements in this framework.

The buildings usually are developed to have a relatively long lifecycle; the scope is that buildings lifetimes are of 30 to 50 years. During design, construction, operation and maintenance phases, several stakeholders are involved, and many information is produced. In order to enhance innovation and information control about all phases of the building lifecycle, is important to improve learning capacity. The learning capacity, in this case, depends mainly on the ability to produce, capture and storage the information and knowledge in an integrated system which every stakeholder can have easy access and learn through this information. Nowadays, an approach that can facilitate learning capacity or information management, in the building industry is the Building Information Modelling (BIM). In this thesis, when comparing body systems and buildings, BIM was associated to the DNA, which reveals its importance.

The benefits of implementing BIM process have been widely accepted for the design and construction phases, as a comprehensive method for information generation, management and analysis (SACKS; PIKAS, 2013). The construction industry starts to understand recently, how the application of BIM can enhance learning capacity in the construction sector but also recognise the benefits of asset the owners (LOVE et al., 2014). Therefore, BIM could be a good strategy to permit the learning capacity of all stakeholders involved in the process to design, construction, use and maintenance of buildings.

For learning capacity, this method is efficient once all the information can be stored and assessed with the same language by all stakeholders. Some studies also show the benefits of BIM implementation for owners, maintenance teams, and also for existing buildings, enhancing the importance of this method in all building lifecycle (LOVE et al., 2014; MOTAWA; ALMARSHAD, 2013b; VOLK; STENGEL; SCHULTMANN, 2014). Fundamentally, BIM improves the information accuracy and coordination enhancing the learning capacity and efficient method to assess information, being prepared to respond to stresses quickly.

Furthermore, the BIM technology can integrate and facilitate the other three resilience dimensions and address the performance requirements being the information channel. The dimension of preparedness unites the earlier three domains of resilience. Thus BIM method can help to foster the persistence of the building system, integrating and correlating the maintenance information, the adaptability, addressing the necessary technologies, and transformability, improving and understanding the building systems.

3.6 SUMMARY: EVOLUTIONARY RESILIENT BUILDING FRAMEWORK

In the first part of this chapter, the concept of a building compared as body complex system was discussed. Secondly, the proposal to understand a building as a fluid object, part of a relational network that can suffer disruptive effects, was outlined aiming to justify the flexible and reconfigurable resilience approach adopted in this thesis. The choice for the evolutionary resilience approach rather than the engineering resilience was made because it seems to be in favour of better integration with the environment.

Some general guidelines for the development of the building resilience abilities were established based on the lessons learnt from the literature. The qualitative description of the abilities was one of the knowledge domains used for the application developed in this research. This application will be an assessing and rating system developed for building shell/roofing, named here as building skin. It will be built using experts' knowledge for the elicitation of indicators for each resilience abilities discussed in this chapter. The next three chapters consist of a description of the process of developing such indicators and rating system, and a case test for the application.

4 THE RESEARCH METHOD: CONTRIBUTIONS TO THE MODEL DEVELOPMENT

Having discussed the research background, defined the research questions arising from the literature review and presented the theoretical framework, the methodology for addressing the empirical part of the research is discussed in the current chapter. It is achieved by following a process linking philosophy, approaches and finally defining the strategy. The chapter starts discussing a nature of research and the "research onion" model suggested by Saunders et al. (2015) and adopted in this thesis to guide and clarify the different aspects that have to be considered in designing a research project. This chapter presents and justifies the research methodological design adopted to develop, validate and test an assessing model based on the theoretical framework constructed in the preview chapter. As such, this chapter develops an outline for the empirical research.

4.1 RESEARCH METHODOLOGICAL DESIGN

Methodology can be described as the "overall approach to a problem which could be put into practice in a research process, from the theoretical underpinning to the collection and analysis of data" (REMENYI et al., 2003). Summarising, research methodology, is concerned with the problems to be investigated and the process to carry on and it will vary according to the type of problem to be investigated. This section describes the research methodology adopted to explore the research questions in order to achieve the aim and objectives of this research project.

Saunders et al. (2015) presented an overall research model that is called the 'research onion". The idea is that the researcher has to "peeled away" to reach the research problem that is in the centre of several layers. These layers are important aspects to consider as a research position in order to determine the methodology for the study. The research onion was adopted here, to organise the aspects to be considered for the construction of the methodology. Figure 20 presents the layers of the research onion which will guide the development of the following sections: research philosophy, research approach, research strategy, research choice and research techniques.

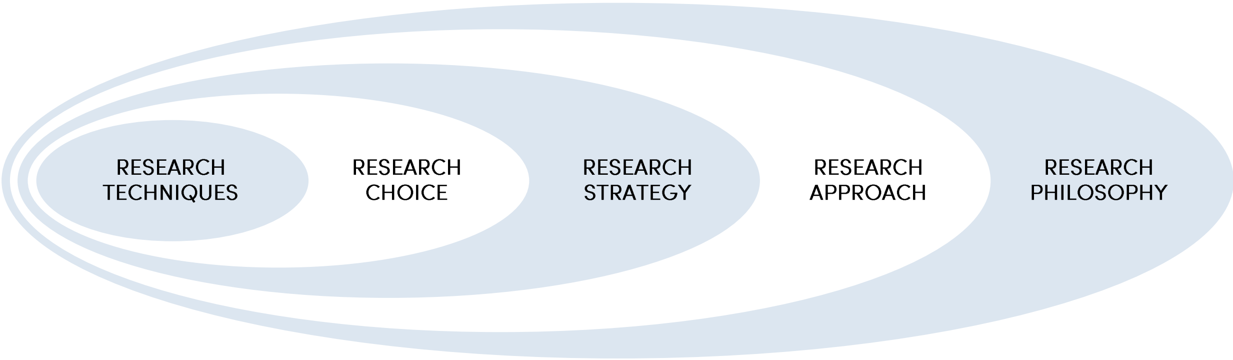

Figure 20: Research onion, adapted from Saunders et al. (2015)

4.2 RESEARCH PHILOSOPHY

Easterby-Smith (2008) argument that there are good reasons why the understanding of the research philosophy is very useful: it can help to clarify the research design, to understand the methods that will work or not to collect data, and finally can help the researchers to create designs that are outside their background. The nature of the research philosophy is briefly explored in the following sections, through the three fundamental concepts of ontology, epistemology and axiology.

4.2.1 Ontology

Ontology describes the nature of reality, what is real or not, also describes what is fundamental or essential and what is derivative from that (VAISHNAVI; KUECHLER, 2007). It is the way that the researcher perceives and makes assumptions about how the world works. Positions on its spectrum range from objectivism and subjectivism (SAUNDERS; LEWIS; THORNHILL, 2015).

The first, position accepts that the objects and events exist independent of awareness of the social actors; the second position, subjectivism understand the meanings and the different points of view of which individual, since everyone experiences a discrete, and subjective reality of objects and events (REMENYI et al. 1998). This research deals with both subjective and objective issues and thus falls in between the two extremes on the ontology spectrum.

4.2.2 Epistemology

Epistemology is related to the nature of knowledge and how we can be sure of what we know (VAISHNAVI; KUECHLER, 2007). It is concerned about what is acceptable knowledge in a field of study (SAUNDERS; LEWIS; THORNHILL, 2015). Positivist and interpretivist philosophies are the extremes view point. Positivism is related to the traditional natural sciences where the common approach is to use existing theory to develop hypotheses and then test those. Positivism aims to establish general laws, cause and effect relationships by using rational methods.

Alternatively, interpretivism aims to explore humans' actions, feelings and understand how the world is perceived and experienced by the individuals (CROTTY, 2003). This research is positioned as more interpretivist, and this position will be justified by the methods chosen to gain more in a deeper understanding of the research question

4.2.3 Axiological assumptions

Axiology is the study of values and recognises the implicit values of the researcher on looking the reality (SAUNDERS; LEWIS; THORNHILL, 2015). It describes the position of the researcher about the data analysis and helps to define the methodology. It can be understood as value-neutral and value-biased research.

The researchers under the positivist approach will be close to the value-free or value-neutral, where the position and the subjectivism of the researcher should not interfere with the results. Contrasting, the value-biased research, recognise the values, beliefs and experience of the researcher, particularly in approaches aligned with the interpretivist philosophy. This research accepts that the researcher knowledge and background helps to define the model outputs.

4.3 RESEARCH APPROACH

Saunders; Lewis and Thornhill (2015) identify two alternatives that can be adopted regardless research theory. The research can use the deductive approach, in with the researcher testing a theory or hypothesis, and the inductive approach in which is necessary the data collection and develop a theory based on the data analysis. There are some attempts to connect this approaches with the research philosophies. However this is not useful and can conduct to misleading. ROBSON (2011) describes the process through with a deductive research should progress, starting with deducing a hypothesis, express this hypothesis in operable terms, testing this operational hypothesis, examining the outcomes, and finally, if necessary, modify the theory in light of the new findings. Inductive research, the theory is driven purely by data, and it is concerned by the context where the events take place (SAUNDERS; LEWIS; THORNHILL, 2015).

In this research, the inductive reasoning is used. The stages of interview and focus group will be used in an inductive attempt to collect and look the model in depth. The main purpose of this phase of the research project, expects to develop a resilience building model for assessing resilience of building skin in the housing building sector to the impacts of the extreme weather events. Therefore, the knowledge developed of this work can be better described based on the design science research approach, also known as constructive research, or prescriptive research, in opposition to descriptive research, typical of the natural and social science (MARCH; SMITH, 1995). Based on the aim and objectives of this study, the method adopted was mainly qualitative, intending produce general theoretical knowledge.

4.4 RESEARCH STRATEGY: FORMULATING THE RESEARCH DESIGN

The present thesis could be classified as an exploratory study, as defined by (ROBSON, 2011), since it attempts to address a new issue, the concept of resilient house buildings. In the pursuit of this aim, the work followed the methodological framework proposed in Figure 21.

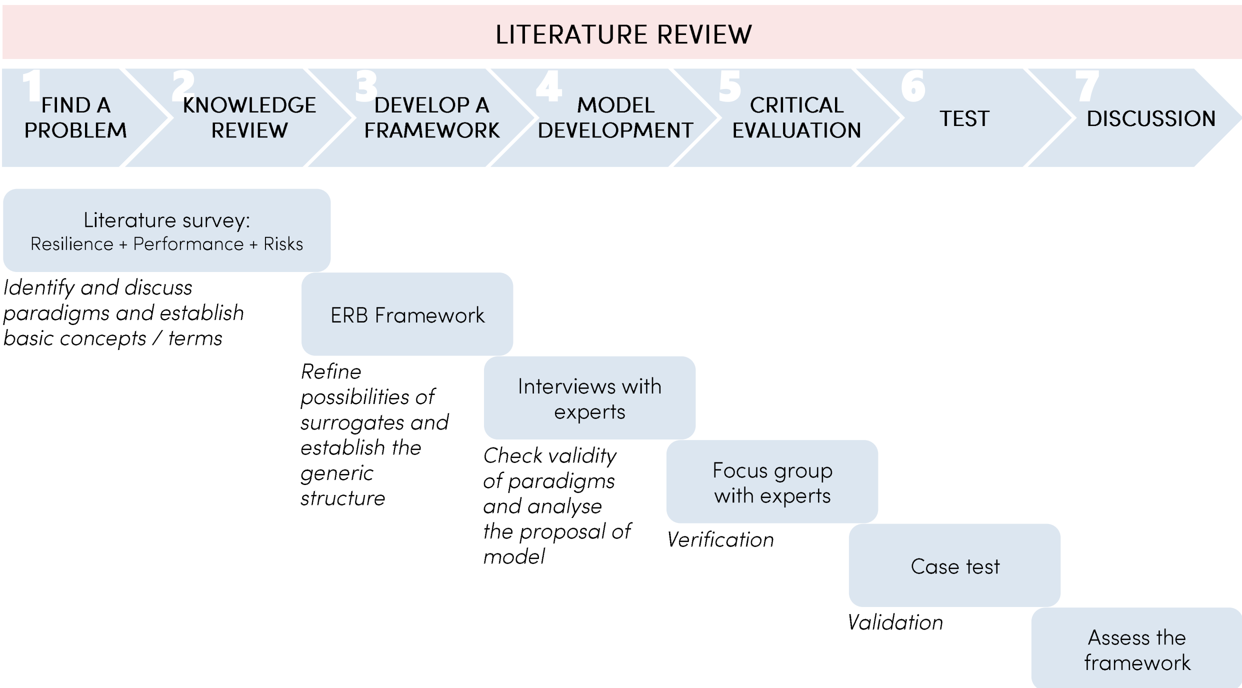

Figure 21: Methodological framework

As an exploratory study, this thesis examined the theories, concepts already in place in the building sector, urban, as in other areas, and used them as the foundation for the development of new ideas. The first phase Find a Problem and the second Knowledge Review, was dedicated to locate and review the accumulated knowledge and theory about Resilience and Resilient Systems. The analysis indicated that the knowledge in this area is still fragmented and needs consolidation, mostly concerning buildings. The literature review was fundamental to provide the basis for the discussion about the characteristics and abilities of resilient systems, about how to understand the risk related to extreme weather events and how the performance-based approach can be a better way to assess building functions. The work went beyond the established knowledge in other scientific fields to provide a new insight for the resilience of buildings, through the construction and analysis of the possible resilience abilities applied to buildings and by advocating the adoption of a holistic view on the design process.

The risks of extreme weather events were previously identified assessing the priorities about the impacts of climate change trends that most affect the cities, focusing on the recurrent events in Brazil. The conceptualisation of vulnerability, hazard, and risk had also been an object of analysis. To clarify these concepts was considered necessary to construct the holistic model. Finally, the analysis of the performance-based approach was considered the way to understand how the building should behaviour.

In order to develop the ERB framework, a range of knowledge is provided in the literature related to the resilience of systems and their abilities. The building resilience aspects were based on a wide literature review for the different perspectives about the resilience of systems. After the definition of the more suitable resilience theoretical approach, a set of surrogates or indicators were defined to be possible assessing building resilience. Carpenter et al. (2001) affirm that the transition from theory to practice requires measurements and for this is necessary the use of surrogates that may be inferred indirectly.

In the Development of a Framework, the three aspects considered above were further connected. As a final product, a framework connecting the most important aspects of each subject were constructed, with the three relationships group: resilience abilities and performance requirements, resilience and environmental risk and uncertainties. Essentially, the framework aims to address the factors that should be considered to aim a resilient building. If necessary, modifications and adaptations in the framework can be embraced in the light of the findings.

Once the framework had been developed, the construction of the indicators was also supported by the documentary research and literature survey, which will guide the analysis of projects, following, literature in the theme. The documentary methods are the analysis of documents that contain the information related to the phenomenon which is the focus of the study (Bailey, 1994), and this analysis should be organised and systematic. To the results of the literature survey were added the insights gained by the author in the Interviews with experts, aiming the Model Development. The Interview exercise considered the knowledge of three distinct groups: Technical, environmental and social. All of them considered fundamental to develop a holistic view on the subject. Figure 22 represents the three-dimensional matrix idea that it will be further developed in this research to analyse the requirements of each group to have a common set of requirements and indicators.

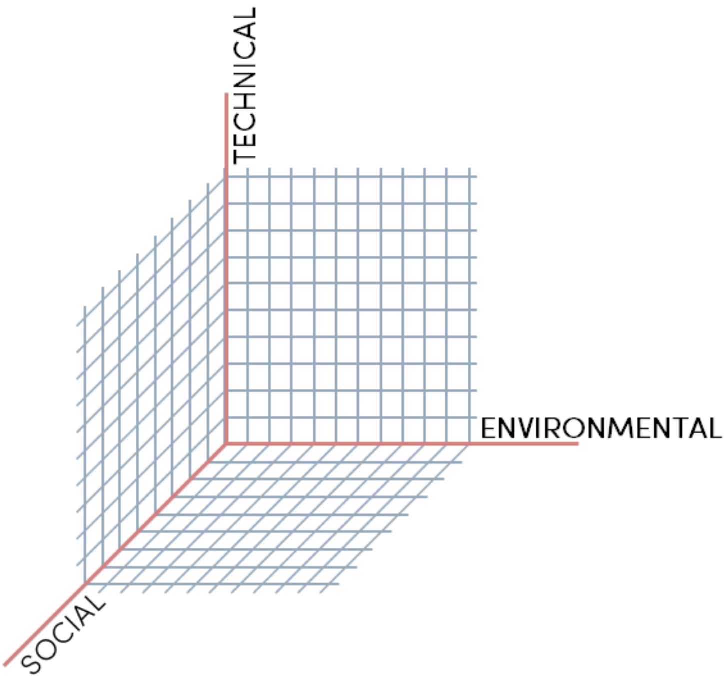

Figure 22: Matrix of analysis

Following, Critical Evaluation exercise carried out with a group of experts from academics and practitioners in Brazil. The critical evaluation exercise is considered a central part of the work because it provides empirical support for the theoretical discussions undertaken in the thesis and checks the validity of the model. The Critical Evaluation phase was also characterised, by the attempt to combine and articulate the various proposals discussed earlier. The methodology used during the exercise is present in the following sections.

The Application of the model phase aimed to assess its practical contribution. The methodology proposed to use in this phase was underpinned by the selection of a real case from analysis of the architectonic projects, construction phase, and post-occupancy documents, in order to test the applicability of the developed framework. The applicability of the framework developed is illustrated by a typical Brazilian social house building condominium.

In the last phase, the results of all the previous phases were consolidated to assess the Theoretical Contribution. This effort demonstrated the soundness of the proposed framework and indicated that introduce the concerns about resilience for buildings could produce meaningful results.

This research was developed in an incremental way; phases of data gathering and knowledge elicitation are alternating with conception and development phases, as suggested by Figure 23. The figure was based on the Multimethodological Approach to Research proposed by (NUNAMAKER; CHEN; PURDIN, 1991).

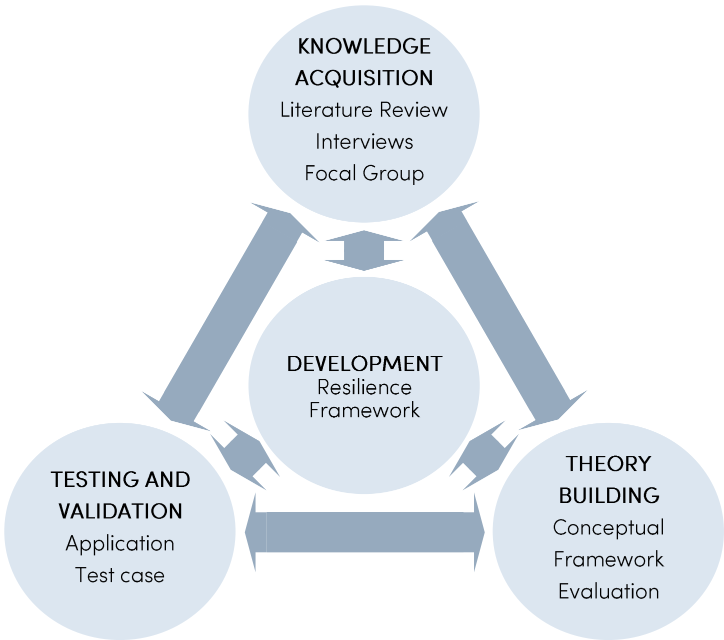

Figure 23: Dynamics of Research, adapted from Nunamaker et al. (1991)

The overlapping of activities seen in the figure was important to ensure that the work kept pace with the changing reality of the subject under study. The study domain of this work has been very active in recent years, with a great number of research projects, public regulations and documents being carried out in various parts of the world. It is believed that the research method adopted was successful in maintaining the work up to date and that the findings and conclusions are useful and applicable to real life problems.

4.5 MULTIPLE METHODS CHOICES

According to Saunders; Lewis and Thornhill, (2015), the research choice is related to the selection or combination of quantitative and qualitative techniques and procedures. For this research, the multiple methods were chosen, since more than one data collection and analysis techniques were used. However, just a qualitative approach was applied, not combining with quantitative techniques, classifying this study in a multi-method choice.

The initial literature review showed that there were existing resilience concepts and frameworks for cities, communities and even some ideas for buildings. However, none was based on the socio-ecological point of view of the evolutionary resilience. Thereby, a framework was first outlined based on literature knowledge about social-ecological resilience, risk assessment and building performance approach. The second step on the research process consisted of the definition of a qualitative research technique in order to improve the framework, built an assessing model for building skin and test the model.

Different issues have been considering in determining the most appropriate approach to satisfy the research aims, as follows:

a) There is a need for more primary data on existing knowledge and application of the resilience abilities;
b) There is a need to get a more in-deep knowledge on different field areas in building, social and ecological disciplines; and
c) There is a need to entail discussions that provide outcomes from the Evolutionary building resilience framework development as to its indicators and adjustments.

These issues justify a multi-methods approach considered to be a suitable path to following this investigation. The data collection techniques chosen were the interviews and the focus group; those were used both to collect new complementary data for the research and to improve the construct validity of the framework based on the experts' opinion. In order to verify the adherence between the results of the proposed resilience indicators and the practical, real-life problems, a case tests had been used. Those methods/techniques are outlined in the next section.

4.6 RESEARCH TECHNIQUES

Bearing in mind the philosophical positioning and the aim of this research the methods/techniques used comprise an ongoing literature review, semi-structured interviews and a focus group. The discussion on the next section expands on the justification for each of the applied methods and how they are related to each other.

4.6.1 Exploratory phase: Literature review

The preliminary stages of any research project involve an initial literature review. The first aim is to identify and understand the theories or models that have been used by previous researchers in the field (Yin, 2003). The aim of the literature review in this specific thesis was to enable the researcher to discover what was already known about the theme in other fields of study (ecology, social and engineering) and based on this construct the evolutionary building framework. This framework will be the guide for the development of the following work. The development and discussion of this framework were presented in Chapter 3.

As such, a systematic reading of previously published and unpublished information relating to the area of risk management, performance-based building approach and resilience on different fields was conducted. These comprised books, journals, conference proceedings, technical reports, PhD theses, standards, terminology, nomenclature, catalogues and library databases. Its main findings and analysis are detailed in Chapter 2.

The critical review of the existing literature and the framework developed drove the research to the next stage: How to translate the resilience abilities in practical indicators to be used in the construction sector? To collect these indicators the following methodology with semi-structured interviews were conducted.

4.6.2 Exploratory phase: Semi-structured Interviews

The purpose of this phase was to investigate whether the ERB framework and characteristics was accepted by experts of the technical, social and ecological domains. The second goal was to obtain possible new indicators for each resilience ability, inferred from the oriented discussion. In this particular research, the development of an assessment model that could encapsulate a common and multidisciplinary body of knowledge seemed to be a very attractive alternative, since the model to be developed could be widely used in the building sector.

Eliciting knowledge from a diverse collection of experts is based on the assumption that a common body of knowledge exists in the domain. Some kind of disagreement is bound to occur, but, in fact, the contradictions and conflicts can be sometimes beneficial for the research process. As an expert is accepted as a person whose background in the analysed subject is recognised by his peers or those who conduct the study as qualified to answer the questions (MEYER; BOOKER, 1991).

For the knowledge elicitation, semi-structured interviews were used as the main data collection technique for the study. In-depth interviews are the most fundamental of all qualitative methods (EASTERBY-SMITH et al., 2002). In qualitative research, the interviews techniques are the most utilised method (ALAN BRYMAN, 2006; BUCHANAN; BRYMAN, 2007). It is a method for collecting data in which the participants are questioned in order to find out about their experience and feelings (JILL COLLIS; ROGER HUSSEY, 2014). Interviews allowed the collection of a series of wide information about building systems whilst maintaining a consistent line of inquiry.

The first step was defining the experts. The purposive sampling technique was adopted for selecting participants. A self-selective, non-probability sampling technique was used to arrive at the sample for the interviews. It is considered the appropriate technique for the specialised type of professionals' requirements to answer the research question (SAUNDERS; LEWIS; THORNHILL, 2015). Yin (2011) explains that the reasoning behind the adoption of purposive sampling technique was to select the cases that will provide the best and relevant data. It is accepted, however, that the samples cannot be considered statistically representative. Nonetheless, the results gathered were considered adequate for the research purpose.

Interviews were conducted with both experts (either academic or practitioners) from public and private sector, as well experts that deal with the design and maintenance building phases, from Brazil. In order to gain a wider viewpoint, considering the multidisciplinary approach that the thematic of risks and resilience has, it was conducted interviews with different field's experts. Therefore, the social and ecological point of view has been considered as fundamental perception to be collected for developing the model.

The interviews conducted as part of this research had an exploratory nature. Semi-structured interviews seemed the most appropriated approach. The interviews were organized by semi-structured questionnaires, whose questions were modified to be appropriated to each group of experts (technical, social and ecological). Semi-structured interviews have predetermined questions, but they can be modified upon the interviewer's perception of what seems appropriate at the time (ACKROYD; HUGHES, 1992).

Recording and transcribing provided a full and accurate record of the interview reducing potential bias of the in note-taking and facilitated the data organisation. Interviews were recorded with the consent of the participants and transcripts were prepared by the researcher. This exercise provided a valuable overview of the data as a starting point for analysis. The interviews provided 27 hours of recorded material as a basis for analysis.

The insights of the knowledge elicitation carried out with the expert's interviews were added to the literature review results. This knowledge elicitation phase is considered a central part of the work, and the interview as part provide the theoretical topics for the focus group discussion. The combination of the knowledge gathered from experts with the results of the literature review provided the basis for the development of the next phases.

The next two sections contain the methods used for verification and validation of the ERB appraisal model investigated along this thesis. The purpose of this process is to understand if the model is developed in the right way (verification) and if finally, it has adherence and represents reality (validation). The first section presents the focus group as a technique for verification of the ERB indicators collected in the exploratory phase (literature review and semi-structured interviews). The second section, the validation method is discussed.

4.6.3 Verification: Focus groups

One kind of criterion that can be employed for verification is expert opinion (HOPKIN, 1993). The strategy chosen divides the verification exercises into two blocks: indicators and rating scale, with emphasis given to the first one. The purpose of the first block is to determine whether the ERB indicators are fundamentally accepted. The second block verifies and rating the various indicators for the ERB applied for building skin and check if they are capable of giving an important evaluation of resilience. The exercises seek to establish whether the concept can generate resilient buildings and if the resilience abilities and indicators can provide a suitable basis for strategies that can measure ERB.

Focus groups can be used for a multitude of purposes and in a variety of settings. In this focus group discussion, a small group of experts was invited to participate in the evaluation of the ERB model. According to Morgan (1998), focus groups are useful, among others functions, for getting participants' interpretations of results from earlier studies. The researcher, assuming the role of moderator, can ask open questions or raise the specific issue to the group, facilitating the discussion.

As the model is intended to be used and understood by professionals engaged in the design stage on the construction project, like architects or engineers, focus groups were composed of this two expertise groups. In the focus group discussions, the researcher presents the model, the indicators and their scale. It was asked participants to recognise or redraw what they did not see fit to be there and explain why. After, they were asked for new ideas as to how the issues identified as constraints could be overcome. Finally, in the second focus group moment, each group of indicators are asked to be prioritised by the participants.

After the focus group discussions, the researcher transcribed the notes as well as the sound scripts collected with the help of an audio recorder. The insights from participants were also noted down.

4.6.4 Validation: ERB appraisal model application

The proposal of measures, metrics has no value if their practical use is not shown empirically (BASILI; SHULL; LANUBILE, 1999). The validation should be part of the process developed in this research of developing a knowledge-based rating system. The third and final stage of development of the model consisted of the validation of the implemented rating system. The approach to validation adopted in this study is concerned with testing the behaviour of the rating system on real world projects.

In more specific terms, the aims of the validation stage were: to check whether the rating system has reached a reasonable level of quality and adherence with the real world; to identify any necessary improvements in the system; and to make explicit gaps in the knowledge base, which could guide future knowledge acquisition exercises or research in the field of resilient buildings.

The challenge in this phase is to define the sample of test cases. However, the main issue is not the number but the coverage, being necessary to ensure the test cases chosen are representative of as many situations as possible (HOLLNAGEL, 1993). For this work, it was used a case that is the common practice in the building sector, in order to push the knowledge in the model. The description of the test case and the results gathered with the application of the model are presented in Chapter 6.

5 PROPOSAL OF THE MODEL FOR EVOLUTIONARY RESILIENT BUILDINGS SKIN FOR SOCIAL HOUSING DEVELOPMENT

The previous chapter is setting out the design and development of the methodology used in this research for the construction of the resilient building skin model. This chapter now presents the qualitative data gathered, its analysis and main findings. It is divided into two sections, the first devoted to the semi-structured interviews and the second to the verification and requirements prioritisation through focus-group discussions. Each section will detail the sample, structure and main findings of its respective data gathering.

5.1 SEMI-STRUCTURED INTERVIEWS

Based on the ERB framework developed in Chapter 3, semi-structured interviews were designed among experts to identify the requirements and indicators to achieve each one of the building resilience abilities. The research in this phase aims to gain a real-life understanding of how the social housing development sector can generate more resilient homes. Interviewees were chosen from three main group of knowledge: Technical (engineering and architecture), Social and Environmental. Interviews aimed at:

a) inquiring about interviews perspectives and thoughts about buildings in relation to risk management, climate change and resilience;
b) identify requirements and indicators for each one of the resilience abilities of the ERB framework.

The selection of those groups aims emphasises the importance of the multidisciplinary approach to deal with the subject. The approach makes possible the analysis of the different viewpoint for identifying the indicators for a resilient building skin based on the ERB framework.

This first section of the chapter will detail the use of semi-structured interview techniques as part of the study at hand as well as examine the interview design, sample and content analysis. Finally, the main finds are summarised, and following the validation and prioritisation through focus-group are discussed.

5.1.1 Interview design

Since the aim of this phase was the knowledge elicitation, the interviews questions were designed to gain a deeper understanding of the characteristics and requirements to translate the resilience abilities into real life building situation. A free form of questions was developed to steer the conversation without leading the interviews- to ensure that the researcher would not to guide the interviewees for having the answer she wants to hear or for them not to try to find the right answer. The questions were simple open-ended questions since this kind of questions is the most productive way of obtaining richer information on the subject. The aim was to have an interview where the conversation would flow in an environment as natural as possible.

The researcher conducted a pilot interview with an architect and an engineer for the test of any issue that might be misunderstood or contain sensitive or wording problems, as well, the pilot test gave the research practice as an interviewer.

At the beginning of each interview, a brief description of the research study undertaken was given to interviewees. The framework behind the question was not exposed to not lead or create some bias in the answers. It was created three different interview scripts for each approach (technical, social and ecological). The structure of the interview was similar for each: it started with questions related to their professional experience. These questions were important since in several moments the researcher was able to gather more in deep information from the interviewees making the link with the professional experiences. The following questions were opening questions to understand the familiarity of the interview with the thematic of environmental risks, climate change and resilience. The subsequent questions were related to each one of the abilities, at the beginning of each block of questions, a brief explanation of ability was provided. For the closing, open questions about any other thoughts about the subject of the interview were used to obtain possible extra information. The APPENDIX A present the three interview scripts.

Interviews were recorded with the interviewee's consent. It was the method considering since recording allows the interviewer to focus the whole attention on the interviewee, and making the connections with other answers without having to worry about taking notes. In addition, the digital recording allows proper analysis, even if the transcribing process is often time-consuming. Some of the interviews are taken by online meetings, due to time and financial constraints. Skype services were the tool used for all the online interviews. It was considered beneficial since interviewees that have time and location issues could participate in the research in more convenient circumstances. This alternative solved the problem of reach key experts in the sector. Interviews took around one and a half hours.

5.1.2 Sample

As mentioned in the previous chapter, a purposive sampling technique was applied to select the experts. In some situations, at the end of the interview, the interviewees indicated other experts that could also fit to answer the questions. Due to time constraints, the sample included experts only from South and Southwest part of Brazil, totalling 18 participants.

Regarding position in the building sector, the sample was composed by both academic and practitioners, focusing on experts in at least one of the subjects. Due to the multidisciplinary approach and even the multi-subject of the abilities, each interview had a personal characteristic, in which the researcher focused on gathering deeper information for each one of the interview expertise. Table 1 summarises the interviews, the focus expertise and present their respective field qualification background and the time that took for each interview .

Table 1: Semi-structured interview summary

Focus expertise	Number	Field expertise	Qualification background	Time
TEC	01	Academic/practice	Civil Engineer	55m
	02	Practice	Civil Engineer	1h 10m
	03	Academic	Civil Engineer	1h 38m
	04	Academic/practice	Civil Engineer	1h 31m
	05	Practice	Civil Engineer	57m
	06	Academic	Architect and urbanist	56m
	07	Academic/practice	Architect and urbanist	1h 12m
	08	Academic/practice	Architect and urbanist	53m
	09	Practice	Architect and urbanist	1h 22m
SOC	10	Academic/practice	Engineer/Social worker	57m
	11	Practice	Social Worker	1h 10m
	12	Academic/practice	Social Worker	1h 05m
	13	Practice	Social Worker	1h 06m
	14	Practice	Social Worker	40m
ECO	15	Academic/practice	Architect and urbanist	1h 08m
	16	Academic/practice	Architect and urbanist	1h 07m
	17	Academic/practice	Architect and urbanist	47m
	18	Academic	Civil engineer/agronomy	1h 22m

TEC– Technical
SOC – Social
ECO – Ecological

5.1.3 Data analysis

Following each interview, the researcher transcribed the sound files and any notes taken regarding that specific interview. The notes taken regarding each interview were then typed and attached to the transcript document. The recordings transcribed were afterwards coded in Nvivo. Labels were added to the text extracts, indicating the main concept or idea expressed by the respondent.

For the data analysis process, the content analysis approach was adopted. Content analysis is a systematic categorising approach used to explored textual information to determine trends and patterns, themes, context information as latent content (MAYRING, 2000). The data gathered was subsequently read, and the main concepts and keywords discussed more often were catalogued. Keywords from each ability were also extracted and classified. This was done over and again as to narrow down a number of concepts that had been after translated under requirements. The main issues and ideas identified as organised following the group categories: technical, social and environmental. The next three section present the findings that emerged from the groups.

5.1.3.1 Technical approach: building experts

The interviewers for the technical approach were selected by their expertise on civil engineering and architectural practices, mainly on the subjects of buildings maintenance, building information management, building performance approach. A mix of practice and academic professional provided a broad view of the subject and issues related. The main objective with this interviews was to collect the key requirements of each one of the resilient building abilities presented on the ERB framework. The criteria were not their knowledge around resilience itself, since, this is a new approach on the construction sector, but their expertise in each one of the resilience abilities established in the ERB framework (Chapter 3).

Interviewees were, firstly, asked about their understanding of risk management and resilience building. The questions were related to how they understand and how could be applied to the building. It is interesting to see the different perceptions given to the subject according to the respondent’s field of expertise. All the civil engineers mentioned that resilience in their point of view was related to getting back to a previous state after a disturbance and the building system could be understood in the same way. One of the interviewee points that this bouncing back also could be by absorbing the changes and highlights the building performance cannot be lost.

> "Resilience in my point of view is how you can adapt to those certain conditions that you are being imposed. So I think resilient people are the ones who best shape themselves with what is happening at that particular moment, and after that, they return to their normal state. When you take this to a building component, as it undergoes an action, it has a displacement or a deformation, and it returns to the original state. It may have some permanent deformation, something like that, but you do not lose performance. (Interviewee, TEC_01)"

Although, the interviewee TEC_05 also, civil engineer, but whose works deal mainly with urban scenarios, contrast the in the resilient point of view:

> "(…) we talk a lot about resilience in our jobs on the urban scale, it is an ability to face new situations, not only necessarily serious situations, but it is the ability to transform according to what happens". (Interviewee, TEC_05)

In addition, all the interviewee that share the same opinion regarding resilience being a bouncing back ability seems to disconnect the building system from the users and other stakeholders. For them, resilience should be an exclusively building ability without any people intervention. Alternatively, the architects seem to give importance to the building function and the user's satisfaction:

> "(...) first the building needs to be safe. Then it has to be thought for eternal use, for the possibility of function changing and finally, it should be possible to incorporate new technologies and innovations in the building". (Interviewee TEC_07)

After, regarding Maintenance process and robust elements, all the interviewees mentioned the central importance of maintainability, and that should be thinking in the design phase. All the interviewees reckoned easy and safe way to access the installations and other parts of the buildings system. TEC_01, was more emphatic, affirmed that when a system part does not have access, the maintenance will not be held in any time.

Other contributions to the maintainability subject were about the use of less number of different elements and materials in each system. Some interviewees stated that, for instance, in some building skin systems, the coating layers could be excluded by using good masonry blocks or apparent concrete. TEC_07 that worked during several years in a government sector, taking care of public school projects and their maintenance also bring this issue. For those school buildings, easy maintenance was one of the most important requirements demanded. He mentioned that because all schools used an apparent masonry wall system as the building envelope. However, he affirmed that for those strategies to succeed, the chosen wall materials (in the example, bricks) should be robust and have good quality.

Finally, as mentioned above, maintainability should be thought on the design project phase. For that, a maintenance plan with standard procedures for inspections and maintenance for each building should be organised. The interviewee TEC_07 also mentioned that for being able to manage the maintenance of hundreds of school buildings, a plan of inspection and maintenance together with the register of each operation was the way to control all the users' demanding.

Regarding, to Adaptability they all agreed that the technology could be a good ally to adapt the system to different challenges and changes. There was a consensus that this could be a difficult process to adopt and in Brazil, where the technology is still backward. However, they seem to agree that it is the right and inevitable path. It was understood that for each need or extreme event (flood, storm, wind, severe load conditions, etc.) there are different strategies to deal. For some interviewee, each case should be analysed in context, but the alternatives should be provided. The strategies suggested was about integrate temporary barriers until cognitive systems, responsive systems and communication and alert systems.

There was a certain misunderstanding about the Reconfigurability concept. The Reconfigurability subject was many times mixed in the Maintenance questions. This issue, demanded from the researcher considering the data and categorising in the optimal ability discussed. What becomes obvious, in questioning about what a system should present for be easily transformed, was the agreement around disassembled systems. This issue deals with two approaches: the system should have parts that can be replaced and others more robust or maybe redundant. The interviewee TEC_04 explain his understanding:

> (…) "Which is not replaceable, has to be evidently more robust. You have to increase the terms a bit. And you also have to increase redundancy. That is, a structure can be a much more redundant structure, right? More robust then you can work with both concepts at the same time, (...) so redundancy and robustness are paramount in those systems whose complexity or characteristics are more difficult to replace. Those elements that are easier to replace, so you do not need so much robustness or redundancy, right? You will negotiate it according to necessity. Always, the need to state the economic factor". (Interviewee TEC_04)

Moreover, modularity, easy and accessible connections, were considered paramount for any attempt of building transformative systems. More than modularity, some interviewees mention that it is especially important the interchangeability between parts and the possibility of add new one.

Finally, the last subject was about Learnability. The interviewees are generally aware of information management importance. They agree that the generation is not an issue in the building sector. However, how to manage and to keep the information during the building lifecycle is a concern. Furthermore, there is concern about the Brazilian construction sector culture, once there is a lack of information using and consultation, that starts in the design project phase and goes through the construction and maintenance phases. Additionally, the sector seems not to learn with others experiences. Interviewee TEC_02 state the following comment about the construction sector context:

> “I think the first step in information management is learning to use the correct data. Today if you look even for our current practice of projects, we often do not make decisions on the basis of actual performance data. For example, we do not have any data to know if I have built 100m from the sea, what degree of saline mist arrives there, nothing is known about it. The first thing is to have the management of the data and information needed. Even the design process itself is very informal in that sense. I'm now working with the design scopes for each speciality, a descriptive analysis of each speciality for performance standards because a lot of things are not written anywhere, so I started with foundations arguing with their association. Look, a good part is the geotechnical risks. You have a foundation and containment solution based on a few things, but none of this gets registered. If in the front I have a question about something that happened and that someone asks if this was considered in the project, we do not keep track of anything. I think this is the first issue, the quality of information, to know how to deal with more formal information indeed. Even weather data, they need to know how to search for climate data and use that in the project.” (Interviewee TEC_02)

However, they think there are some issues around information management, they all agree that the concepts and advances around Building Information Modelling (BIM) could be a solution in the long term. They acknowledge the difficulties and limitations around the implementation of the BIM concept with all the building system stakeholders, but they also feel that there are increasing use and awareness around BIM. Nevertheless, there is a sense that BIM could help generation, dissemination and management of information during all building lifecycle. But they generally fell that the practitioners do not take enough action.

5.1.3.2 The Social point of view

For this study, the semi-structured interviews with social workers were used to explore the surface of the communication with users. Construction sector practitioners are not used to engage with users for a long-term after a building is delivered. In some cases, as the governmental programs for social housing, as an instance, the dwellers are not consulting at any moment. Post-occupancy surveys are scarce and usually done by academic purposes. For this reason, a social approach interviews were considered important in this research to have an overview of these type of relations. Professional Social Workers, whose expertise is families and communities in vulnerable situations dealing with environmental risks, composed this interviewees group.

The more prominent keywords in the interview's content were information, technical knowledge, social knowledge, bond, continuity, individual autonomy and flexibility. These were emphasised by all interviewees in one way or another as influencing on the resilience capacity of a family group. The resilience concept was perceived as a process that starts before the disaster, creating strategies for prevention and preparation. The main concepts and their interrelations, as revealed by the semi-structured interviews, are outlined in the cognitive map, represented in Figure 24.

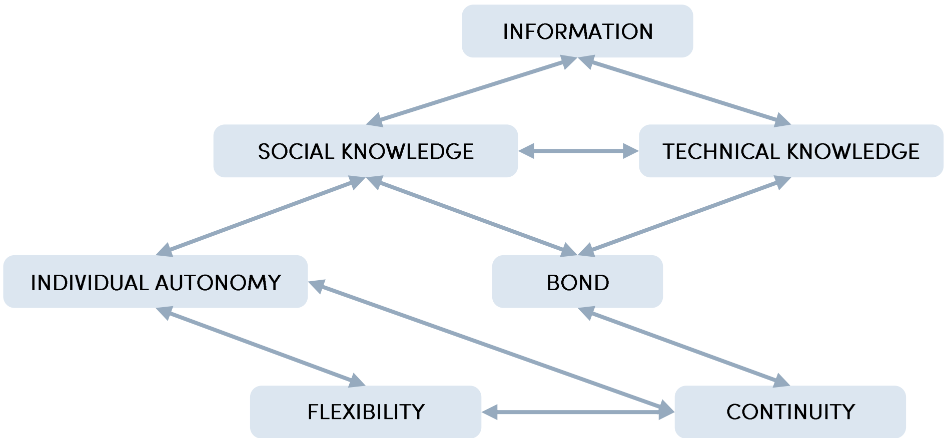

Figure 24: Cognitive map of the most mentioned concepts and their relations

The semi-structured interviews carried out with the social approach confirmed some characteristics of the evolutionary building resilience framework outlined in Chapter 3. The information availability, accessibility and comprehensibility was identified as the main issue to reduce vulnerability and built resilience. The lack of information was linked to a lack of preparedness on how to respond to EWE risks. SOC_14 cited that:

> "Information is very important. For instance, the risks identification, and the manner to minimise them is the information needed to enhancing prevention strategies and if a person can identify the community issues it can also identify itself and it family issues". (Interviewee SOC_14)

Further, it was stated by the interviewee SOC_13, "(…)All members of a family, including children and adolescents, should have a minimum level of information about how to protect themselves and the house and to whom ask for help". It is interesting to highlight that the importance gave to the information corroborate with a central point of the ERB framework developed in Chapter 3. However, to ensure that this information is well understood and the lesson learned was recognised as the main issue in this process.

What made information comprehensive in this context, stated by all the interviewees, is the integration of the social and technical knowledge. The main issues considered were related to the technical language that is unfamiliar to most of the dwellers. The general complaint is that the architects or engineer struggle to communicate information in terms everyone can understand. In some circumstances, the social worker was called to translate the technical language and communicate clearly. Furthermore, they agreed that this is important since the issue is communicating concerns or protection measures for residents of risk areas and in some cases, there is urgency on the clear understanding. The lack of this understanding can lead to a misjudgement of the risks. The interviewee SOC_13 advocates that:

> "Firstly, it is necessary to understand the level of understanding of this community about the theme, to understand the culture, and to know how to dialogue with the community, a diagnosis. Afterward, we can give the historical dimension and the scientific approach, so they can have arguments, using the language more accessible as possible. It is important, always checking what they understand and what is being communicated. I think it is not a mass communication; the ideal form is in small groups. It can be communicated through the example of other locations that suffered from unexpected extreme events. It could be with written, visual material in visible places of the house, posters, and videos. Visual material is the best form." (Interviewee SOC_13)

A second issue was related to the lack of consideration of the local citizen knowledge. The interviewees acknowledge the importance to take into account this "local knowledge" when making plans and building projects. The local dwellers know the terrain and neighbour and, therefore, might suggest better solutions or shed some light on questions. However, can be argued that they do not have the technical knowledge desirable in these scenarios, the interplay between the two knowledge, that they call as "social knowledge" and "technical knowledge" was highlighted as fundamental in this process.

More than just considering both the technical and social values for a resilient community, it was argued that the two knowledge should be long-term linked. The interviewee SOC_11 affirm:

> "The information cannot be delivered just once. It is a relationship of continuity. The municipality needs maintain the relationship with these communities. It cannot be: I gave you the key, and now it is up to you, here it is the manual. This relationship needs to be maintained. If the population does not understand certain things, technical assistance is responsible for clarifying." (Interviewee SOC_11)

They understand that the link must be created before any project and should be carried out during all the lifecycle of the building, as technical assistance, provided by the government. However, they generally feel that the municipality or public sector, in general, does not take enough action in order to improve the communication between the technicians and the citizens. This long-term communication was considered important for the moment of EWEs. Allowing a trust relationship between the residents and the experts providing technical advice about the building maintenance and conservation besides alerts of a dangerous situation. Additionally, continuous technical assistance plays an important role in prevention. It is the task of these professionals to advise the building owner on measures to preventing damage on the building reconfigurability.

However, although the interviewees acknowledge the importance of continuous technical assistance they recognise the importance of the improvement of individual autonomy. They recognise that the dwellers, mainly in the most vulnerable communities, need to have the information and the tools for intervention on their own houses. In fact, when this population are allowed to implement certain measures to protect themselves and their houses from EWEs they can be more willing to take action to improve the quality of the houses. However, in order to create this individual autonomy, it is necessary to increase their risk perception and provide the technical assistance indicating the measures to be taken. They recognise that the government should take responsibility and provide safety to the residents, but they also should help them to increase their capacity. Once again, the link between the socio and technical knowledge was emphasised.

Finally, the technical assistance and the individual capacity can be successful in dealing with the houses if the building system used is flexible. The interviewees stated that the layout and the building systems should be flexible in a way that rooms could be added and walls could be changed. The flexibility to rebuild some part of the building system was considered important when dealing with EWEs. The layout flexibility had relation with the families' configuration. Interviewee SOC_11 exemplifies the need for more rooms in the house:

> "Their family configuration is very diverse, the child who was born in that house is an adult today. She is very likely to bring her husband into the house. Then this house will have to be renovated, will have to suffer some increase, which was one room would turn into two rooms. The main family that I have been attending since 2008, located on the Ilha das Flores, already has two daughters who got married and stayed there, in the same house." (Interviewee SOC_11)

Ilha das Flores is a small community located on one of the islands of the Guaíba Lake in Porto Alegre. It is a flood-prone area and several times the flood caused huge damage to houses of low-income residents. These families had seen the risk increase over the past years. The dwellers construct their own houses with the help of family members, friends or untrained workers with little access to engineering knowledge. The common techniques are wood or brick houses. The interviewee SOC_11 brings an example from this community related to these two types of construction.

> (…) "In Ilha das Flores, for example, they have a type of soil, which does not have much load capacity, so we were studying if they could have a house with wooden structure and on stilts, higher than they have built. Because they construct brick houses, over time appear cracks, has appeared at the school itself; they had to demolish the building and rebuilt the school. However, the wooden buildings, which are built in the background, they remain resistant. Therefore, this is an example, they already know it, even in our conversations when I was seeking some social technology of resilience guidelines with them, and they mentioned that." (Interviewee SOC_11)

The second example was related to the lack of flexibility of the brick technology facing flood event. In addition, it was been judge that the wood material should be a better material for flexibility (for being easier to repair) but also for being adequate or more adaptable to that environment. Besides this reflection, the interviewee point that the residents still prefer the brick houses for considering "stronger and safer" houses. The interviewee thinks that just with information will be possible to break the prejudice and start to use technology that is more appropriate for this kind of community.

Therefore, regarding the development of better communication and information dissemination between the technical and social approach to improve building resilience, interviewees agreed that it should:

a) Use of a plain language to make communication more understandable. Be simple and intuitive;
b) Comprehend the social knowledge;
c) Have a continuous relationship between technical assistance and users; and
d) Built flexible houses

5.1.3.3 The environmental system thinking

The main idea of this approach was to develop knowledge and get insights about the environmental issues relating to the construction of buildings. The sample interviewers chosen for this approach included professional experts on construction, but that also are professional consulting in green building design, sustainable innovation and years of research on sustainable cities and green built environment. This professional profile seems the better choice to achieve the proposed aim.

Although the semi-structured interviews have been designed to support the resilience framework and generate knowledge that can be used to extend theories of building sustainability and innovation and their relations with the environment, it is noted that semi-structured interviews are likely to prompt narratives and thoughts about requirements that have not been anticipated within research design. Additionally, the research problem exists in a real-world context, and the interviews with professionals that deal with the real issues enable the researcher to locate the research and the model in its context.

In response to the question about the resilience concept, all the interviews understand resilience as a broad concept, being adaptable and learning with comprehensive range changing situations, not just extreme events. This factor had a great impact on the requirements and topics that came into discussion. The wide resilience concept brought new challenges and expanded the types of events to what to be resilient. However, this condition was not considered an issue; on the contrary, the discussion was accommodated as additional ideas into the model.

In this group of interviews, it is important to highlight, that it was encouraged the discussion associated with the relation between buildings and environment, looking for understanding how they impact each other. The data gathered was organised following some categories. The main topics identified relating to buildings and their relations with the environment fell under the following categories: Holistic architecture, Short building lifecycle and Energy crises.

The holistic architecture idea was the one mentioned by all respondents independently of the field of expertise. They understand that each building has their challenges and all the environment constrain should be previously understood. Especially significant is the impact that the building cause in the surrounding and the people that lives close to it. Additionally, the impact of the environment on the building was not ignored. At the same time, one of the interviewee (EC0_16) highlight that in many cases, nature can teach how to build a safer building. In fact, one of the interviewees that has a large experience building in very extreme environments and had designed buildings for Antarctica continent said that the way of animals behaves, the wind, even the colour of the ice, could give tips of how is the best way to build.

A second issue that the interviewees also argued is related to the short building lifecycle. The concern was expressed by the big amount of natural resources and energy spent to construct a building, which is expected a lifecycle of only 50 years. At the same time, a reflection was made about who will be the people responsible for the building recovery when those buildings get old. The interviewee ECO _18 add a valuable thought about that situation

> "(…) These old dwellings are occupied by people of fewer resources due to ageing, this gradually gets more accentuated, and we have a situation that in many buildings in Porto Alegre, around 50 years old that the dwellers are extremely resistant to do any maintenance work by the costs that this entails. So start to happen a situation, which certain apartments or housing units are abandoned, and in a little while you arrive at another cycle, that is the building that can be invaded. Invasion by homeless, whether commercial or residential, and this is a precarious situation. They occupy illegally, they do not have electricity, no sewer, no water, and things all tend to accentuate more and more, and you think ok, when you come to the end of the useful life, how will we act on the edification towards the restoration is often very expensive, and this ending to be a problem to the cities." (Interviewee ECO_18)

Regarding this issue, the interviewees agreed that buildings need to be designed for a longer lifecycle. The strategies can involve the use of durable materials, systems that can be improved if necessary along the time, disassembled systems associated with modularity and robust structural systems. Furthermore, considering to increase the building lifecycle, strategies of thinking in projects that can be more flexible, and in single-family houses, supplementary areas should be provided to increase the building.

Finally, the users are understood as a fundamental part of this process. For this reason, post-occupancy evaluation should be provided together with building manual with information about building operation and maintenance, and additional training. All these strategies attempt to monitor the building in use. Additionally, that information should be regarding also about the actions that needed to be taken in case of extreme events. The interviewee ECO_15 that lived in Japan for several years brought her experience:

> "(…) So I lived for a few years in an environment when I entered a place, I had to register, and I received a bundle of things. (..) That's all what you have to be prepared for, the whole bible of knowledge (…), when there is a disaster, you have to take this attitude, you have to call this number, you have to do it, you have to have a kit, and in that kit has to have this has to have that. So I was embedded in a disaster culture and that all people speak the same language because children since three years of age are already doing simulated within schools. Because every Japanese lived a great disaster at least once in life." (Interviewee ECO_15)

Although all the interviewees mentioned the previous subjects, the Energy crisis was the most worrying issue for this group, and always the central topic of the discussions. The building adaptation including strategies of less energy consumption, changing behaviour and types of energy production were consider urgently needed to achieve less pollution.

> "(…) these issues of energy generation, or energy paradigm shift, will require a fit of our whole way of living and at the same time, there are in parallel the impacts of rising pollution, soil, water, air, and food." (Interviewee ECO_18)

In fact, the interviewees consider that deal with energy crises was vital for resilience and more than that, justify a building being resilient. It has been argued that any innovation and building with long lifecycle is just consider accepted if it is sustainable and had the combination of energy saving and efficient and economical energy generation technologies, identified as incremental innovations. For this reason, have been decided to address also this issue in this work, which previously just considered the effects of the EWEs. The interviewee ECO_16 defends:

> "(...) So today we try to make it mainly bioclimatic strategies because there I am associating the issue of user comfort and energy. Energy can be never forgotten, energy and water management we can never forget. Then, minimally, this building should be designed with the best possible efficiency regarding bioclimatic strategy, so that in 50 years from now, is still efficient." (Interviewee ECO_16)

5.1.4 Findings

The semi-structured interviews were undertaken to shed some light about how to describe through requirements the resilient abilities presented on the ERB framework. Following the semi-structured interviews and their content analyses adding literature support for a broad discussion purpose, the main findings are outlined below.

Resilience concept diverges from field area but the main core is similar, and each group have more or less the same understanding. Interestingly, the focus was different in each one of the groups. Once the technical group was focused on the building characteristics, the ecological point of view saw in the environment and in the cities the bigger concern. In contrast, the people or the users was the attention point focused for the social group. Those variations in interpretations were already expected, and it was the motivation for the choice of the three group's interviews in the first place.

Following the discussion around their viewpoints on resilience and resilient buildings, the researcher extracted and summarised from the interviews, the requirements of each one of the abilities. Additionally, the researcher classified and excluded the duplicated requirements or the ones that are content into another. The compiled list of requirements is presented as follow. Regarding Survivability:

a) Use available technology and products that were extracted, produced or manufactured locally;
b) Minimise the number of different materials and elements;
c) Provide the possibility of use of Social Technologies;
d) Provide a maintenance and inspection management system;
e) Select materials using the precautionary principle; and
f) Provide access for inspection and maintenance equipment.

Regarding the development of a system that could be adaptable to circumstances, whereas mostly interviewees stated that they believe that intelligent features could help in the processes some of them also showed some disbelief. However, in all the interviewees were concern about to be “adaptable to what?”. Therefore, the requirements were taken from the questions related to the kind of risks a building minimum should be prepared, in a Brazilian scenario. In this respect, the main points considered were:

a) Flood adaptation;
b) Extreme temperatures adaptation;
c) Storm adaptation;
d) Energy crises adaptation; and
e) Severe loading condition adaptation (fire, explosion, earthquakes, landslides and flash floods)

The Reconfigurability demanded from the researcher a comprehension and systematisation about which requirement should be classified either on the Survivability scope or Reconfigurability. So when it comes to Reconfigurability is important that the system has:

a) Reconfiguration guide;
b) Robust and durable elements and connections;
c) Accessible and disassembled connections;
d) Human scale elements;
e) Modularity and Interchangeability; and
f) Be independent of others systems.

Finally, it had been extracted from the interviews the requirements related to learnability or Information Management for interviewees better understanding. Regarding this subject the identified requirements from the interviews can be listed as follow:

a) User's requirements information;
b) Risks and environmental constraints mapping;
c) Design information;
d) Build Information - Plan of work construction; and
e) Operation and maintenance information.

The Figure 25 presents a summary of the requirements identified and linking to the group's interviews they were mentioned.

ABILITIES	REQUIREMENTS	Tec.	Soc	Envi.
SURVIVABILITY	Provide an inspection plan system	■	■	
	Provide access to the parts of the building quickly and without barriers	■		
	Provide the possibility of use of Social Technology		■	
	Selection of durable components using precautionary principle	■		■
	Easily obtainable building materials		■	
	Standardisation: minimise the use of different materials and elements	■		■
ADAPTABILITY	Flood adaptability	■	■	
	Storms adaptability	■	■	
	Extreme temperatures adaptability	■	■	■
	Energy crisis adaptability			■
	Severe loading condition adaptability	■		
RECONFIGURABILITY	Components Modularity and Interchangeability	■		■
	Robust components and connections	■		
	Human-scale components		■	
	Independence of other building systems	■		
	Disassemblability of the connections	■	■	■
	Provide adequate reconfiguration documentation		■	
LEARNABILITY	Operation and Maintenance Information	■	■	
	User's requirements Information		■	
	Risks and environmental constraints mapping	■	■	■
	Construction Information	■		
	Design Information	■		■

Figure 25: Final list of requirements

5.2 MODEL VALIDATION

Once the literature review and semi-structured interviews were carried out, the researcher had enough data to move on the pinpoint the main requirements to each one of the abilities (Survivability, Adaptability, Reconfigurability and Learnability). The model, as validated through a focus group, will be detailed in the next chapter. Yet, it is useful to see the drafted model presented and discussed at the focus group to understand better the issues explored in this chapter[1].

It is important to highlight that, given the extensive and multidisciplinary nature of the resilient building approach, the scope of this model had to be limited. While the resilience abilities developed by the researcher on the ERB framework could be applied to a different kind of buildings and building system (foundation, structure, envelope, installations), this model with the respective, requirements and evaluation criteria, will be applied just to the house building skin, considered here as the building shell/roofing areas. This choice does not mean that there are not important advances that should be made in other areas. Another constraint is the fact that the discussion about the requirements, as well the elicitation of the expert opinions on resilience were based on the realities prevailing on Brazil. While reflecting some global tendencies, they were just analysed in the Brazilian context and should be validated to other countries before being extended to them.

The researcher was able to develop the ERB model based on the findings of the literature and interviews data. This first ERB model version was composed by a set of requirements and evaluation criteria to each one of the requirements. After developing the ERB model for the building skin system, it was considered necessary to verify if the requirements identified and the appraisal rating scale were accurate, understandable and comprehensive. For this purpose, a focus-group discussion was set up aiming to verify the ERB model besides seeking to obtain further insights into the matter.

5.2.1 Focus groups composition

In order to validate de ERB model, a focus group discussion was set up to obtain insights and ideas for further developments and corrections. Gathering in the group, practitioners and academics from different fields was considered the optimal way to verify the model. As such,

[1] Please consult Appendix B, bearing in mind that this is the earlier version of the ERB model and not the final one.

the group comprised experts from distinct backgrounds, but each one with a specific objective in the group besides the common group discussion. Also, it is important to highlight, some of the participants also had been part of the interviews group and were aware of resilience issues.

The group comprised six professionals with distinct aims in the focus-group discussion:

a) The first participant was an architect practitioner, PhD. in energy performance homes and is currently working with green projects, which aim was to take care of the environmental point of view in the model.
b) The second participant was a civil engineer with experience in the performance of buildings and social projects. This participant aimed to check if all the requirements and evaluation criteria were accordingly with the performance-based approach and not prescriptive-based.
c) The third participant was a civil engineer and a social worker. Additionally, the participant works in projects with vulnerable populations on risk areas. The objective of this participant was related to the interest of the vulnerable communities, aiming not to lose this perspective.
d) The fourth participant was an architect, with PhD. in civil engineering with experience on information technology and disassembling systems. The aim here was mainly looking for the information management requirements and the reconfigurability issues.
e) The fifth participant was a civil engineer and PhD on production engineering. The main function was to check the manufacturing process and the better way to establish indicators and evaluation scales.
f) The sixth participant has PhD. in administration, whose experience concerns to the learning capacity on disasters situations. The objective of this participant was to analyse the issues related to risk assessment and EWEs of the model.

It is important to notice that, besides each one have distinct “functions”, all of them has a construction sector or risk assessment background and were able to discuss all themes. It is important to highlight that besides the participants and the researcher, also a PhD from the research group (GRID) had taken part of the focus group as an additional facilitator, to help to moderate the discussion and time constraints.

5.2.2 Focus Group: Structure of discussion

After initial instructions, the researcher, that assumed the role of facilitator, gave a brief presentation of the thesis subject and the specific aim of the focus group and the objectives of each participant. Then, it was given to each participant a set of four A2 boards content a list presented on detailing the requirements and the respective rating scale. Participants were then asked to take a moment to think about the requirements of the first board (Survivability) and link with their expertise and their main objective. Afterwards, each one of the requirements and the rating scale of the four boards (Survivability, Adaptability, Reconfigurability and Learnability) were discussed on the group.

It was invited that each one of the participants takes notes of their questions or suggestions on their boards. Also, it was asked for participants to comment and if possible identify other requirements that were not considered on the boards. The model was presented, and all the participants are active, and richer insights were allowed in the discussion.

At the end of each board discussion, it was asked if was possible to rank the requirements. If the answer was positive for that group of requirements, it was asked that the participants put a green bullet on the most important and a red bullet on the less important. Afterwards, it was discussed if the group reached a consensus and the researcher synthesized on her on board the results of their consensus. All session was recorded on audio and video for further analysis. The session lasted over four hours and was successful in verify the correct understanding of the identified requirements, bringing new insights for the evaluation rating scale and for ranking the requirements.

5.2.3 Overall outcomes

The first positive insight given by the group was that the resilience subject was very important and prone to discussion. The resilience abilities defined in the ERB framework was explained to common understanding, and no issues were razed about them. However, only the requirements to each one of the abilities were into the discussion. And since the requirements to achieve each one of the abilities was come from the interviews, they were prone to different insights and interpretations. As it was expected, the experts from different field areas reacted by adding or questioning the proposed model. This was considered to be very positive as far as the model development is concerned.

The main issues that were raised about the validity of the requirements were about the requirements that were collected with the social approach interviews. One of the architects considered that the households/users should not take measures themselves about risk situations or the recovery of buildings. He fell that the civil construction professionals should take responsibility for that action. However, after some explanations by the social worker participant about how a vulnerable community deal with extreme events, the group came to an agreement that for practical functioning, the households should also play a central role in the house security.

Besides this discussion, all the requirements were considered valid to achieve the resilience ability, and no new one was considered necessary to be included. Regarding the proposed scale, although, several changes and suggestions have raised. That changes included some concerns about more prescriptive then performance-based, in some cases, and in other situation about the discrepant differences between the levels. In all the cases, the scale was discussed by the group, and a new one was proposed in agreement.

During the focus group, it was suggested the inclusion of a new label between the requirements and the scale. A label called indicators should represent or indicate the level or measure of how the requirement could be accomplished. The idea of including this new label on the model was welcoming for all, as a better way to understand the model.

Survivability

Survivability was presented to the group as *the ability of some elements of a given system to overcome acute or continuous stresses. In this model, this ability is achieved through the use of the precautionary principle for the selection of elements and systematic preventive maintenance*. The group was invited to keep this information in mind to analyse the requirements presented for this ability. It was confirmed that all the requirements of this group posed to discussions were important to achieve building Survivability.

However, some were considered an issue and some constraints were identified. Those issues were raised mainly by the practitioners and are related to the increase cost of the houses besides Brazilian construction sector culture issues. Some concerns were raised as the Brazilian construction sector is resistance to change and novelty, besides lack of interest in increasing the quality of the houses. Even so, during these discussions, some defended that culture and behavioural issues are ever changing and there is no reason to believe that the construction practice may not change, or adapt to enable it. People will not resist the change if they see the benefits.

The requirement **Selection of materials using the precautionary principle** raised the concern about the building increasing cost. Regarding this, it is important to highlight that the concern about increased the relative cost of the construction phase and consequent the price of purchase. However, if it was consider a broader view, during all the lifecycle the cost of using long lasting durable materials will pay back. For this reason, the requirement was preserved.

Besides the technical concerns about **providing the possibility of use of Social Technologies** regarding legal responsibility, it was understood that it is necessary a minimum level of dwellers empowerment. It was emphasised that for this be a safe action, besides de building system be adapted to that, the dwellers should receive sufficient information on how to proceed, considering that they were non-skilled construction workers. Nevertheless, the idea of social inclusion and empowerment was considered important for this scenario.

The requirements **easily obtainable building materials** and **standardisation: minimise the use of different materials and elements** did not raise any further concern and was accepted as it was exposed.

Through the discussion, all seem to agree that cultural issues could be a barrier to achieve the requirements **provide an inspection plan system;** and even the **provide access to the parts of the building quickly and without barriers,** raised some concerns. However, all agreed that this is a bad cultural behaviour and, however, that must change. The group consent to keep the requirements due to the importance of both actions to maintain the building survivability.

For this set of Survivability requirements, the scale suggested was accepted and considered clear. Finally, the discussion about the level of importance among the requirements came to an understanding and will be presented in Chapter 6.

Adaptability

Regarding the development of a system that could be adaptable to changing situations, it was presented to the group the following concept: *the ability of a given system to absorb and be flexible while sustaining damage. In this model, this ability is achieved through the existence of alternative systems that allow the choice of more efficient alternatives. It indicates the agility of which the system can adapt to a new requirement in real time.* In this set of requirements, two main concerns were raised. Firstly, if all the EWEs that can affect the building skin was contemplated, and second issue was if **energy crisis adaptability** should be contemplated.

For the first issue, other situations had been mentioned (water crises, for example) however, they concluded that the building skin system does not have a central role in those situations. The same guideline was used to consider **energy crisis adaptability** accepted. Besides this event is not an EWEs, can be the consequence of several types of EWEs (flood, windstorm, and drought) and the building skin play a central role. Besides that, they all agree that energy crisis will be a significant bottleneck in a close future, and cannot be left to chance.

Therefore, the requirements **extreme temperatures adaptability, flood adaptability; storm adaptability; severe loading condition adaptability (fire, explosion, earthquakes, landslides and flash floods) and energy crisis adaptability** was defined as an acceptable set of events whose a building skin design have to cope and be adaptable.

Cultural and costs issues were raised about the scale suggested, since, the adaptability measures indicate automation and intelligent systems. The scale five was considered very difficult to achieve. However, all agreed that those technologies are the future in building sector and for a broader model should be important also consider these aspects.

Regarding the hierarchy between the requirements, all interviewees agreed that no one was more important than other from a resilience perspective (dealing with uncertainties). Then, if a local risk analysis indicates that some of the events as more likely to happen, a specific measure should be taken. Therefore, all the adaptability requirements will have the same value.

Reconfigurability

The Reconfigurability concept was presented to the group participants as *the ability to facilitate the system's transformation. In this model, the addition, switching, or removing of building skin system components must be easier, allowing horizontal and/or vertical expansion or reduction.* Once again, the issues related to building costs and Brazilian culture were mentioned, even though, the requirements were approved and considered paramount for the building sector, especially in social housing.

Regarding the Reconfigurability requirements, the participants seemed to understand and agreed to the requirements. Some issues regarding user’s role on Reconfigurability process was raised. It was highlighted the importance of the **human-scale elements** and accessible and clear **provide**

adequate reconfiguration documentation, should be paramount to provide for the users. The architect practitioner mentioned that technical assistance also should be provided for a safe reconfiguration.

The **disassemblability of the connections** and the **robust components and connections;** was considered transformation facilitators and important design principles to take into account.

Nevertheless, the requirement that indicates that the building skin system should be i**ndependent of other building systems** was considered paramount. However, all agreed that **modularity and interchangeability** were the most important between the requirements to produce building skin that can be further reconfigurable. All the participants, seem to understand that the Reconfigurability, besides allowing the parts are changing, layout additions also benefit greatly to performance increments, which it is, as a final point, the main objective in this model. The discussion about this set of requirements took more time around the proposed appraisal rating scale, which will be presented in Chapter 6.

Learnability

Finally, related to Learnability, it was presented to the focus group participants as follow: t*he ability that promotes learning. It is achievable through the input, storage, classification and output of information, and efficiently communicated among all stakeholders.* For this set, all the requirements were accepted, and no one was added. The participants noted that different from the previous sets, the learnability requirements has a broader view and could be applied to all the building systems, although this acknowledged the importance, and no requirements were considered to be excluded.

Also, it was noted that the requirements **user's requirements information** and **risks and environmental constraints mapping** were information produced externally to the building product. Even though, they considered basic information for any building product development.

The requirements about **design information, construction information** and **operation and maintenance information,** are related to the building development phases, and with the data that should be produced in each phase. All agreed with the importance of the BIM concept in order to promote learning. The BIM approach was contemplated on the rating scales of each of these three requirements, indicating a path to follow to moving forward. Here some adjusts was made on those rating scales to better represent the use of BIM in these building development phases.

Interestingly, in the step of ranking the requirements, all participants agreed that the **operation and management information,** in other words, the information produced during the use phase, was the most important requirement between them. At the same time, they all agreed that **operation and maintenance information** is also the most challenging and neglected process to deal in the Brazilian housing sector in what concern the production of information.

5.3 CONCLUSIONS

The semi-structured interviews shed some light on the issues that were raised during the literature review and how to turn to real-life the ERB framework developed in Chapter 3. Although eighteen interviews might seem a small sample, the multidisciplinary approach generated very rich data that enabled the researcher to gather convergent ideas about resilient abilities. In specific regards, interviewee's viewpoint in each group varied, but the core was the same. And the interviews for each group has stopped when achieved saturation, that means, when the collection of new data does not shed any further light on the issue under investigation (HARVEY, 2000). It was clear that deal with the EWEs and their uncertainties is an important issue for all. The interviewees recognise that risk and resilience on building construction, especially social houses, is much neglected, resulting loss of money and low-performance houses. This issue made some interviewees further develop their insights and ideas on how, on their point of view, the problem could be addressed.

The semi-structured interviews contribution to the research was fundamentally important in producing the ERB model, establishing the requirements and the guidelines for the proposed appraisal rating scale. They provide for an in-depth understanding of the issues and possibilities around how to achieve each one of the resilience abilities established on the ERB framework. It is important to highlight that the three approaches were chosen (Technical, Social and Environmental) allowed a broader view in this scenario.

Combining data gathered through literature review and the semi-structured interviews culminated in the first draft of the ERB model which was subsequently verified in a focus group discussion. Throught the focus group session, the researcher was thus, able to verify the clarity of each requirement, if all the requirements were contemplating, if two or more was not saying the same, check the acceptance of the proposal appraisal rating scale and finally, to have insights of the level of importance of each requirement in order to achieve each one of the abilities. The outcomes of the section produced the results presented in Chapter 6 concerning the model, composed by the requirements, indicators, scale and finally the hierarchy process. Thus, the next chapter will detail the final model.

6 THE ERB MODEL: THE PROPOSED INDICATORS FOR SOCIAL HOUSING SECTOR

The objective of this step of the research was to identify key indicators for the development of more resilient building skin (BS) systems for the social housing sector, approaching the ERB framework to real-life indicators. For this, a series of semi-structured interviews with experts in multiple areas were carried out.

After completing content analysis of the semi-structured interviews and the literature review about the subject, requirements were identified, and a rating scale was proposed. To develop a model that aims to approach reality, it was imperative to understand the phenomena under the point of view of actors in the field. As such, data of interviewees with technical (architecture and engineering), social and environmental expertise was collected. After, a preliminary model was developed and analysed the clarity and importance of the requirements to verify the model by the practitioners. To accomplish this, a focus group was set up with stakeholders within the construction sector and social inclusion, and the inputs were incorporated in the final model.

It was clear since the beginning of the semi-structured interviews and was confirmed by the focus group discussion, that this model has fundamental importance for social housing more than for other types. Although the EWEs are destructive and a threat for any buildings, is far worse for the social houses and the low-income people. Thus, this model has as main targets, the social housing, built by governmental programs as well as the non-engineered construction. Non-engineered construction is made by semi-skilled or non-skilled workers and with a lack of know-how, appropriate materials, accurate monitoring and building regulations (CHARLESON et al., 2016).

In this context, special attention should be paid particularly to the BS, since it is the system that separates the interior against the environment and the extreme weather events. Thus, the model developed and presented in the following sections is a concern to the building skin system only. In this research, house building skin is interpreted as the area where different internal and external forces are interplay to maintain a constant internal safe and comfortable environmental conditions. The BS system includes both opaque and transparent wall elements as well as the roof.

This chapter is divided into three interconnected sections. The first detail the final requirements, the indicators and the appraisal rating scale to each one of the resilient abilities. This is done following the model presented in the focus group with the proposed changing. Figure 26 shows the new label created in the focus group (indicators) and how the dimensions will be organised on the model.

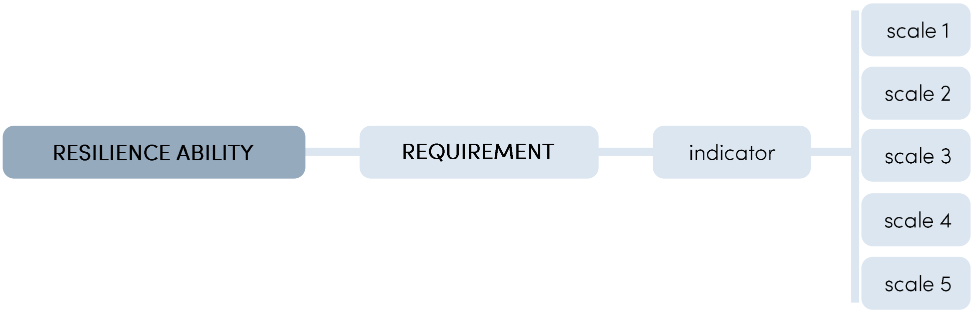

Figure 26. Organisation of the hierarchy of the model

The second section of the chapter is devoted to present the structure of the appraisal content, the opinion of the experts, the requirements interaction matrix and the final ranking of the requirements. It is presented the hierarchical organisation for the indicators. The third section present the validation of the model presenting how the model can evaluate a real-case. The graphics are shown through a real case example, of a social housing condominium, developed through My House My Life program.

6.1 ERB MODEL – GUIDELINES

This section discusses in detail the requirements, indicators and the appraisal rating scale proposed. All of them derive from the literature review undertaken, the semi-structured interviewees and the focus groups conducted as part of this research project. This identified set of items was considered the key issues to achieve each one of the resilience abilities proposed on the ERB framework (Chapter 3). The section is divided by those abilities for clarity. However, all of them are complementary to achieve the evolutionary resilience proposed on the framework.

Since for this research, resilience is understood in a performance-based approach, the building behaviour in use is also a key issue. For this reason, the responsibility of the various construction stakeholders, including the users must be clear. Based on the NBR 15.575 (ABNT, 2013), the stakeholders and their responsibilities were mapping and indicated in each one of the requirements. Figure 27 presents the key stakeholders on the housing building sector for increase building resilience. The letters between brackets are the symbols used to relate them to the requirements.

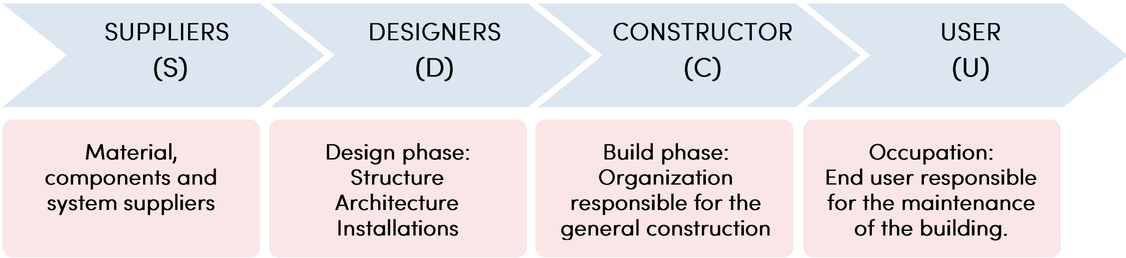

Figure 27: Multi-stakeholder's perspective for Building resilience

Additionally, the rating scale system created focused on a performance-based approach to building skins that can be affected by EWEs. It was designed to be a system that scores points for the less favourable situation to the best goal. As a result, Figure 28 illustrate score proposed. It is important to highlight, that besides the follow scale starts with one point, and it is possible that the real case building do not present even the poor solution, reaching thus, zero points.

Points	Classification
1	Poor solution. Minimum condition acceptable.
2	Below average solution.
3	Average solution.
4	Above average solution.
5	Excellent. The aim to achieve.

Figure 28: Appraisal rating scale system

Based on the appraisal rating scale, to each one of the indicators was established a poor solution until an excellent solution. These solutions were identified on the semi-structured interviews and literature and finally verified on the focus group. The focus group verification aimed to check if the appraisal rating scale was easy to interpret the meaning of each point if all the scale points are identically interpreted by all the group, and the scale's point map closely the indicator proposed. Following, each one of the resilience abilities and their set of requirements, indicators and appraisal rating scales are detailed. APPENDIX C organise of all the requirements, indicators and appraisal rating scale in a table format, for a complete and summarised overview.

6.1.1 Survivability

The first ability indicates characteristics of a system in which some elements can overcome acute or continuous stresses and still persist. In this model*, this ability is achieved through the use of the precautionary principle for the selection of materials and systematic preventive maintenance*. The evolutionary resilience principle adds in this ability the component of the human action and preparedness, which permits a degree of choice on the more suitable materials and in the maintenance of the BS. Figure 29 presents the final requirements and their following indicators. The scale (1 to 5) description is presented further the figure.

Survivability

Requirement	Easily obtainable building skin materials					D, C
Indicator	Distance and availability of components and materials					
Scale	1	2	3	4	5	

Requirement	Standardisation: minimise the use of different materials and elements					D, C
Indicator	Number of different elements					
Scale	1	2	3	4	5	

Requirement	Provide the possibility of use of Social Technology					D, C
Indicator	Number of self-building elements					
Scale	1	2	3	4	5	

Requirement	Provide an inspection plan system					D, C, U
Indicator	Level of inspection and frequency					
Scale	1	2	3	4	5	

Requirement	Provide access to the parts of the building skin quickly and without barriers					D, C
Indicator	Accessibility					
Scale	1	2	3	4	5	

Requirement	Selection of durable components using precautionary principle					D, C
Indicator	Durability of the components' material					
Scale	1	2	3	4	5	

Figure 29: Requirements and Indicators for Survivability

The first requirement is the **easily obtainable building skin materials.** It is believed that the shortest distance associated with the abundance and availability of building systems components is paramount to facilitate the maintenance of any system. For this purpose, the project teams should select local raw materials, preferably. The vernacular architecture is an example of this indicator. It is culturally connected to the environment and foster social resilience to the local EWEs. This type of building systems is developed in harmony of the cultural environment and social knowledge. The idea is that using local materials increase the appropriate maintenance due to the facility of obtaining the materials and train local workers. In this way the **Distance and availability of components and materials** is the indicator. The appraisal rating scale turns to be starting from the poor solution in (1) The system has some components or materials produced in abundance but the purchased can happen only on importation; (2) The system has some components or materials produced nationally but far from 800 Km and scarce with few suppliers; (3) The system has some components or materials produced nationally far from 800 km in large quantities and amount of suppliers; (4) All the components and materials are produced in an 800 km radius, but scarce with few suppliers; (5) All the components and materials are produced in an 800 km radius in large quantities and amount of suppliers.

Standardisation: minimise the use of different elements. The design team should be encouraging for use the lowest possible number of different elements on the building skin design. Besides, the use of standard parts and components is also welcoming. Ensuring less different elements allows the reduction of junctions and facilitates maintenance allowing simplicity and flexibility. The idea is minimising the building skin complexity, reducing the selection of critical materials, and assuring that any part has a function. This helps on reducing the different maintenance methods and tools needed. The indicator for this requirement is **Number of different elements' material.** To answer these requirements, the design team should be encouraging to reduce the number of different layers and finishes on the building skin and try to use the same material for different components (an example is the use of wood for the structure and ceiling in a roofing system). Thus the appraisal rating scale starting for the poor solution (1) More than 20 different elements' material; (2) Up to 20 different elements' material; (3) Up to 15 different elements' material; (4) Up to 10 different elements' material; (5) Up to 5 different elements' material.

Provide the possibility of use of Social Technology. Low cost and easily accessible maintenance of construction systems must be considered, to allow future repairs and can be replicated among its multiple users**.** Social Technology (ST) can be understood as the Brazilian Social Technology Network explain, as "products, technics, and methodologies that can be replicated, developed with the community and represent effective solutions of social transformation". Ultimately, in the building environment, the ST search for the collective autonomy in the social production of space and the civil construction, favouring relations of production in which workers also acquired autonomy. The conception of housing as a process not restricted to the conventional sequence of design, construction and use is another consequence of autonomy. Finally, it is an act of Social Inclusion. In order to assess this requirement on the context of the production of the BS system, it was defined as **Number of replicable self-building elements,** as an indicator of how this system allows the implementation of Social Technology. Likewise, careful consideration should be given to the workers training and building manuals. However, for the ST for self-maintenance works well, the building skin system should allow users autonomy. For the rating development, it was considering the data collected by the semi-structured interviews about the BS parts that should be more important the maintenance autonomy. In this way, the appraisal rating scale starts with: (1) Presence of replaceable roofing through self-maintenance; (2) Presence of windows and doors that allow self-maintenance; (3) Presence of roofing, windows and doors that allow self-maintenance; (4) Presence of roofing, windows and doors and any part of the vertical opaque elements, that allow self-maintenance; (5): The entire building skin allows self-maintenance

Provide inspection plan system is an important requirement to achieve Survivability**.** A management plan for inspection must be considered to facilitate maintenance plans and have a constant and systematic knowledge about the building behaviour. The inspection is a fundamental activity to check whether the building meets the performance requirements. Without inspection do not exist information about the building skin whole life performance. It is the responsibility of the constructor, householders/users and public sector, during the building lifecycle, the safety of the users and neighbours, ensure that the building is being properly maintained, the risk factors are well known, and that the improvements were carried out accordingly. In that case, it is essential to safeguard all data to allow better maintenance procedures. It is believed, that those informations is getting through a systematic and periodic inspection. For this requirement the indicator **Level of inspection and frequency**. It is believed that a proper inspection should be performed by a building inspector, certified in one or more disciplines and qualifying to make a professional judgment. However, it is considered that the user also can have an important role. Therefore, the appraisal rating scale for this indicators was proposed as: (1) Basic routine inspection undertaken by the orientated user; (2) Routine inspection undertaken by the user with systematic feedback to a suitable qualified professional; (3) Basic routine inspection undertaken by the orientated user with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by a professional building inspector; (4) Basic routine inspection undertaken by the orientated user with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by a professional building inspector at times specified in the maintenance manual; (5) Training of its users to do a routine inspection with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by an professional building inspector at times specified in the maintenance manual, plus full inspection of the building skin not exceeding a five year period.

Provide access to the parts or components of the BS quickly and without barriers. To allow better maintenance procedures, the entire system must allow access for inspection and maintenance. This requirement can be fulfilled providing possibilities regarding maintenance accessibility on the system components. Those access as a pre-requirement must be safe and ergonomic. Additionally, maintenance of BS system often involves scaffolding. Those can be disruptive and costly, in this way, it is important to avoid when possible or provide an easy way to fix them. Also, in general, could be interesting the use of components that can be easily clean or self-cleaning, e.g. self-cleaning windows. The indicator for this requirement is the **accessibility level.** The appraisal rating scale starting for the poor solution: (1) Some entry points are viable to some system's parts, besides not planned and not to all system; (2) Planned access points are presently providing access conditions after disassembling some entities; but there are not panned access point to all system; (3) Planned access points are present providing access conditions and easy access provision for regular cleaning of components; (4) Direct access to all system and his components after disassembling one or more entities and easy access provision for regular cleaning of components; (5) Direct access to all system and his components, easy access provision for regular cleaning of components and easy access to other critical (hydraulic, electric, etc.) systems' parts.

Selection of durable components using the *precautionary principle*[1]. The search for more tolerant, less fragile elements must always be the primary focus. All building skin require a level of maintenance if they are to fulfil the expected performance during their lifecycle. However, the choice for more durable components/material focus on reducing this constant required maintenance. The design team also should be encouraged to select materials and components thinking on the durability with considerations for future impacts of EWEs. For that, every system

[1] Precautionary Principle is a strategy to cope with possible risks where scientific understanding is yet incomplete. Available: http://unesdoc.unesco.org/images/0013/001395/139578e.pdf . In this model, the uncertainties are related no just about materials but also to the environmental threats.

components and materials should be assigned to a specific purpose, to fulfil durability standards, always considering local variables and maintain its primary role, even when partially damaged. Additionally, the use of the precautionary principle, consider the uncertainties related to the EWEs and the required caution in chose some components, especially the innovative and not tested ones. The indicator is related to the **durability of the components**. The appraisal rating scale is divided into categories that represent the durability period between maintenances, this rating system was based on the "Guide for Building façade maintenance"[1]: So, the appraisal rating scale starts with (1) components where maintenance is acceptable at short intervals, typically two to five years, for either protective or decorative purposes; (2) components where the first maintenance is envisaged to be at about five to ten years; (3) components where the first maintenance is envisaged to be at about ten to twenty years; (4) components that will not be maintained during the design life of the building; (5) components that will not be maintained during the design life of the building considering local variables and the risks and uncertainties of EWEs, preserving minimal performance when damaged.

6.1.2 Adaptability

The second ability the ERB system is to absorb and be flexible while sustaining damage. In this model, this ability is achieved through the existence of alternative systems that allow the choice of more efficient alternatives. It indicates the agility of which the system can adapt to a new requirement and new circumstances in real time. It implies flexibility and the possibility of choosing between alternatives. Adaptability implies to have strategies to be a problem solving for certain emerged situation. Since, in this model, the focus is the EWEs, mainly increased by climate change, only those were being listed. However, a number of others emerged situation could be adding, like fire, explosion, terrorism, for example.

It is important to highlight, that this part of the model intended to help manage residual risk for a single house scale. Other measures, takes on a regional, city or neighbourhood scale, as avoiding build in risk areas as in the case of flooding areas or landslide risk, or raising floor levels always have to be implemented before. Figure 30 present the main situations and requirements that were considered fundamental mainly in the Brazilian context:

[1] Building façade maintenance. A guide for building owners and occupiers. Available on www.bre.co.uk

Adaptability

Requirement	Flood adaptability					D, C, U
Indicator	Level of agility of the flooding protections.					
Scale	1	2	3	4	5	

Requirement	Storms adaptability					D, C, U
Indicator	Level of windows protection system autonomy					
Scale	1	2	3	4	5	

Requirement	Extreme temperatures adaptability					D, C, U
Indicator	Level of ventilation and radiation controlling.					
Scale	1	2	3	4	5	

Requirement	Energy crisis adaptability					D, C, U
Indicator	Level of user's comfort during energy crises and energy production sufficiency					
Scale	1	2	3	4	5	

Requirement	Severe loading condition adaptability					D, C, U
Indicator	Total of the severe loading condition adaptable characteristics presented by the building skin.					
Scale	1	2	3	4	5	

Figure 30: Requirements and Indicators for Adaptability

The first requirement is the **flood adaptability**. It was considered that the BS system being as the separation of the internal and external environment, plays a fundamental role in the flood effects, allowing skin resilience besides the protection of other systems**.** In this model, the flood adaptability by the building skin system works in two steps: preventing water flooding entering the house and mitigating its effects by reducing building's damage and recovery time. This way in all cases as a minimum pre-requirement mandatory will be the utilization of components that allow easily removal and can be fast replaced (such as sacrificial materials) or material totally waterproof (do not allow any further problems with mould and humidity) that can resist to the flood effects. And the indicator was conceived as a **level of agility to handle flooding protections**. In this way, the appraisal rating scale proposed was: (1) Temporary flood protection system formed by flood barriers on the doors that are wholly installed by the users during flood event (e.g. Sandbags); (2) Temporary technology of removable and demountable flood barriers positioned on the doors that are supplied with pre-anchors for the barriers, installed by the user; (3) Pre-installed barriers positioned around the building skin, activated manually (e.g. flip-up barriers); (4) Pré-installed barriers positioned around the BS activated by a push button or automatically triggered by sensors (e.g. flip-up barriers or drop-down); (5) Self-closing technology of pre-installed flood barriers positioned around the building skin, automatically raise the barrier, coupled with an environmental data gathering and warning system;

Storms adaptability is the second requirement on the list. Those events usually are associated wind and heavy precipitation. It is important to highlight that in an area where tornadoes or hurricanes occur, building a safe room must be considered for life saving purpose. Keeping this in mind, this requirement provides guidelines for BS system to withstand mostly extreme wind events. For the roof it was consider that the better way to deal with storm, hailstorms, was to choose material having improved durability and impact resistance to withstand the destructive forces of storms. Considering that the best practice in design and construction were used, the windows are the weak point on the system. Because of that, the storm adaptability focus mainly on the windows. For this reason, the indicator for storm adaptability was defined as the **level of windows protection system autonomy**. Following, the rating scale was defined as: (1) Technology of detachable and temporary barriers on windows installed by the user (e.g. plywood); (2) Technology of detachable and temporary barriers on windows installed with permanent anchor systems, installed by the user; (3) Pre-installed permanent protective barriers on the windows, activated and operated by the user (e.g. shutters); (4) Pre-installed permanent protective barriers activated remotely; (5) Pre-installed automatic permanent barriers, coupled with an alert system of environmental data collection and impact rated laminated glazed systems.

Regarding **extreme temperatures adaptability,** the BS system must provide shelter and safe conditions with comfortable internal temperature in the event of extreme heat and cold bursts, reducing the need for artificial climate control and energy consumption. However, it was accepted the need of air-conditioned and heating system in extreme temperatures, the idea is to achieve better internal comfort by building skin strategies of ventilation and radiation control. The design team should be encouraging to think on system that are able to adapt to temperature variations, with systems controlling ventilation and radiation. The indicator for this requirement was proposed as the **level of ventilation and radiation controlling**. Considering that, the appraisal rating scale proposed predict was minimum (1) The opaque elements of the building skin should have high thermal storage capacity, and user-managed ventilation systems (opening and closing windows, for instance); (2) The opaque elements of the building skin should have high thermal storage capacity, and user-managed system of sunlight control and ventilation (opening and closing windows and shutters to block sunlight); (3) The opaque elements of the building skin should have higher thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing; (4) The opaque elements of the building skin should have higher thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing and ventilation controlling; (5) The opaque elements of the building skin should have higher thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing, ventilation controlling. The system should have monitoring, storage, and learning capabilities, also able to learn key internal and external parameters. Presence of real time device activation, using Machine-to-Machine (M2M) strategies.

Energy crisis adaptability must to consider that the BS system should be able to help the building's adaptation in the event of energy shortage or crisis, caused by extreme natural events or possible energy crisis due to lack of fuel. This requirement aims to allow natural lightning and ventilation conditions throughout a day. Also, as a goal, the association with renewable energy production in the BS system, allowing to a better adaptation to variations on energy distribution should be associated. The indicator for that should accomplish both the **level of user's comfort during energy crises and energy production sufficiency**. Following the indicator, the appraisal rating scale proposed was: (1) Natural lightning and internal comfort conditions in all building rooms; (2) Natural lightning and internal comfort conditions in all building rooms associated to solar water heating systems; (3) Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid; (4) Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid and solar-battery system to storage generation enough for temporary emergencies; (5) Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid and solar-battery system to storage generation enough for later use and self-sufficiency.

Severe loading condition adaptability (fire, explosion, earthquakes, landslides and flash floods). To withstand severe pressure conditions (impacts, earthquakes, landslides and flash floods) and movement caused by continuous stresses (thermal and structural movements), the

BS system should have: a) Ability to support and adapt to small deformities; b) The structural components has the ability to withstand horizontal pressure; c) independence between structural and non-structural components. The indicator is **total of the severe loading condition adaptable characteristics presented by the building skin.** The rating scale was proposed as follow: **(**1) At least one of the characteristics is present on the building skin design; (2) Having 2 out of the 3 characteristics present on the building skin design; (3) Having all 3 characteristics on the building skin design; (4) The building skin has all 3 characteristics, with constant monitoring and inspection procedures; (5) The building skin has all 3 characteristics, active compensation systems and ensure the monitoring of key parameters through cognitive and communicative systems such as Internet of Things (IoT) to share signs of imminent failure and evacuation alerts.

6.1.3 Reconfigurability

The third ability is Reconfigurability. The idea is to reorient the system to a new and positive trajectory, after passing by adverse events with survivability and adaptability. It is related to the ability to facilitate the system's transformation. In this model, the addition, switching, or removing of BS system components must be easier, allowing correction, to increase performance or horizontal and/or vertical expansion or reduction. This ability must be decided a priori, and the design team should work on the details to think how this will occur easily. Reconfigurability helps to manage the uncertainty of the EWEs, enhancing resilience. Reconfigurability can also, be configurable to a state in which some level of functionality and performance can be maintained. For instance, the separation among systems allows one be stronger when other have a partial failure, as in the case of the separation between structure and BS system. Consequently, Reconfigurability reduces the probability of building complete failure effectively. In addition, it is important that this ability allows more than one-time change, rather the BS should be capable of changing to any need.

The approaches that can be taking in buildings are the concepts of plug and play, as ship containers and the idea of modular architecture. Both approaches that came from areas as aviation has also been applied in the building sector. Additionally, for a BS system and ultimately for building to be easily reconfigurable, the whole design should be lead to that. The layout, the site plan and the structure also need to be projected to accomplish easy Reconfigurability. This model, however, presents the discussion about the BS, with this in mind, some main requirements should have been taking to account. Figure 31 presents those requirements and their respective indicators.

Reconfigurability

Requirement	Adequate reconfiguration documentation					D, C, U
Indicator	Level of reconfiguration information guide					
Scale	1	2	3	4	5	

Requirement	Robust components and connections					D, C
Indicator	Number of possible and disassembled and reassembled					
Scale	1	2	3	4	5	

Requirement	Disassemblability of the connections					D, C, U
Indicator	Complexity of the equipment needed for disassembly the connections					
Scale	1	2	3	4	5	

Requirement	Human-scale components					D, C, U
Indicator	Number of workers needed for each element					
Scale	1	2	3	4	5	

Requirement	Components Modularity and Interchangeability					D, C, S
Indicator	Level of interchangeable possibilities					
Scale	1	2	3	4	5	

Requirement	Independence of other building systems					D, C
Indicator	Level of independence between the systems					
Scale	1	2	3	4	5	

Figure 31: Requirements and Indicators for Reconfigurability

The first requirement here is to provide **adequate reconfiguration documentation.** The best way to the BS be reconfigurable during the lifecycle is its ability to disassemble and reassemble. However, not even the best-disassembled BS design will be effective if the stakeholders do not understand how to implement the reconfiguration. Therefore, to accomplish that, all the information related to the parts, components and methods to do so must be documented and disseminated. Beginning in design and continuing through the construction and use phases, identify and storage of all information for the disassembly and reassembly method, possible upgrading, with the possibility to track materials, components and connections. The indicator proposed to assess this requirement is the **level of reconfiguration information guide.** This requirement intent to evaluate the minimal effort to the best possible future alternatives. However, any items of the appraisal rating scale are not useful unless the future modification been also documented. As a result, the appraisal rating scale star with: (1) Detailed design and construction documents and the as-built information; (2) Graphic instructions with illustrated step-by-step for the dismantling process for components and connections; (3) Complete manual with tools and disassembly procedures (step-by-step), with labelled components; (4) Complete manual with tools and disassembly procedures (step-by-step), with permanent labelled components with information about their materials composition and properties; (5) Complete manual with tools and disassembly procedures (step-by-step), with permanent component tags built into them, which all information can be organised in databases and with wireless technology be sent through the internet.

The second requirement on this list is the selection of **robust components and connections.** The building system's elements must be designed with the use of materials that allow reassembly. The design team should choose components and connections with consideration to withstand repeated disassembled and reassembled procedures, avoiding damage and deformation. Also should be considered the future impacts of those components and connections, since if they have a high quality will retain value in case of reuse. Thus, the material should have good quality for disassembly. The systems suppliers should provide this quality, and the design team should be encouraging to specify for that. For assessing this requirement, the indicator is clearly **the number of possible and disassembled and reassembled.** The appraisal rating scale proposed also indicate that this number of procedures should be realised with minimal damage and repairs needed. Thus, as follow: (1) The building skin system allows disassembly, but without possibility for later use or reassembly; (2) The building skin allows disassembly with the possibility of some elements (e.g. windows, roof tiles) being re-used doing some repair; (3) All the elements of the building skin allows at least one disassembly and reassembly cycle with some repair needed; (4) All the building skin allows multiple disassemblies and reassembly cycles, with some repairs needed; (5) All the building skin allows multiple disassembly and reassembly cycles, without damage and no repairs needed.

Thirdly, there is the need to design easy disassembled connections or the **disassemblability of the connections.** The idea is to use connections with simple disassembly procedures without causing damage to environments. It is also important to consider the ease of connection identification and access. The idea is avoiding expensive equipment or a large number of different tools needed. The design team should be challenged to develop BS systems with no need for equipment and where the components could be detached easily by joints and connectors, eliminating chemical connections. Exposed connections can be a strategy to approach this requirement. Nevertheless, the equipment needed should be kept to a minimum. Therefore, to evaluate the disassemblability of the connections to a building skin can be indicated by the

complexity of the equipment needed for disassembly the connections to do so. The appraisal rating scale indicate that for achieve this: (1) The connections between the components of the building skin can be disassembled using more than one type of electric equipment; (2) The connections between the components of the building skin can be disassembled using one type of standard electric equipment; (3) The connections between the components of the building skin can be disassembled using non-standard manual equipment; (4) The connections between the components of the building skin can be disassembled using standard manual equipment; (5) The connections between the components of the building skin can be disassembled with no need for equipment.

Also associated with the Reconfigurability, there is the necessity that the disassembled components are sized to suit this objective. Thereby, the **human-scale components** issue was indicated as one of the requirements and should be kept in mind by the design team. Those components will decrease the labour needed to disassembly and are especially important for the users living in social houses since most of those are of low income and cannot afford to spend so much on safety and equipment. The safe disassembly should be paramount. Therefore, the indicator for this requirements are **the number of workers needed for each element**, to handle the components safely and with no risks for developing musculoskeletal disorders and health issues. The rating scale proposed was: (1) More than one element does not have human-scale components and need a working team and equipment for handling[1] and moving them; (2) At least one element does not have human-scale components and need a worker team and equipment for moving; (3) At least one element does not have human-scale components and need just worker team for moving; (4) All the building skin elements have human-scale components and are easily and moved with no need of equipment, and the components weight is not too heavy safely manual handle by at least two workers; (5) All the building skin elements have human-scale components and are easily moved with no need of equipment, and the components weight is not too heavy safely manual handle by one worker.

In order to allow for Reconfigurability, it is fundamental to have possibility to switch, change and be compatible dimensionally among the BS components. Thus, **the components modularity and interchangeability** was considered a key requirement. Modularity, in this context, indicates the possibility of changing, adding, or removing, certain parts of the element without altering the

[1] According to the U.S. Department of Labor, handling means: Seizing, holding, grasping, turning, or otherwise working with the hand or hands. In this model, the worker handling also includes moving, carrying, lifting or lowering the components manually.

rest of it or the BS as a whole. The interchangeability indicates that besides that, it is still possible the components change among different elements. The elements must have adequate measures to allow eventual replacements following the demands, allowing flexibility Otherwise, even with easy disassembly, the possibility of a real Reconfigurability is critical restrict. The idea is that among all the components and also system, the possibility of interchange can be promoted through the principles of modularity and standardization. The indicator for this requirements is the **level of interchangeable possibilities.** Thus, how many possibilities of changing the component position on the BS, the highest is the score in the appraisal rating scale. This indicator has a narrow view indicating just the dimension of the components as evaluation criteria. The appraisal rating scale proposed was: (1) The components do not use modular measures; however, the components with the same function has the same dimensions; (2) Some components follow modular measures, it is possible to change for others new but not interchange with others components of the building skin; (3) All the components follow modular measures and are coordinated and interchangeable, but not among different elements; (4) All the components are modular, coordinated, labelled for traceability and there is the possibility of interchange all components and elements of the systems; (5) All the components are modular, coordinated, labelled for traceability using IoT appliances and sensors and there is the possibility of interchange all components and elements of the systems.

The last requirement identified for the Reconfigurability was the necessity of **independence of other building systems.** In order to allow the BS easy Reconfigurability, each system should perform independently. The design team should be encouraged to project the structural, installations systems separated from the BS system. This decision will allow an increase in flexibility for the separation of the structural elements, non-structural elements and the functional (electric, hydraulic etc.). The separation among the BS and the structural system is paramount to promote Reconfigurability without affecting the building core. Additionally, it is appropriate for the project of a more robust structure allowing the possibility of scalability in the case of single floor houses. The indicator for this requirements was proposed as the **level of independence between the systems,** which how more independent the BS systems perform of the others building system, bigger is the score. Therefore, the appraisal rating scale proposed for this indicator tries to represent this level of independence as follow: (1) The building skin is projected as a monolithic load-bearing walls, but at least the hydraulic and electric systems are independent or easily accessed; (2) The building skin is integrated to the structured or physically adhered and cannot be changed, but it is independent of all the others functional systems; (3) The building skin is integrated to the structure, however, it is easy to maintain and low cost and independent of the other systems; (4) Elements of the BS system can easily be changed without affecting the structure and the remains systems; (5) All the BS could be replaced without affecting the structure and others systems.

6.1.4 Learnability

This ability, the information collected, aims to be the DNA of the building. It is the set of information collected during all the phases of the building lifecycle which purpose is to *promote learning. It is achievable through the input, storage, classification and output of information, which is efficiently communicated among all stakeholders.* This group of requirements do not deal directly with the EWEs. However, it is fundamental and plays a central role on the achievement of the other three previous abilities presented (Survivability, Adaptability and Reconfigurability). Two key issues were identified on this requirement's set. The first issue was related to the quality of information collected in each phase and the second, how this information will be well managed and communicated among all stakeholders. The questions around this ability are: which is the relevant information that should be provided? And, how can this information be delivered to the relevant people?

It has been argued on the interviews and on the focus group that only users' manuals are not effective for the social housing sector. It is necessary to deliver technical knowledge to users in a way that they can understand and learn. Therefore, the information should be produced in a form that can be stored and accessed easily beside its effective dissemination. To address this issue, various approaches can be adopted as technical guidelines, building manual, training procedures, being all of them with plain language[1]. Therefore, the plain language communication is pre-requirement for all the information produced about all the requirements that follow. The requirements in this group are divided into information about the users, information about the environment, and information about the project, construction and use phases. Following, Figure 32 present the requirements and indicators proposed.

[1] "A communication is in plain language if its wording, structure, and design are so clear that the intended audience can easily find what they need, understand what they find, and use that information." Accessed in http://plainlanguagenetwork.org/

Learnability

Requirement	User's requirements information					D, C, U
Indicator	Level of user's requirement knowledge.					
Scale	1	2	3	4	5	

Requirement	Risks and environmental constraints mapping					D, C, U
Indicator	Level of environmental risk knowledge					
Scale	1	2	3	4	5	

Requirement	Design Information					D, C, U
Indicator	Level of development of the design phase information					
Scale	1	2	3	4	5	

Requirement	Construction Information					D, C, U
Indicator	Level of development of the construction phase information					
Scale	1	2	3	4	5	

Requirement	Operation and Maintenance Information					D, C, U
Indicator	Level of development of the construction phase information					
Scale	1	2	3	4	5	

Figure 32: Requirements and Indicators for Learnability

The first requirement considered important for the promotion of learning to increase resilience is the **user's requirements information.** The needs and requirements of users must be sources of information for the design development, and it is recommended that these sources are always up to date. The user's requirements identification, as the broader view of the "social knowledge" identification (section 5.1.3, knowledge that arises from the communities) were considered both fundamental to increase the resilience of the buildings. Therefore, a building should embrace that information during the design as well as during the lifecycle. It is important to understand how is the best way to accomplish the user need, as well as to understand their constraints about how the building will be operated and maintained. The more detailed information and knowledge about those requirements, the easier will be to achieve a more resilient building. Additionally, this information is important to guide and determine suitable strategies for BS maintenance, adaptation and reconfiguration. In this way, the indicator proposed was **the level of user's requirement knowledge**. The rating scale starts for a minimum and basic level of user's requirements until a level where that information is updated during all the building lifecycle. By consider that it, the appraisal rating scale proposed was: (1) Development of briefing considering user's needs, but such building is not designed in response to any particular user; (2) Development of briefing considering the specific client/users' needs and knowledge; (3)

Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements; (4) Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements, additionally should be carried out regular post-occupation analysis; (5) Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements, additionally, should be carried out regular post-occupation analysis and technical inspections.

The local **risks and environmental constraints mapping** is the second requirement, and it is a paramount type of information. Besides resilience deal with the uncertainties and the unpredictable events, all the information gathered about the environmental risks is important in order to prepare the BS for possible threats and to orient towards a resilient building. Therefore, the information related to the surroundings coupled with possible risks must be mapped. Although, the data collection about the environment constraints is a common practice to develop any building, here it is proposed a deep understanding of the cause and consequences of the possible risk of EWEs. In order to accomplish that, a multidisciplinary team should be considered to map the types of EWEs, the susceptibility, threats and finally the risks. Additionally, this risk mapping should be constantly updated during all building lifecycle. Thereby, the system's vulnerability can also be monitored during extreme events and transmitted through IoT concepts, monitoring environmental parameters. The indicator for this requirement is the **level of environmental risk knowledge** for management. The appraisal rating scale proposed was based on the risk management concept proposed by the group CEPED/GRID[1]. The rating scale was configured as follow: (1) Develop the inventory of all the EWEs that occurred in that specific region. This inventory, can be obtained by governmental agencies, media collection or any other source of information; (2) Point one, plus mapping the susceptibility of EWEs happening in that local; (3) Point one and two plus mapping of local vulnerabilities and threats for the human activities. This mapping could be done with the help of the local population; (4) Risk mapping indicating possible future reconfigurations; (5) Risk mapping indicating possible future reconfigurations; plus, constant mapping during the building's lifecycle, through automated monitoring of risks, generating alerts in case of imminent failure through IoT systems.

The third requirement deal with the level of information developed during the design stage. In this way, the **design information** was considered an important source of data that should be

[1] For additional information check the section 2.1, Chapter 3.

developed and storage for consultation during all the building lifecycle. The goal is generating a better quality of information and make this information accessible to all the stakeholders. All project decisions, calculations and simulations results must be generated and stored to be future accessed. Additionally, a set of documents about those with plain language should be generated to support the possible user's intervention. The indicator for this requirement is the **level of development of the design phase information**. The appraisal rating scale proposed was developed considering the set of information that should be developed, storage and available for the users after the building was built. Another methodology that was taken to account for the rating scale setting up was the Level of Development (LOD) specification proposed by the American Institute of Architects[1] that are intended to improve the quality of communication among users of BIM. The final rating scale proposed was: (1) General architectural Projects, 2D drawing and CAD developed, (2) Architectural, structural and installations projects, using 2D drawings and detailed construction documentation with descriptive guides; (3) Use of 3D model BIM, with LOD 300 - An accurate model building with precise quantity of elements, size, shape and location. Non-graphic information should be attached to the model; (4) Use of 3D model BIM, LOD 350 - An accurate model building with a precise quantity of elements, size, shape and location, and the interfaces among the building systems should be represented. Non-graphic information should be attached to the model; (5) Use of 3D model BIM, LOD 400 - An accurate model building with a precise quantity of elements, size, shape and location, with detailing construction and assembly information. Non-graphic information should be attached to the model. Additionally, all its documentation, prototyping virtual reality and simulations should be provided.

The following requirement is about the information produced during the construction phase. Although a considered amount of information could be produced in the design phase, many issues and new configuration are expected in the construction stage. Therefore, **construction information** was considered an important requirement to improve the quality of information provided to the user. Any eventual alteration must be updated accordingly. Such information should be generated with field verification and must be stored for future consultation. It was defined that the information about costs was not an important asset. Such information, besides commonly produced during the construction phase, would not be useful for future user's consultation. The indicator for this requirement is the **level of development of the construction phase information.** Finally, the appraisal rating scale proposed started with: (1) As-built

[1] Available at: https://www.aiacontracts.org

drawings - revised set of 2D drawings (architectural); (2) As-built drawings - revised set of 2D drawings (architectural, structural and installations); (3) As-built drawings - revised set of 2D drawings (architectural, structural and installations). In addition, a list of suppliers should be attached. (4) As-built BIM Model (4D BIM (construction time and schedule) – LOD 500 – Model with a field verified representation of size, shape, location, quantity and orientation as constructed for maintenance and operations. (5) As-built BIM Model (4D BIM (construction time and schedule) – LOD 500 – Model with a field verified representation of size, shape, location, quantity and orientation as constructed for maintenance and operations. Non –graphic information should be added as time for construction, schedule and suppliers lists. In addition, an organised file with lessons learned [1]in the construction phase should be provided.

The last requirement is the **operation and maintenance information.** The aim here is to identify and provide all the information needed for operation and maintenance by the facilities management staff or users. Information about the building's operation and lifecycle must be generated and stored based on the design, the construction and during its use phase, indicating a nd orienting all maintenance, repairs, restoration and possible transformation of the building system. Such information is paramount to support the abilities of Survivability, Adaptability and Reconfigurability. The indicator is the **level of development of the use and operation phase information**. The appraisal rating scale proposed was: (1) Provide a building manual with easy and accessible information for management and use and should be provided with the summary of the building; (2) Provide a building manual with easy and accessible information for management and use, the summary of the building; key reference suppliers, and information about energy management and conservation; (3) Provide a building manual with easy and accessible information for management and use, the summary of the building; key reference suppliers, and information about energy management and conservation. In addition, a specific and detailed operation and maintenance manual, providing training that include an introduction to the maintenance of the building system, in case of emergency, (for instance fire alarm) and energy and water saving; (4) Point 3 plus, organization of all project information, user guide, inspection and operation and maintenance plans inside a BIM platform; (5) Point 3 plus, organization of all project information, user guide, inspection and operation and maintenance

[1] "Project Management Institute (PMI) Project Management Body of Knowledge (PMBOK) defines lessons learned as the learning gained from the process of performing the project". Available at https://www2a.cdc.gov/cdcup/library/pmg/implementation/ll_description.htm. In this model, the lessons learned should be collected in the construction phase.

plans inside the BIM platform, being managed and fed with new information and learned lessons during the building lifecycle.

6.2 THE ERB APPRAISAL STRUCTURE

This section presents the hierarchy ranking defined among the requirements. All the requirements were considered important; however, it was considered essential to highlight the ones that would be of greater impact to accomplish the ability proposed. Since there are several requirements to consider and some of them may be inevitably conflicting, the ranking was considered fundamental for the ERB model development. A two-phase strategy was established to define the ranking requirements. The first step was submitting the requirements to the expert's opinion. Those opinions were collected on the focus group discussion, as presented on 5.2 section. The second step, a correlation between the requirements was analysed to understand how each of the requirements would interact with the achievement of the others. This approach allows the perception of trade-offs among the requirements.

6.2.1 Overview of the opinion from experts

Following the research design, the requirements were discussed on the focal group regarding the importance level to achieve the proposed ability. The requirements were only assessed and ranked inside the limits of the ability group they belong. The importance level among the abilities was not consider once, for the ERB framework all the abilities are equally paramount. The aim was check if the experts identify distinct importance level among the requirements and to what degree this happens. The goal here was not ranking in order to exclude any requirement, once this question was placed on the focus group and in common agreement, all the requirements should remain.

The results are shown in Figure 33, where the scores given by the experts are presented. Since it was suggested to the experts to mark with green bullets the most important requirements and with red bullets, the ones that could be consider fell behind. As a result, some consensus come to light and the expert answer were shown as they marked. This approach was used to avoid the common answer that "everything is important", and guide the group to think about a rank order.

The number of green and red bullets also varied. For some of the experts, there were two green and two reds bullets, for others one red and two green bullets, or just some of them are green, and no red bullet was considered. Those answers raised after the group discussion when some agreements and disagreements were arising. Therefore, the ranking methodology used was considered a better way to represent the open character of the focus group guided discussion without excluding any personal opinion. Additionally, in this case, where there is a lack of available data to compare the performance indicator, adding to the multi-criteria and holistic approach of the requirements, the expert's opinions were considered suitable as a ranking criterion.

ABILITIES	REQUIREMENTS	Code	Experts 1	2	3	4	5	6	E_{il}
SURVIVABILITY	Provide an inspection plan system	S1	9	9	9	9	9	9	54
	Provide access to the parts of the building quickly and without barriers	S2	9	9	3	9	9	9	48
	Provide the possibility of use of Social Technology	S3	1	3	9	3	3	9	28
	Selection of durable components using precautionary principle	S4	3	3	3	3	3	3	18
	Easily obtainable building materials	S5	3	1	3	1	1	3	12
	Standardisation: minimise the use of different elements' materials	S6	1	1	1	1	1	1	6
ADAPTABILITY	Flood adaptability	A1	9	9	9	9	9	9	54
	Storms adaptability	A2	9	9	9	9	9	9	54
	Extreme temperatures adaptability	A3	9	9	9	9	9	9	54
	Energy crisis adaptability	A4	9	9	9	9	9	9	54
	Severe loading condition adaptability	A5	9	9	9	9	9	9	54
RECONFIGURABILITY	Components Modularity and Interchangeability	R1	9	9	9	9	9	9	54
	Robust components and connections	R2	3	9	9	3	3	9	36
	Human-scale components	R3	9	1	3	1	9	1	24
	Independence of other building systems	R4	1	3	3	9	3	3	22
	Disassemblablity of the connections	R5	3	9	1	3	1	3	20
	Provide adequate reconfiguration documentation	R6	1	3	9	1	1	1	16
LEARNABILITY	Operation and Maintenance Information	L1	9	9	9	9	9	9	54
	User's requirements Information	L2	3	9	9	9	3	9	42
	Risks and environmental constraints mapping	L3	3	3	9	3	9	9	36
	Construction Information	L4	9	3	3	3	9	3	30
	Design Information	L5	3	3	3	3	9	3	24

Figure 33: Expert's assessment of the importance level for the proposed requirements

At first, the Experts Importance Level (E_{il}) column indicate the proportional and cumulative answers reached. This index is used in the composition of the final score that a BS system will gain, highlighting the more relevant requirements. For this ranking system was assigned weighting factors, where the red bullets (least important) represent 1 point, the white (moderately important) was considered 3 points and for the green bullets (most important) was consider 9 points. This ranking system was considered suitable to represent the disparity among the requirements from the expert's point of view.

Figure 33 shows that in the Survivability group the item to “Provide an inspection plan” (S1) has a common agreement about the highest importance level. The requirement “Provide access to with the parts of the building quickly and without barriers” was also well supported and had only one disagreement opinion. Interesting, the experts noted that both are fell behind on the national construction sector, besides paramount to think in any building system resilience. In relation to the less important requirements, it was considered that “Standardization of materials (…)” was not paramount for Survivability. The explanation for this might be found in the concern expressed by the practitioners about the impact in design innovation by the adoption of such a restriction. Also, the “easily obtainable building materials” had been pointed as not having great importance to achieve Survivability. Disagreement can be noted on the scores related to the Social Technologies requirement, where one expert mark as a red bullet, where other two marked with green bullets. The explanation for this might be found in the different backgrounds of the experts (architect practitioner and social worker). Again, this was considered valid and important, due to the multidisciplinary character and the respect to the individual opinions aimed at this proposed assessment.

Following, the value was normalised to adjusting values measured on a different number of requirements to a notionally common scale. Therefore, in order to visually depicts the most significant requirements, for their total score were calculate the percentage for each requirement (E_{il^*}) (the subtotal for that requirements points divided by the total for all categories), and create a Pareto chart for each ability’s requirements group. Figure 34 shows the Pareto chart representing the experts’ assessment for Survivability requirements.

Code	E_{il}	Cumulative E_{il}	Percentage (E_{il} *)	Cumulative percentage
S1	54	54	33	33
S2	48	102	29	61
S3	28	130	17	78
S4	18	148	11	89
S5	12	160	7	96
S6	6	166	4	100

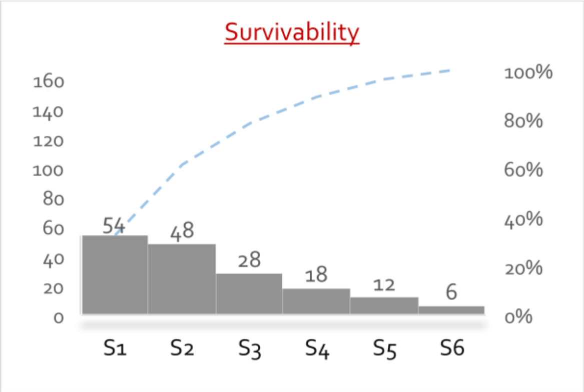

Figure 34: Table and Pareto chart for the Expert importance level of the Survivability requirements

Regarding Adaptability, all the experts of the focus group agreed that there were no differences on the importance level among the requirements. There was a consensus that any of the adaptability requirement is more important than other since each one is related to a specific event. There was, an issue related to the distinct probability of the occurrence of events, and their low or high risk. However, since it was understood that resilience deal with the unpredictable events, and has a great deal of uncertainty, it was an agreement that all requirements proposed should receive the same importance. The Table and Pareto chart for the importance level of the Adaptability requirements are shown in Figure 35.

Code	E_{il}	Cumulative E_{il}	Percentage (E_{il} *)	Cumulative percentage
A1	54	54	**20**	20
A2	54	108	**20**	40
A3	54	162	**20**	60
A4	54	216	**20**	80
A5	54	270	**20**	100

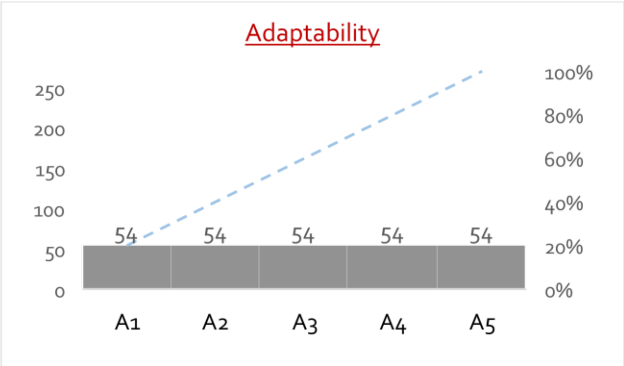

Figure 35: Table and Pareto chart for the Experts importance level of the Adaptability requirements

Concerning to Reconfigurability group of requirements seems to have the biggest diversity on the importance level distribution. As shown in Figure 33 the only requirement that was confirmed by all the experts as the most important was about the use of “Components' Modularity and Interchangeability” (R1). They all agreed that for real implementation of reconfigurability on the construction sector this requirement is the essence. The “Robust and suitable components and connections” (R2) also had been mentioned more strongly by some experts. It was interesting to note that, for all the requirements remained were the judge as “most important” for at least one expert. Again, since the goal was to have all the expert’s perception, it was calculated all the points sums and the respective percentage for each requirement. Figure 36 shows the final ranking among the reconfigurability requirements represented by the table with the sum and percentage and the Pareto chart.

Code	E_{il}	Cumulative E_{il}	Percentage (E_{il} *)	Cumulative percentage
R1	54	54	**31**	31
R2	36	90	**21**	52
R3	24	114	**14**	66
R4	22	136	**13**	79
R5	20	156	**12**	91
R6	16	172	**9**	100

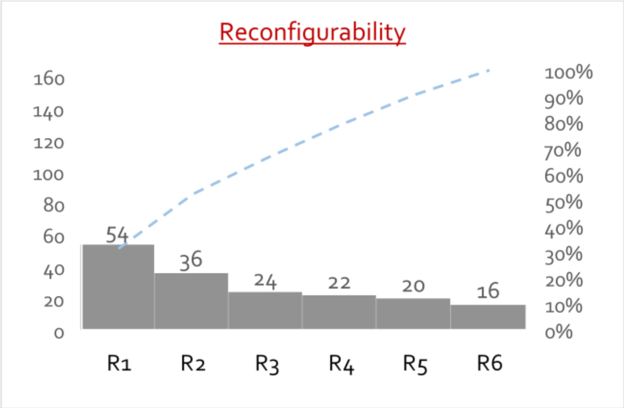

Figure 36: Table and Pareto chart for the Experts importance level of the Reconfigurability requirements

Within Learnability requirements, the emphasis was given to: “Operation and maintenance Information” (L1) and “user’s requirements and values identification” (L2) as key requirements. Interesting, but not surprisingly, experts that had worked with risk management and risk perception also suggested that “risk and environment constraints mapping” (L3) should be considered as most important. The experts feel that for this group of requirements, although some requirements should be highlighted as most important, there were not requirements least important. Therefore, only the green bullets had a place in the exercise of raking the learnability requirements group, as can seem in Figure 33. Figure 37 shows the final ranking among the Learnability requirements represented by the table with the sum and percentage and the Pareto chart.

Code	E_{il}	Cumulative E_{il}	Percentage (E_{il} *)	Cumulative percentage
L1	54	54	**29**	29
L2	42	96	**23**	52
L3	36	132	**19**	71
L4	30	162	**16**	87
L5	24	186	**13**	100

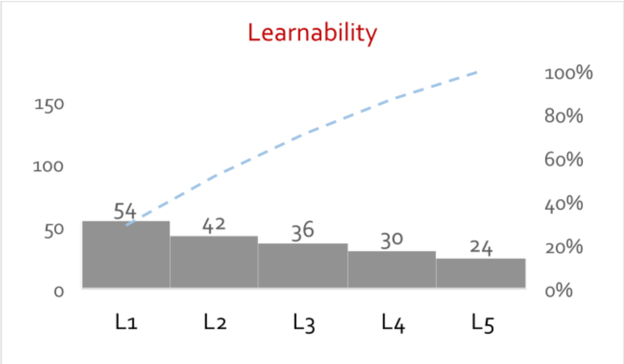

Figure 37: Table and Pareto chart for the Experts importance level of the Learnability requirements

To summarise, it was considered that the method adopted to collect the expert’s opinion and the importance level was successful. The collection step, allow some group consensus, while respecting the different personal opinion. Finally, it was assigned importance levels by normalising the results and ranking the requirements. However, since each ability has some different and sometimes divergent requirements, it was considered important also to determine the potential positive and negative interaction between the requirements, where some potential trade-offs may be considered. This step is detailed in the next section.

6.2.2 Requirements interaction

This step aimed to discovery and assess the relationships among the set of requirements of each ERB ability. Since the requirements collected were held by different experts' group (social, environmental and technical) who may have conflicting views, this trade-offs analysis is an essential activity to comparing and prioritising the requirements. The idea is to trace influences between the requirements and find some potential clashes.

There are some methods to help with requirements engineer, among them the House of Quality, part of the Quality Function Deployment, a method developed by Yoji Akao in 1966. The QFD is a method for designing a product or service based on customer demands. The "roof" of the House of Quality investigates the relations among the product characteristics searching for trade-offs. Additionally, there are other more complex methods to deal with requirements interaction, as the multi-criteria decision making (MCDM). However, for this step it was not considered necessary the exploration of this methods since the idea was not choosing among the alternatives only ranking them.

Therefore, the main objective of this step was to analyse how the requirements would interact among them. In this step, again, the interactions were assessed only inside each ability (Survivability, Adaptability, Reconfigurability and Learnability) set of requirements. Consequently, a matrix to each one of the abilities was created to represent those interactions. The matrix format was chosen since better represent how a requirement interacts with each other. The scale used to evaluate the relation was the effect on the achievement of the requirement listed (-3 negative great, -1 negative little, 0-nothing 1-little 3-great). In order to finally ranking the requirements, the first step was to analyse how each requirement of the column (j) would affect the achievement of the requirements on the row (i). The matrix has to be filled by the researcher, taking into account the understanding of the requirements and the appraisal rating scale proposed. Additionally, the points were summed to indicate the requirement score based on the intensity of the relations. Figure 38 shows the interactions among the requirements and the summarised results (I).

Effect on the achievement of the requirement listed (-3) negative great, (-1) negative little, (0) nothing, (1) little , (3) great.	Easily obtainable building materials	Standardisation: minimise the use of different elements' materials	Provide the possibility of use of Social Technology	Provide an inspection plan system	Provide access to the parts of the building quickly and without barriers	Selection of durable components using precautionary principle	I
Easily obtainable building materials	3	0	1	0	0	0	4
Standardisation: minimise the use of different elements' materials	0	3	1	0	0	0	4
Provide the possibility of use of Social Technology	0	0	3	1	0	0	4
Provide an inspection plan system	0	0	3	3	1	0	7
Provide access to the parts of the building quickly and without barriers	0	0	3	3	3	0	9
Selection of durable components using precautionary principle	0	0	0	0	0	3	3

Figure 38: Interaction matrix for Survivability set of requirements

The Survivability matrix (Figure 38) shows that no negative effect was found among the requirements, and there is some positive effect. The matrix shows that **provide access to the parts or components of the building quickly and without barriers** will benefit the **possibility of use of Social Technologies** and to **provide an inspection plan**. Additionally, **provide an inspection plan** would probably add great benefits to the **possibility of the use of Social Technologies**, since people can have more information during the BS lifecycle.

Following, to better represent the ranked requirements and using the same order of magnitude of the expert's opinion (E_{il}: Experts importance level, Section 6.2.1), adjusting the values on different scales for their total points, were calculate the percentage for each requirement (the subtotal for that requirements points divided by the total for all categories) normalising the scales.

Figure 39 summarise the results of the total score for the Survivability interaction requirement normalising the results and achieving the Interactions level normalised (I*).

Survivability Requirements	I (ranked)	Cumulative I	**Percentage (I*)**	Cumulative percentage
Provide access to the parts or components of the building skin quickly and without barriers	9	9	**29**	29
Provide an inspection plan system	7	16	**23**	52
Easily obtainable building skin materials	4	20	**13**	65
Standardisation: minimise the use of different materials and elements	4	24	**13**	77
Provide the possibility of use of Social Technology	4	28	**13**	90
Selection of durable components using the *precautionary principle*	3	31	**10**	100

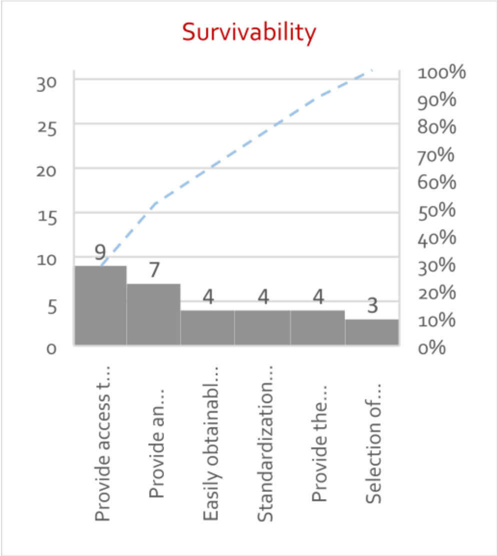

Figure 39: Table and Pareto Chart for the Requirements Interaction for Survivability

Regarding adaptability, the same procedure was used to understand the possible interaction among the requirements. Figure 40 depicts the requirements interaction exercise expressed as a matrix. It was considering that the strategies for **flood adaptability** and **storm adaptability** have a great interaction with each other. Also, the fulfilment of the **extreme temperatures adaptability** requirement it might influences in a great effect the achievement of the **energy crisis adaptability** requirement. Finally, it is important to note that the **energy crisis adaptability** benefits the achievement of **flood, storm and extreme temperature adaptability** since some of the strategies for those requirements might depend on energy systems. As interaction outcomes, no negative interaction was founded.

Effect on the achievement of the requirement listed (-3) negative great, (-1) negative little, (0) nothing, (1) little , (3) great.	Flood adaptability	Storms adaptability	Extreme temperatures adaptability	Energy crisis adaptability	Severe loading condition adaptability	I
Flood adaptability	3	3	0	0	0	6
Storms adaptability	3	3	1	0	0	7
Extreme temperatures adaptability	0	1	3	3	0	7
Energy crisis adaptability	3	3	3	3	0	12
Severe loading condition adaptability	0	0	0	0	3	3

Figure 40: Interaction matrix for Adaptability set of requirements

Summarising the adaptability requirements analysis, Figure 41 illustrates the final ranking resulted in the interactions for the Adaptability requirements. In line with the matrix, Energy crisis as a proportion of all requirements, shows a distinguish position.

Adaptability Requirements	I (ranked)	Cumulative I	Percentage (I*)	Cumulative percentage
Energy crisis adaptability	12	12	34	34
Storms adaptability	7	19	20	54
Extreme temperatures adaptability	7	26	20	74
Flood adaptability	6	32	17	91
Severe loading condition adaptability	3	35	9	100

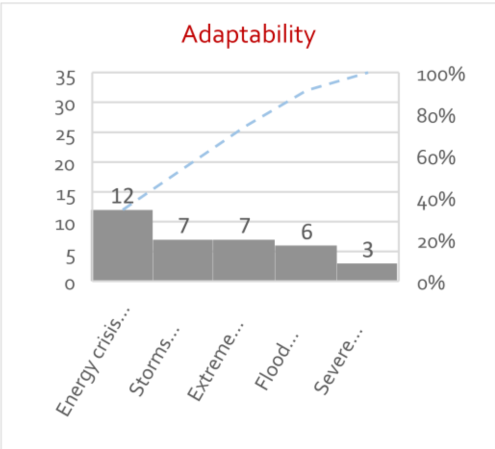

Figure 41: Table and Pareto Chart for Adaptability requirements

For the reconfigurability, the analysis for the requirements interaction directs towards a few positive interactions and again, no negatives relationships were identified. Here the requirement about the **independence of other building systems** will impact positively on **disassemblability**

of the connections since this predict that all the connections of the system should be easy to disassembly. Also, it can be helpful to achieve the **human-scale components**. Finally, the **disassemblability of the connections** might help to achieve a human-scale requirement. Figure 42 reveals the extent to which the requirements interact with each other.

Effect on the achievement of the requirement listed (-3) negative great, (-1) negative little, (0) nothing, (1) little, (3) great.	Provide adequate reconfiguration documentation	Robust components and connections	Disassemblability of the connections	Human-scale components	Components Modularity and Interchangeability	Independence of other building systems	–
Provide adequate reconfiguration documentation	3	0	0	0	0	0	3
Robust components and connections	0	3	1	0	0	1	5
Disassemblability of the connections	0	0	3	3	0	1	7
Human-scale components	0	0	0	3	0	0	3
Components Modularity and Interchangeability	1	0	1	0	3	0	5
Independence of other building systems	0	0	3	3	0	3	9

Figure 42: Interaction matrix for Reconfigurability set of requirements

Figure 43 illustrates the relations between the requirements interaction results and their respective normalised results.

Reconfigurability Requirements	I (ranked)	Cumulative I	Percentage (I*)	Cumulative percentage
Independence of other building systems	9	9	**28**	28
Disassemblability of the connections	7	16	**22**	50
Components Modularity and Interchangeability	5	21	**16**	66
Robust components and connections	5	26	**16**	81
Human-scale components	3	29	**9**	91
Provide adequate reconfiguration documentation	3	32	**9**	100

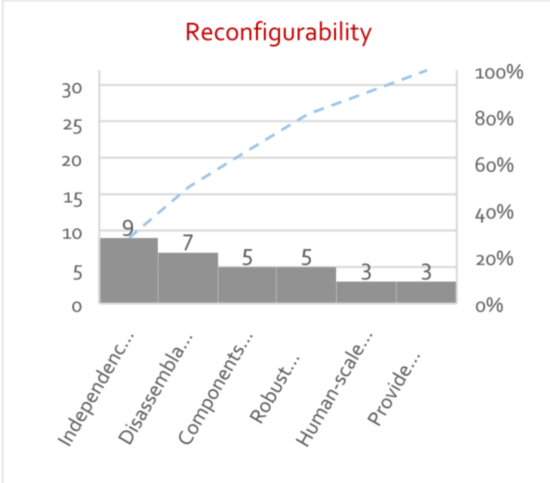

Figure 43: Table and Pareto Chart for Reconfigurability requirements

Regarding Learnability, several positive interrelations can be pointed. The **risks and environmental constraints mapping** are useful for all the remaining requirements. The **user's requirements information** is as well valuable asset to better achieve adequate **design information, risk and environmental constraints mapping and operation and maintenance information**. Since learnability aims to promote learning and enable the users to learn how to operate and maintain under EWEs those interrelations make sense. It is worth noting that this matrix presents more positive relations them the previous, and as all of the previous matrix no negative relations was plotted. Figure 44 present the matrix with the requirements interactions.

Effect on the achievement of the requirement listed (-3) negative great, (-1) negative little, (0) nothing, (1) little, (3) great.	User's requirements identification	Risks and environmental constraints mapping	Design information	Construction Information	Operation and Maintenance Information	I
User's requirements identification	3	3	3	1	3	13
Risks and environmental constraints mapping	3	3	3	3	3	15
Design information developing	0	0	3	3	3	9
Construction Information	0	0	0	3	3	6
Operation and Maintenance Information	3	3	0	0	3	9

Figure 44: Interaction matrix for Reconfigurability set of requirements

Finally, Figure 45 shows the summarised and ranked results of the matrix and their respective the Interactions level normalised for learnability requirements.

Learnability Requirements	I (ranked)	Cumulative I	Percentage (I_*)	Cumulative percentage
Risks and environmental constraints mapping	15	15	29	29
User's requirements Information	13	28	25	54
Design Information	9	37	17	71
Operation and Maintenance Information	9	46	17	88
Construction Information	6	52	12	100

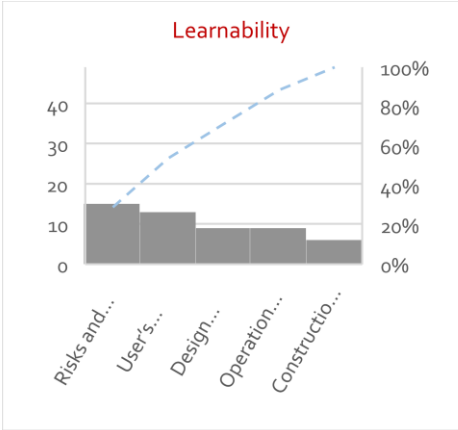

Figure 45: Table and Pareto Chart for Learnability requirements

6.2.3 Development of the ERB model formulation for resilience appraisal

The previous discussion illustrated the general construction of the ranking points for the opinion of the experts about the importance level of each requirement and the Interaction among them. In this section, the procedures to establish the ERB appraisal model is developed, through the expression for the Requirements importance level (R_{il}). The basic equation used to express the Requirement importance level would consist of a simple linear sum between the Experts Importance Level (E_{il*}) and the Interaction Importance Level (I_{il*}), both of them normalised as follows:

$$R_{il} = E_{Il*} + I_* \qquad (1)$$

A simplified notation is adopted where E_{il*} represents the normalised level of importance gained by the expert's evaluation and I_* represent the normalised points gained after the application of the interaction matrix. It is important to notice that both values were the percentage of the importance level that each requirement has in relation to the others in the same ability group. Because of the need to consider all the abilities with equally effects, as discussed in the previous item, the final sum of both the expert's opinions and the interaction matrix values were converted it to a ratio that represents a fraction of 100. Table 2 present the final Requirement importance level normalised.

Table 2: Final Requirement importance Level

ABILITIES	REQUIREMENTS	Eil*	Iil*	Ril	Ril*
SURVIVABILITY	Provide access to the parts of the building quickly and without barriers	29	29	58	29
	Provide an inspection plan system	33	23	56	28
	Provide the possibility of use of Social Technology	17	13	30	15
	Selection of durable components using precautionary principle	11	10	21	10
	Easily obtainable building materials	7	13	20	10
	Standardisation: minimise the use of different materials and elements	4	13	17	8
ADAPTABILITY	Energy crisis adaptability	20	34	54	27.0
	Storms adaptability	20	20	40	20.0
	Extreme temperatures adaptability	20	20	40	20.0
	Flood adaptability	20	17	37	18.5
	Severe loading condition adaptability	20	9	29	14.5
RECONFIGURABILITY	Components Modularity and Interchangeability	31	16	47	23.5
	Independence of other building systems	13	28	41	20.5
	Robust components and connections	21	16	37	18.5
	Human-scale components	14	22	36	18.0
	Disassemblability of the connections	12	9	21	10.5
	Provide adequate reconfiguration documentation	9	9	18	9.0
LEARNABILITY	User's requirements Information	23	25	48	24
	Risks and environmental constraints mapping	19	29	48	24
	Operation and Maintenance Information	29	17	46	23
	Design Information	13	17	30	15
	Construction Information	16	12	28	14

Finally, once the proposed model presents an appraisal rating scale system (1 to 5) that aim evaluate the BS of a social house or a housing development, each one of the requirements would be individually analysed and finally summed to achieve the Ability Final Score. Distribution weights to each requirement and their respective result of the appraisal rating scale might them be used to express the final score in each ERB ability. Hence, the Ability Final Score (AFS) might be expressed by:

$$AFS = \sum_{i=1}^{n}(s_i \times R_{il*I}) \qquad (2)$$

Where R_{il} are the weights expressing the underlying system of values that give more importance to some requirements over others (Table 2) and *s* is the relative score of the appraisal rating scale that various 1 to 5. It is linked to each requirement, as discussed and presented in the section 6.1 ERB Model – Guidelines. And *n* in the number of requirements of each ability.

With the Ability Final Score for each ability it is possible to express the results for the EBR appraisal model. The ERB abilities evaluation might be represented by a radar chart with the overall assessment scores. This representation will be presented in the next section where an application example takes place.

6.3 APPLICATION EXAMPLE

The utility of this model must be assessed according to its ability to accomplish its aims. The objective established for this model was to bring to real-life the evolutionary resilience framework concepts, to assess the resilience of buildings skin. Therefore, after its development, the model was validated through its application into one case scenario. It is important to highlight that the intention with this phase is to test and validate the model application and its use. The resilience of the case and how to be improved is not into the analysis. During the application revealed some limitations in the scale, and some adjustments were made. Therefore, in this phase, tests were performed to verify the suitability of the appraisal model as a tool for resilience evaluation of building skin in the housing sector.

The chosen case is housing modalities of the MCMV programme. The housing condominium is multi-housing development, with single-family and attached houses. The case is an example of a private development (market-oriented) to deliver houses to the MCMV Group 1.5. The MCMV programme and the housing condominium case is detailed in the next section.

6.3.1 MCMV Programme

The production in the Brazilian construction sector, mainly for social housing, had increased and pushed the sector to build more fast and cost-effective buildings. The scaling up of the housing supply last years was partially due to the MCMV governmental programme. With this programme, the country has made a provision of affordable housing at scale for the low and middle-income households. The programme divided the potential beneficiaries into four groups: group 1, comprising households with 2 minimum wage (up to BRL 1.800,00); group 1,5, households up to BRL 2.350,00, group 2 comprising households with income between BRL 2.351,00 and BRL 3.600,00, and group 3 including households with income between BRL 3.600,00 and BRL 6.500,00. The housing production can be market-oriented (undertaken by the private sector) or social-oriented, whereby social movements, community organisations and housing cooperatives take responsibility for housing production.

For the scope of the Group1 (the low-income households), it is also predicted social programmes to support beneficiaries in adapting to their new environment. Usually, they have to create new habits, since they are used to living in informal settlements, where there are no obligations and rules to live in condominiums and collective use. The social support programmes cover some important issues like basic guidance on building maintenance, environmental education, management of condominium; use and maintenance of common facilities; activities aiming at improving livelihoods and enhancing income opportunities, social integration among others. The market-oriented developments to other groups of income do not have this obligation.

In relation to building systems and construction characteristics, the MCMV programme encouraged the development of a series of innovative construction techniques mainly aiming speed up and costly construction. The quality of the housing, mainly the Group 1, considered as Social Interest Housing, received special attention regarding their performance. A series of orientation guides have been provided by the Ministry of Cities and some construction sector organisations, to establish the minimum requirements to meet the Performance Standard NBR 15.575 law.

The standard performance-based approach led to an innovative solution to deal with the constraints of the sector. Therefore, some new building technics began to be tested and implemented for the sector. Examples of those systems are the in-situ concrete construction, with steel shuttering used to cast the structural walls and slabs; the steel frame and wood frame houses. However, the more traditional bricks and concrete block masonry is a common practice. In the MCMV programme both the innovative BS systems and the traditional processes had a successful application, but remain issues related to them. Particularly, during EWE, when the BS is the element that separates and protect against the environmental threats.

The external wall of different types, windows and doors and the connections are included. Traditionally exterior walls can be classified into some different design types and materials employed. The most common social housing BS system includes the brickwork constructions as masonry bearing wall using ceramic bricks or blocks or concrete blocks, and more recently reinforced concrete walls.

6.3.2 Market-oriented case

The first case example was a market-oriented initiative, an example of a partnership between the federal government and private developers. It is an example of a housing project catering group

1.5. The land for the project is located in Porto Alegre, and it comprises 1175 houses. The condominium is composed of attached houses, where the dwellings share a common wall or walls with another unit. The individual units have 41 m², two bedrooms, integrated living and dining room with side kitchen and a small external laundry. The houses have private open spaces in front and the back of the house. In front of the house, a parking place is also available. The construction system used was bearing ceramic blocks masonry, and the front door is wood material. The windows of the bedrooms and living room are composed of single glazed aluminium frames with horizontal sliders and aluminium shutters. The kitchen opening is an aluminium frame with a horizontal slider door, and the bathroom window is the awning type. Ceramic roof tiles and timber frames compose the roof. Figure 46 presents a picture of the front house (a) and the internal layout (c).

Figure 46: Picture of the front house (a); the condominium (b) and internal layout (c)

This application phase was more analytical than quantitative. Documentation collection and interviews were carried out with architect responsible by the design project and additional information was collected with the construction site engineer. A visit to the condominium had been taken after the interviews for a better understanding of the houses. For this reason, all the process for the housing development had answers, and the model could be fully applied. Therefore, it is necessary to complete access to design, construction, delivery and post-occupancy information to fully address the model application. Although this could be an issue in practical terms, it is fundamental to accomplish the holistic view aiming in the Evolutionary resilience approach.

Each one of the requirements was analysed, and a score had been given following the developed the ERB appraisal model. Table 3 presents the requirement importance level (R_{il*}), the score (S) received to each one of the requirements and summarised the Ability Final Score (AFS), for Survivability.

Table 3: Survivability Final Scores

ABILITIES	REQUIREMENTS	R_{il*}	S	
SURVIVABILITY	Provide access to the parts of the building quickly and without barriers	29.0	2	58
	Provide an inspection plan system	28.0	2	56
	Provide the possibility of use of Social Technology	15.0	3	45
	Selection of durable components using the *precautionary principle*	10.0	2	20
	Easily obtainable building materials	10.0	5	50
	Standardisation: minimise the use of different materials and elements	8.0	2	16
		AFS		**245**

Regarding Survivability, the only requirement that was fully attended was the **easily obtainable building skin materials.** All the building materials are produced in 800 km radius. Additionally, the components and materials are commonly used by the general public and are sold widely in many**.**

The **possibility of use of Social Technologies** was presented on the roofing, windows and doors that allow self-maintenance. Besides masonry can be considered a non-engineered construction type, it is needed at least a semi-skilled worker for appropriate maintenance. Additionally, since the system is a bearing masonry, extra safety measures should be taken to perform any alteration. The constructors themselves also orient that any alteration on the system can be done. Therefore, it was not considered as all the BS allowing self-maintenance, technical assistance is fundamental for safety reasons. The requirement of s**tandardisation: minimise the use of different elements** has received score 3. It was accounted for less than 15 different elements' materials for the composition of the building skin, considering opaque elements, openings, and roofing.

The requirement of **providing access to the parts of the building quickly and without barriers** was attended condition to receive score 2. The BS is simple and easily accessed externally, and although there is a trapdoor planned to access the inferior part of the roofing, no point is previously designed to support a stair to access the superior part of the roofing, or even to any protective measure to avoid falls. The **selection of durable components using the precautionary principle** had received 2 points. Besides the system uses the precautionary principle (tested systems), for the coating type (plastering with a layer of acrylic paint) the first maintenance is envisaged to be at about five to ten years.

Regarding **provide an inspection plan system,** this requirement also scored 2 points. The users are orientated when they receive the house to make a visual inspection regularly and notify problems to the constructor, at least during the first five years that the house had been occupied. However, do not exist any agreement on regular inspection plan by the constructor. Also, there are not governmental (national or local) regulation or policies that are mandatory in this regard. Therefore, a full inspection plan is not a reality in this case scenario. Following, the adaptability appraisal is shown in Table 4, where are presented the requirement importance level (R_{il*}) and the score (S) received to each one of the requirements followed by the summarised Ability Final Score (AFS).

Table 4: Adaptability Final Scores

ABILITIES	REQUIREMENTS	R_{il*}	S	
ADAPTABILITY	Energy crisis adaptability	27.0	1	27
	Storms adaptability	20.0	3	60
	Extreme temperatures adaptability	20.0	2	40
	Flood adaptability	18.5	1	19
	Severe loading condition adaptability	14.5	1	15
		AFS		**160**

Since the houses analysed under this appraisal model have not solar water heating systems, or energy production alternative, the score for the requirement of **energy crisis adaptability** just met the minimum condition acceptable. The houses ensure natural lighting and ventilation conditions in all building rooms, accomplished by having opening systems on the BS.

The better score in this ability group was related to **storm adaptability** receiving 3 points. The housing BS, particularly the windows, are provided of external shutters. This windows device added to the characteristics of the opaque part and roofing system ensure the score of 2 points for **extreme temperatures adaptability**. The shutters are considered as an adequate strategy for adaptability of the internal thermal comfort, controlling the amount of sunlight and ventilation that enters the room.

The others requirements were evaluated receiving a score of 1, attending the minimum condition acceptable. For **severe loading condition adaptability,** it was considered that just the ability to support and adapt to small deformities was presented on the BS under appraisal since it is well known that masonry have a very low resistance when subjected to horizontal actions. For **flood adaptability**, any adaptable design strategy had been thought, however, a temporary flood protection system formed by flood barriers on the doors that are wholly installed by the users during flood event is a strategy that can be easily applied to this system.

Table 5 shows the Reconfigurability final scores for the case under appraisal. It is possible to visualise that one of the requirements do not accomplish even the minimum condition acceptable, receiving 0 as a score. The requirement **independence of other building systems,** is not minimum attended since the skin is projected as a monolithic load bearing walls and the hydraulic and electric systems are not independent and cannot be easily accessed.

Table 5: Reconfigurability Final Scores

ABILITIES	REQUIREMENTS	R_{il*}	S	
RECONFIGURABILITY	Components Modularity and Interchangeability	23.5	2	47
	Independence of other building systems	20.5	0	0
	Robust components and connections	18.5	2	37
	Human-scale components	18.0	4	72
	Disassemblability of the connections	10.5	4	42
	Provide adequate reconfiguration documentation	9.0	1	9
		AFS		**207**

However, surprisingly, in the other requirements of the Reconfigurability set, the housing case under appraisal had better results. Since the BS system is constructed using ceramic blocks, small openings and roofing tiles, all the building skin elements have **human-scale components** and are easily moved with no need of equipment. Additionally, the components weight is not too heavy for safely manual handle by at least two workers. Therefore, for the requirement **human-scale components**, the score was 4.

Also for the **disassemblability of the connections** the score was 4. Besides the masonry is not suitable for disassembly, the high score is due to the roofing and the openings whose fixation is given by screws and just be sealed with silicone sealant. The indicator for this requirement is the complexity of the equipment needed for disassembling the connections. In any case, the connections could be disassembled using the standard manual equipment.

Robust components and connections received score 2 since, just some elements (e.g. windows, roof tiles) of the building skin allows disassembly with the possibility of being re-used doing some repair. The masonry element, do not allow this type of procedure. Regarding **components modularity and interchangeability** the score received were 2. For the reason that some components have modular measures. In that case, the windows have modular measures and can be changed for others new but not among them, since they all have different measures.

Finally, about **providing adequate reconfiguration documentation requirements,** the score was a minimum adequate condition. Besides the constructor delivers a detailed design and construction documents, added to a user manual, no information is provided about how to disassemble or do repairs. Instead, the user manual advises against any system modification. The last set of requirements, regarding Learnability, is the requirements that received the lowest scores. Table 6 presents Ability Final Score (AFS).

Table 6: Learnability Final Scores

ABILITIES	REQUIREMENTS	R_{il*}	S	
LEARNABILITY	User's requirements Information	24.0	1	24
	Risks and environmental constraints mapping	24.0	1	24
	Operation and Maintenance Information	23.0	1	23
	Design Information	15.0	1	30
	Construction Information	14.0	0	0
		AFS		**101**

In discussion with the architect responsible by the project, the issue about the u**ser's requirement information** was raised. The user's needs are not properly analysed in order to truly understand what increase the value to users. The design was based on assumptions that the users do have some particular requirements. However, the main focus was on reduced cost. In this scenario, offer the opportunity of individual customisation is a burden. Therefore, the design was developed based on a standard user, and the score for this requirement was considered as 1.

Regarding **risks and environmental constraints mapping**, it was considered a previous mapping provided by the municipality about the flood quota in the region. The condominium was projected considering this quote and a detention basin was designed for retention of floodwaters from the Salso River. However, that was the only issue considered, any other susceptibility that could be created with the occupation, or any other problems was mapping. Thus, for this category, the score was also 1.

A building manual was provided to the users with easy and accessible information for management and use, also was available the summary of the building. Additionally, it is the procedure regarding the constructors to set a one-hour meeting to orient the clients. Even though information was provided about all the building system, key suppliers, and some about maintenance orientations, there is a lack in prescriptive information that enables sustainable use of the building. There is not information, about thermal comfort, energy performance or even risks prevention (except to fire). Thus, for **operation and maintenance information**, the score was 1.

The remaining part of the building manual presents the **design information** with the basic 2D drawings of architectural dimensions, standard hydraulic and electric systems. Since the structural system is load-bearing masonry, it was not available a specific drawing. However, the building manual explains the system and guide the user never to make any change in the building system. Since there is descriptive information about the systems, this requirement received a score of 2. By contrast, since the manual is standard, and the only information provided to the clients/users, the **construction information** requirement received a score of 0. Any revision was made on the building to provide even the as-built drawings.

As an outcome of the previous analysis, the final results for the ERB model can be expressed for the case under appraisal. Figure 47 presents the final result for the case analysed. The ERB abilities are represented by a radar chart with the overall appraisal results. This way to show the data was to consider useful to represent the model results. Each axis of the graph represents one of the abilities that was analysed. The scale on each axis represents the level of that ability. And the web of lines that links the axes shows haw the house BS system under appraisal rates on each ability.

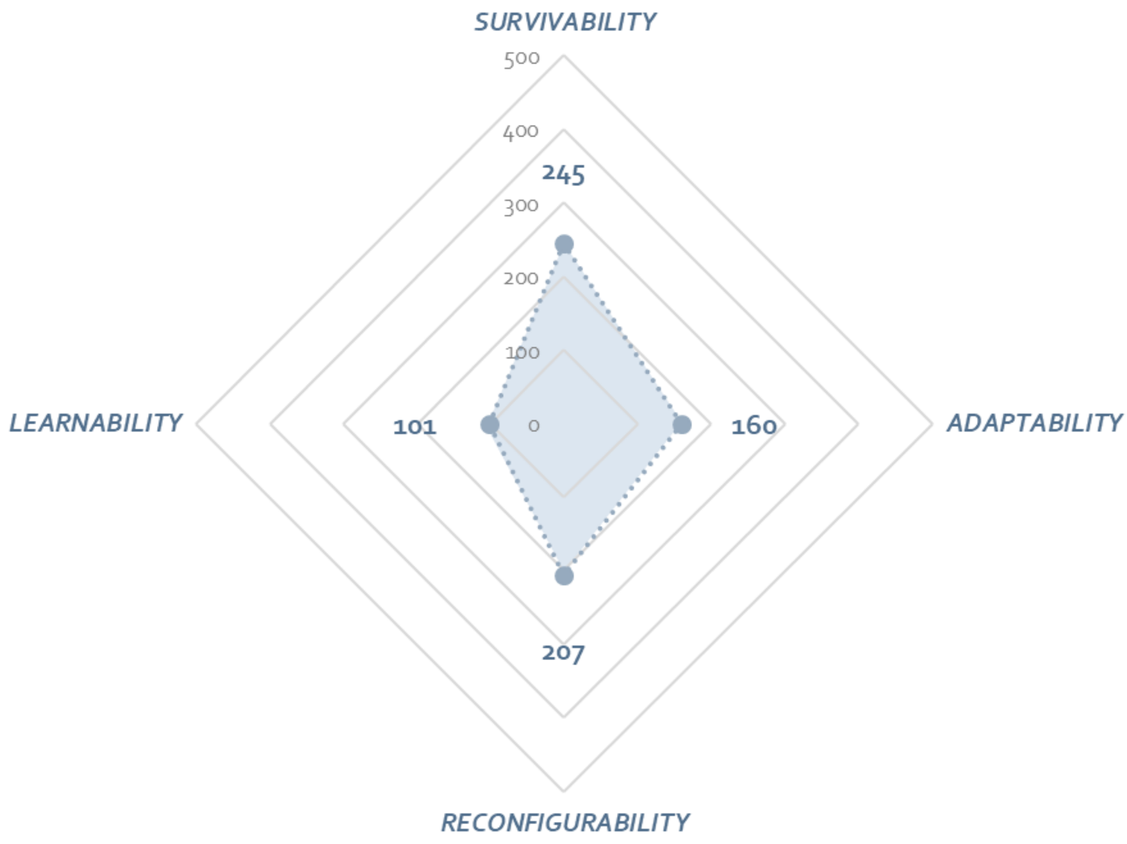

Figure 47: ERB model appraisal result

In the example, the “cave in” pattern represents where the case analysed is underperforming. It is clear that the Learnability is fallen behind and should consider serious improvements. Although the remain abilities also did not have high scores, being Survivability above the other results, being close to the half of the points it is can be achievable. These results were expected, and it is not surprising in any measure. The case study represents a significant amount regarding the constructive type (load bearing masonry) and also regarding the project development. This method received several criticists from both, academic and practitioners, as a system that not even perform well or cope with changes. The radar graph representation also could be used to compare alternatives housing development process under the ERB appraisal model.

7 DISCUSSION

This chapter connects the evidence from the empirical research in chapters 5 to 6, back to the theoretical framework on evolutionary resilience in chapter 3. It identifies different evolutionary mechanisms that can be observed throughout the stakeholder's assumptions. The chapter presents the three main contributions related to resilient buildings. The first section highlights the evolutionary resilience point of view adopted in this thesis to understand the issue. The second section, discuss the effort to bring to real life the resilience theoretical approaches. The third section conceptualizes the challenges arising from the building sector from the evolutionary resilience perspective. These theoretical considerations might be relevant for other contexts and contribute to the international discussions on the future of resilient buildings.

7.1 EVOLUTIONARY RESILIENT BUILDINGS: LESSONS

Extreme weather events management in building environment is facing some major challenges leading to increasing risks. Those events are often conceptualized as externals threats, or natural events, whose effects need to be minimized or, if possible, eliminated. However, the analysis of these issues indicates that the reality is far more complex. The increased urban development and human population and the effects of climate changes creates frequent scenarios with a great deal of uncertainty.

Considering this complex and unpredictable scenario, in recent decades, new approaches in facing the extreme weather events, not as natural events, rather as an interaction with the human, cities and different driving forces has brought new insights on risk management. For example, in dealing with flood risks, the policies have been changing from flood protection to resilience management, or from resisting the risks (robustness) to accepting and adapting to it (flexibility) (TEMPELS, 2017). The building projects, especially the dwellers, as an important part of the complex urban environment, should pursue these aims too.

In chapter 3, it was developed a theoretical framework for resilient buildings. The assumptions underlying this theoretical framework was based on the evolutionary resilience approach, where there is not an equilibrium state, and the system is in a continuum transformation. The outcomes from this evolutionary process were translated to the building system, and surrogates were developed in order to understand how a building could respond to these abilities. The effort was in understand how a building could be evolvable in an actual context, and also on how will be the challenge for the future.

It was no intention to prove any conclusive resilience strategies to buildings development, even it was not considered that a building could be fully resilient. Rather, the focus was in understanding how they can be safer, healthier and more sustainable through a flexible, transformative and evolvable approach. Therefore, the building should meet the evolutionary resilience principles to improve the building performance, which finally promote continuous innovation and generates value. At last, the generation of value contributes to the well-being of current and future society (BARRET, 2008).

In fact, it is not the aim of this framework to conceive buildings that last forever, conceived as immutable standards of performance. Rather conceive buildings that can be able to learn and be able to transform for all the future needs, being either social, cultural or environmental changes. This idea of not built just for the present needs is also expressed on John Ruskin famous book "The seven lamps of architecture":

> "Therefore, when we build, let us think that we build forever. Let it not be for present delight, nor for present use alone; let it be such work as our descendants will thank us for, and let us think, as we lay stone on stone, that a time is to come when those stones will be held sacred because our hands have touched them, and that men will say as they look upon the labour and wrought substance of them, "See! this our fathers did for us." (RUSKIN, 1892)

In the development of the evolutionary resilience theoretical framework for buildings, there were two main contributions related to the construction sector. These theoretical have to do with an understanding of the changing context of the building environment. This changing context is mainly related with extreme weather events, increased by the climate change, but also by a fast and growing population, advancing in technology facing demographic, economic, cultural and social change that frequently need transformability. The central idea is that the building change in the moment that is inhabited and should be able to be transformed during its entire lifespan.

The first contribution is the complex and fluid network approach to the interpretation of the building lifespan. This change of mind set allows to understand that the building should be able to transform and be transformed by the rest of the network. In a broad view, it means that the building could suffer changing in materials, performance, shape, position and also meaning. This point of view allows to see the building as a complex and dynamic system, and not in a linear behaviour (as presented in Figure 48) as the literature use to show (POSSAN; DEMOLINER, 2013), and also followed by the Performance Standard NBR 15.575 (ABNT, 2013).

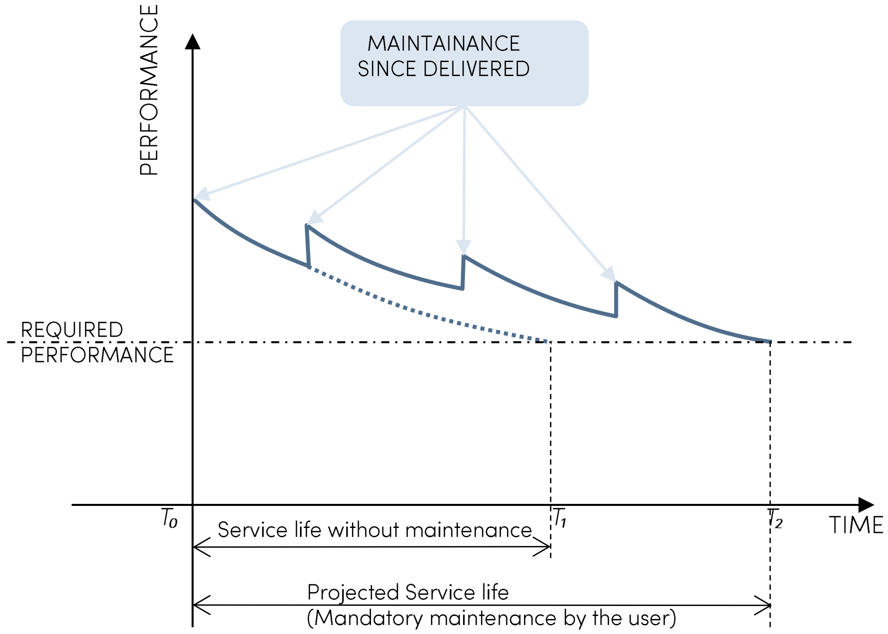

Figure 48: Performance achieved regarding maintenance (adapted from NBR 15.575 (ABNT, 2013))

The consideration of the complex nature of the building is in line with the recent theoretical developments on the urban scale. This idea is also grounded by Laboy and Fannon (2016), that affirms that the "*buildings exist in dynamic panarchic relationships among technology, human use, and the natural environment"*. Therefore, this work confronts the linear view of building life cycle, as shown in Figure 48. For this reason, the evolutionary resilience concept seemed the most appropriate to deal with this complexity and was selected to implement a resilience approach to the building once it brings the principle of complexity and non-linearity.

The second contribution is related to the particular evolutionary perspective applied to building systems. The question that was asked was to what extent a concept that originates from the natural sciences could be translated to the building environment context, and more specifically to the building itself, without denying the specificities, issues and constraints of this system. If the evolutionary resilience would literally translate, it runs the risk of losing its meaning. In order to achieve the evolutionary resilience framework for buildings, some surrogates' abilities and the relationships among those were proposed.

The survivability, adaptability, reconfigurability and learnability were built upon underpinnings of the Evolutionary resilience concept. Their main contribution was to adapt those constructs to the house-building sector, enabling them to be more readily used in defining evolutionary resilience building. Those abilities are grounded in the notion presented by Carpenter et al. (2001), Davoudi et al. (2013), and Folke (2006). Also, the work of Siddiqi and deWeck (2008) was a help to understand reconfigurable systems, besides to not deal with resilience concept. In light of those ideas, the framework was entailed in considering the development of the concept of the evolvable building.

The survivability is grounded on the notion of persistence, where besides rejecting the idea of the simple robustness some features should persist (DAVOUDI et al., 2013). The innovation brought by the building survivability is to propose that is achieved through the use of the precautionary principle for the selection of materials and systematic preventive inspection and maintenance. The adaptability reflects a fast adaptation for protection to an eminent EWE. Reconfigurability implies the reorientation towards a new and better building phase; the easy is the possibility to disassembly closes is to achieve this objective. Finally, learnability is perhaps the most important among the abilities and plays a central role in their achievement. Learnability implies a close interaction among the interplays of the building during all the building phase. The innovation is to understand that the building and the information produced about it should enable the user to learn how to use it (operation and maintenance).

It should be pointed out that, besides the definition of those surrogates were adopted to evolutionary resilience approach for buildings, the agenda of sustainability has being always kept in mind. It is believed that no innovation is welcome in the building sector if it is not sustainable. Therefore, both agendas resilience and sustainability should be adopted to propose new concepts on the building sector.

Finally, a further aspect of this framework that would be interesting in the future to explore is the co-evolution concept. It is closely connected to evolutionism, however here, the idea is that this evolutionism takes place in interaction with others system. Holling (1996) p. 31 conclude that, “both the biota and the physical environment interact such that not only does the environment shape the biota but the biota transforms the environment”. At this point, could be explored how the building and the users interact and ultimately how different type of buildings could affect the user’s behaviour and resilience.

7.2 THE ERB MODEL: TOWARDS A PRACTICAL APPROACH

In order, to bring the ERB framework to real life perspective, it had been made a series of semi-structured interviews with experts to collect possible requirements that could enhance the building Survivability, Adaptability, Reconfigurability and Learnability. During the interviews, it had been perceived that the significant and urgent need of resilience should be designed for social housing. As a result, the final ERB model for social housing building skin content was established after the identification of possible requirements through the continuing literature review, the semi-structured interviews analysis and the focus group discussion. All requirements and indicators were built during that analysis and relations were identified between them. Others were drawn after deep consideration of the real-life impacts and possible future possible outcomes and solutions.

The established methodology was directly related to the idea of considering the building as a complex system with multiple relations. Emphasising here the relationships between user and building, which necessarily implies that the building must have, besides use, maintenance, operation and conservation, but more than that, the building system must allow and engage the users in these activities. Additionally, the environment is involved in the process and, therefore, attributing the threats and constraints to building resilience. Consequently, all data collection of the established methodology investigates the environmental, social and technical issues regarding housing.

When speaking about Survivability, has to be considered the aforementioned relation between user and building. The main point was to provide dwellers empowerment to act doing the preventive maintenance or to have access and the knowledge to know when and who to call for technical assistance. Maintenance can be either preventive or corrective. Preventive maintenance is related to the routine activities and should be attached to a maintenance plan. The corrective maintenance happens when something needs to be fixed, caused by a specific event or natural ageing.

Those maintenance activities are essential to control the first stages of degradation and most essential to prevent failures of building elements (FLORES-COLEN; DE BRITO, 2010). These preventive actions also aim to maintain the designed performance of the building system under EWEs. During the service lives building deteriorate, and their obsolescence can be controlled if they are adequately maintained. Despite the range of studies already carried out about maintenance management to orientate Maintenance and Operation teams, in social housing context the users/dwellers play a crucial role. They will be responsible for taking care of maintenance, but after all, they will be affected by the maintenance strategies chosen on the design phase.

It is clear that there is an increase in the cost of maintenance attributed to faulty designs (AL-HAMMAD; ASSAF; AL-SHIHAH, 2009). This statement is also concluded on Gibson, (1979) book, where the most common faults which may be grouped as follows: failure to follow well-established design criteria; inexperience of the fundamental physical properties of materials; use of new materials or innovative forms of construction which have not been appropriately tested for use; misjudgement of climatic events and conditions under which the material has to perform; and poor communication between different members of the design and construction teams. The requirements in this investigation, corroborate to deal with those issues. Additionally, to those faults, this thesis introduces that the lack of communication and inability to deliver technical knowledge to the users is also a design fault.

Also, decision-making in building maintenance can consequently be considered as a process marked by uncertainty, and that demands regular data gathering and analysis. Therefore, an inspection plan should be in place. However, the inspection is assumed as an activity exclusively technical, in this investigation, the inspection plan aims to establish a better communication channel between users and technical team. Survivability highlight the need of the user presence. However, this should not just aim an effective way to deliver technical knowledge to users, rather has to be established a collaborative environment where the Social technologies can also be acknowledged and implemented.

UNESCO also recognises the possibility to use Social Technologies as an important issue, and in 2016 they published the Guide “Towards resilient non-engineered construction”. The guide mainly considers earthquakes damages and provides a perspective on safer non-engineered buildings as basic knowledge. Also, the guide recognises the cultural value of this type of construction and the need to find new channels to deliver technical knowledge to construct safer non-engineered houses.

Although the guide only mentions non-engineering houses, the same issue happens in governmental housing supply. The houses delivered by programs are modified, usually adding new spaces as soon as possible, as the examples mentioned on 6.3 section. Those modifications mean that the house does not meet the user's requirements but also generate other problems. Those additions usually are made with not appropriate technologies reducing the design building performance and potentially the building resilience. However, it is not being considered here that those modifications should be avoided, on the contrary, that should be encouraged and predicted.

In order to afford those layout modifications but also adjustments to increase performance under the EWEs the building system should be designed to allow Reconfigurability. It is understood that flexibility of design as user-requirement studies have a fundamental effect on maintainability on building lifespan, however, the resilience concept adopted in this work is focused on extreme weather events. The resilience for the social use could be the thematic for future studies. In this way, requirements for flexible layouts was not contemplated on this model.

The discussion about flexible layout is broadly accepted, however, in practical terms the discourse is not fully applied, as presented in section 6.3. Besides that, the ERB model aims more than layout increment; rather it aims reconfigurability of the BS system in order to increase performance over time and fundamentally provide a fastest and costless system recovery.

Reconfigurability is, however, a fundamental ability to increase flexibility, resilience and ultimately building service life. According to ISO 15686-1, service life is the period after construction in which the building and its elements match or exceed the minimum performance requirements. In this context, the EWES uncertainty is not taken into consideration. Reconfigurability on this work, suggest that the fastest and costless the system return to match or exceed the minimum performance requirements the closest is to achieve the physical resilience of the system.

Regarding Adaptability, the proposed scale was based on the idea that the building skin is the boundary between the inside and outside and have focused on providing shelter and protection keeping the inside insensitive from the outside (LOONEN et al., 2013). Adaptive building skin on the other hand are looking for an understanding of the exterior environment to increase and protect the interior. In the literature, adaptive building skin also have been called a climate adaptive building shell. The concept of adaptive building envelopes has a relationship with biomimicry, intelligent buildings, smart materials and nanotechnology (Modin, 2014).

> "A climate adaptive building shell (CABS) has the ability to repeatedly and reversibly change its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building

> performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort" (Loonen, 2010).

The ERB model assumes those ideas but increases the complexity of the environment addressing the EWEs uncertainties. The understanding of this complexity is important to deal with resilience in the context of uncertainties and unpredictability. Here the role of the user is decreasing while the BS has increasing his ability to change functions, and being more intelligent.

Besides the difficulties to assume those costly intelligent features for social housing, it is believed that intelligent features, robotics, autonomous features, the IoT (Internet of Things), and the application of these intelligent technologies to nano-materials, energy, buildings and other industries are rapidly changing the world we live. The future of society, economy and industry as well the way people live will be radically different from the present.

If the housing sector manages these transformative technological changes, it can create economic growth, and help the environmental ecosystem. If the sector cannot manage them properly, it could end up being slaves to technology. Proper housing technology management includes the management of not only the technical system, but also the economic, environmental, social, and regulatory aspects of technology.

Finally, the DNA of the building, the main capacity to learn and evolve is dependent on the capacity to produce, manage and transmit information. Learnability term is used in software testing, according to IEC 25010 (ISO, 2011) Systems and software engineering -- Systems and software Quality Requirements and Evaluation (SQuaRE) -- System and software quality models, Learnability means "degree to which a product or system enables the user to learn how to use it with effectiveness, efficiency in emergency situations". In this investigation, Learnability is related not just to the knowledge produced about the building but how this can be kept and transmitted to the users thought a plain language.

In the application investigation it was clear the importance of the relation among all the stakeholders. For this reason, the public sector should not just deliver a house; rather a life plan building should be provided. Two main issues arise from an evolutionary perspective in this scenario: the observed gap between the EWEs risk, users need information and the building sector, and the issue of shared responsibility, which arises from the interaction between in the public sector and society. The lack of a fruitful co-evolution in the social housing sector can be overcome by creating supporting building solution (Adaptability, Reconfigurability and

Survivability) on the one hand and to engage in processes all the stakeholders (learnability) on the other. The fundamental change in the Brazilian housing sector could be a more interrelated and less linear stakeholders' relation around the building. This means that the responsibilities should be constantly shared and not transferred among them. Figure 49 presents the innovative way that represents the stakeholder's relation in an evolutionary resilience perspective.

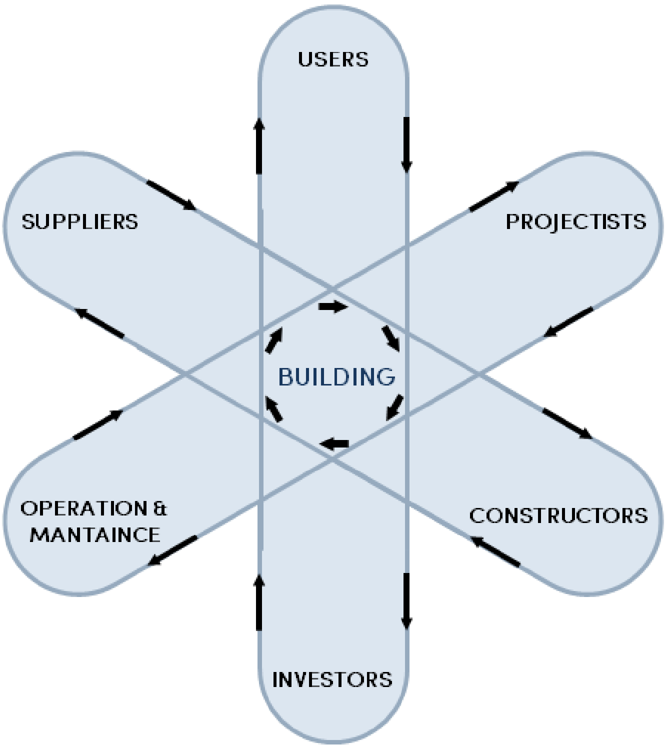

Figure 49: Innovative stakeholder's relation in housing sector

Finally, this model highlights one of the most important ERB framework contributions. This framework contrast with the conceptualisation of building resilience, presented in the literature (HOLLNAGEL, 2014; LABOY; FANNON, 2016), which are mostly related to building and environment relations only. Moreover, the literature on resilience discusses the complexity and uncertainty related to the systems, but the human factor, mainly the user's contributions, have not been addressed.

For these reasons, a model to assess building resilience was developed to present real-life surrogates, based on some important assumptions of resilient social-ecological systems from (DAVOUDI; BROOKS; MEHMOOD, 2013; GUNDERSON, 2009), who highlighted the transformability, being a "volatile and uncertain process" where the system shift to something new. The model tries to avoid a linear understanding of the building life cycle, acknowledging the fact of a building as a complex and fluid artefact having the human intention as an important act of transformation.

7.3 INTERACTIONS BETWEEN RISK AND RESILIENCE: BALANCING ROBUSTNESS AND FLEXIBILITY

The interaction of the shelter and the climate extremes is characterized by a balance between robustness and flexibility. The successful building will be the one that is flexible to adapt to changing circumstances. On the other hand, a shelter asks for sufficient robustness, as structures that are costly investments and must be safe for long periods of time. Following, these simultaneous and contrasting needs are discussed in relation to social housing context. It elaborates on the need for a new building design that balance these issues of robustness and Evolvability.

7.3.1 The required Flexibility

The intensity of EWEs is unpredictable in the long term, as the climate are variable. Moreover, the climate seems to be changing towards to increasing intensity and frequency of extreme weather, and those extremes reveal the vulnerability many human systems to this current variability (IPCC, 2014). The urban building stocks was not developed for dealing with those extremes and not even with the variability.

Although the focus of this researches is the uncertainties related to EWEs and how this should be considered on building expected performance, it is paramount to discuss a range of uncertainties around building development that requires more flexible approaches. For example, user's interventions, intentional or unintentional, induces alterations on the building projected/expected performance and lifespan. The lack of maintenance, bad renewals, the simple use and operation have impacts on the building system. Particularly the building skin, which is affected by the external impacts, need a constant inspection and maintenance, in order to renovate the finishes for esthetical and functional aims. The user's commitment in doing such maintenance is difficult to control, increasing the variability to define a specific lifespan.

In addition, social aspects of the building use are subject to long term change. Considerable change on family size and needs for more space, should be considered mainly for low income families. Those families cannot afford other places in the city and the building skin is usually a barrier for changes. Also, the social need for constantly changing new and upgraded technologies. There is constantly need for timely renovations on different system like electrical services (usually incrementally), HVAC, hydro sanitary, and improved closures. In the future, desires as smart homes feature, integrated solar energy, and information systems will be highlighted. As soon as the family could afford improvements, those are taking place, being the building system flexible or not for that. If not, those renovations could lead to a non-expected and probably a decrease in building performance.

Additionally, the multiple actors on the construction sector leads to relational uncertainty. This type of uncertainty emerges from the parallel and equivalent existence of multiple knowledge on housing development (TEMPELS, 2017). Different actors (architects, engineers, constructors, users…) understand the issues differently and hold different values and beliefs. Therefore, they may have different risk perception and judgment on potential interventions. As such, the results of the communication among the actors are considered uncertain, and lead also to performance uncertainty.

All these elements are associated with a range of complexities and leads to uncertainties to deal with the building design and mitigated through modelling and prescriptive standards, since they are inherently unpredictable. Therefore, building design can no longer be based just on prescriptive approaches, based on linear methods of risk assessment, implementing the optimal solution. The inherent uncertainty and social complexity of the social housing development requires more flexible and adaptable design leading to a social autonomy.

However, there are some clear issues and discomforts to more flexible approaches, such as the technical constrains of dealing with renovations made for non-skilled workers, and the social difficulties (issues of justice, legal certainty and liability). Nevertheless, there is the need of minimum security, habitability and sustainability that need technical and robust approaches mainly in structural improvements. However, in face of increasing climate extremes, the use of only traditional approaches have failed and the need for Evolvability for building is becoming an essential approach.

7.3.2 The need for robustness

Buildings are composed by a set of systems, (skin, utilities, structural, etc.). which one with a determined function and expected performance. The structural system must to be reliable and provide stability resisting forces against the the EWES. This reliability is achieved by usually be design for a minimum required level of building performance, based on a probability that the system will not fail under impacts. An important argument for traditional design is the resistance against all EWEs, preventing and avoiding any damage. The design strategy will count with robust structures, fail safe and solutions for minimizing water entry. They are considered with a preventive character and are based by stating return periods and building damage levels. Many countries use the return periods and damage associated as risk-informed criteria in order that engineers could design structures to meet the expected performance (MEACHAN, 2010). The traditional Standard NBR 6118 (ABNT, 2014), for instance, deals with the design of concrete structures and stablishes that the quality requirements of any reinforced concrete structure are the bearing capacity, the performance in keeping full service condition during all the service life, and durability that is considered the ability of the structure to withstand the environmental influences anticipated and defined jointly by the structural design author and the contractor at the beginning of the project design. Other traditional and important standard is the NBR 6123 (ABNT, 1990) that deals with the effect of wind load on buildings. This standard also leads to robust structures.

The Building Performance Standard NBR 15575 (2013) the current Brazilian house building control, contain a number of security, habitability and sustainability requirements. The requirements connected to security prioritize the resistance of the systems evaluated. The standard recognises that climates changes (among others) can affect the projected building life span. However, any requirements, criteria or recommendation are present to deal with those changings, and, to all the risks considered, is indicated resistance design strategies. Nevertheless, all the resistance design strategies, are desirable because they make the building robust and this is important for security and survivability. However, all buildings should provide at least EWEs resistance and allow resilience at any time as opportunities arises.

7.3.3 Balancing flexibility and robustness: an evolutionary perspective for evolvable buildings

So, there is a need for robust buildings in one hand and on the other hand there is also a need for Evolvability and flexibility to conduct to resilient buildings. Both approaches are legitimate and have advantages and disadvantages (Figure 50). Therefore, it is not a matter of choosing one above the other, rather, the question is how to accommodate both needs. A balance between flexibility and robustness need to be found in order to design buildings that are both safe and evolvable, fundamental to any resilient building. This section addresses this balance by discussing the evolutionary resilience approach and the interactions between those needs.

	Robust design	Flexible/Evolvable design
Perception of EWEs	EWEs are predictable, and is possible a establish a trend or a frequency	EWEs vary and are unpredictable
Perception of vulnerabilities	A quest for elimination of vulnerabilities and fail-safe alternatives	Failures will happen
Goal	Risk management orientated	Resilience management orientated
Means	Defending against the extreme events and reinforcing the structure and skin	Adaptation of vulnerable parts to minimise the consequences, while allowing some damages recovering by reconfiguration
Advantages	Constant conditions, Easier decision making for design and construction, Clear division of responsibilities among the stakeholders (architects, engineers, users, constructors...)	Cope with uncertainty and complexity scenarios associated to EWEs, Deal better with changing users' needs Promote dwellers autonomy
Disadvantages	Too inflexible to cope with uncertainties and changing scenarios Could be not cost effective for renovations and retrofits	Cooperation among the stakeholders Legal and technical issues Cultural constraints about new technologies

Figure 50: Characteristics of robustness and flexibility-based approaches to building design

Considering the relation among the users and the building during the longer stage of building life cycle, shed a light on this co-evolving relation. In one hand the building provides a safe shelter to the users that is responsible for this safe place. This means that there is a relation between the user's/dweller's knowledge and the building performance. When the focus is social housing programs or even non-engineering buildings, the users cannot afford to pay for qualitied technical support or skilled workers. The UNESCO report corroborates with the idea that a possible solution for this issue are to train the users to play this role (CHARLESON et al., 2016). To promote this approach, besides the basic technical knowledge, the risk perception and awareness should be provided through lectures, workshops or trainings. The Evolutionary resilience approach thus, provides seeing the building as something that will be transformed by users and by nature, being the user an important protagonist in this scenario.

Additionally, the technical knowledge should also be involved. Research and development must to be close in order to provide safer solutions to be used on site. One example, presented by the UNESCO report are the connections of the wooden-house construction in Japan. The connections used to be done on site for skilled carpenters. However, the lack of those professional added to a number of failure at connections started to be an issue. To cope with that, technologies of industrialized pre-cut timber and connections was being provided, no requiring high skilled workers for built. Nowadays is the most conventional technology used in houses.

The evolutionary resilience approach tries to add to the building the character of a fluid system and the evolvable character. The building does not just need to be designed to cope with performance expectation, rather should be thinking how this performance will be maintained through time (risk approach) additionally, how the performance will be maintained through changing conditions during the time (resilience approach).

Although this seems obvious, it is not a standard practice. The Brazilian housing sector, experimented great advances last years due to governmental program as “My house my life”. Together some new building system started have be on the spotlight of the construction sector, as the load bearing masonry and reinforced concrete walls. Although, those systems can be rationalized building system for low income housing, being fast and cost effective to construct, the resilience inefficiency during the use phase is outstanding. This inefficiency is related to the lack of flexibility for changes and maintenance.

The Performance Standard NBR 15.575 (2013) consider as a minimum lifespan for the envelope as 40 years and in other hand 20 years for hydro sanitary systems. The life expectancy of a building's parts is varied and if considering EWEs that can damage the weak parts or simple for updating news systems those differences could be even bigger. Considering system as those cited above, where the hydro sanitary, electric system and sometimes even the windows and doors are not independent, the chances for renovations are minimum. Additionally, the maintenance is also a very difficult activity, being possible to be considered not worthwhile. Such buildings are at risk of lose their performance and eventually be abandoned. Those systems consider just the robust approach, failing to accomplish any type of flexibility.

However, the tendency towards this approach is not a current practice worldwide. Recently, it was published the British standard BS 85.500 (BSI, 2015) – Flood resistant and resilient construction – guide to improving the flood performance of buildings. The aim of the mentioned standard is to give recommendation and guidance of how to improve the resistance and resilience of buildings by reducing the impacts of flooding. The innovative approach introduced these parallel strategies. The flood resistance aims to prevent the flood water entering the building and the resilience approach aims to reduce the consequences of flood water entering. It is accepted that just the resistance approach is not enough to deal with this event and with uncertainty approach, in some situations, it is more cost-effective to plan for water ingress.

The American Institute "National Institute of Building Science[1]" also bring out the aspect of resilience management to deal with natural and manmade hazardous events. Strategies for resilience can be developed for improving and maintaining the operational and physical performance of the building stock. They suggest as characteristics for resilience the 4 Rs: robustness, resourcefulness, rapid recovery and redundancy.

In a more up to date point of view, Laboy and Fannon, 2016 presents a theoretical overview of building resilience, which acknowledges the approach of the evolutionary resilience. They recognize that buildings exist in dynamic panarchic relationships and for that the social-ecological resilience models best engage with this context.

The need for building performance during the lifespan seems close to solution. The development of the operating system for buildings, information mainly about energy performance seems closer to the users, providing them with real-time access to energy consumption data. Together with BIM, the internet of things (IoT) can also be employed not just on the construction phase but on all the building lifespan. The building sector must be prepared for this massive shift that new technologies will bring, even if this seems far away, mainly when dealing with the social housing sector.

Additionally, the need for flexibility for the future will face challenges bigger than just evolvable building systems. The layouts through modular blocks could be a progressive pathway. Temporary high quality and performance modules could be created to accommodate temporary

[1] https://www.wbdg.org/resources/building-resiliency. Assessed on 09 August 2018

needs. Those plugs and play solutions should also be thinking on the level of the use of the land and properties rights.

In the city scale, Tempels (2017) discuss the dilemma of flexibility and robustness for the spatial planning point of view. The author concludes that there is a gap between the government and society where should be shared responsibilities. Additionally, it is necessary to create more flexible and adaptive condition planning in order to be able to deal with the uncertainties of the environment.

Coworking and coliving spaces seem to be the next disruptive innovation that may lead to flexibility. They are redefining spaces as services and is already affecting the way the architecture should deal with those spaces. The questions that remain is how this new approach of work and live will change the engineering and the way it is constructed.

Besides those initiatives, the question that remains is, could be the evolutionary resilience approach a disruptive innovation on the housing sector? The construction industry is one of the least efficient and innovative industries, and, besides this is a worldwide issue, Brazil seems to experiment process even more likely to craft industries. However, this inefficiency that is presented in several characteristics, like layout, flexibility, waste production, energy efficiency, etc. need to change not just to lead to a sustainable future, rather deal with the increased frequency of the EWEs.

8 CONCLUSIONS AND RECOMMENDATIONS

The problems related to the uncertainties in projecting climate-change impacts in housing developments and the need to provide safe, healthy, and sustainable dwellings, but also resilient, provides the background of this investigation. The research problem revealed a gap in the literature regarding the resilience term, often criticised for its conceptual vagueness and abstractness. The evolutionary approach was chosen as the theoretical background. The evolutionary resilience approach provides the basis for developing the requirements and the indicators to finally access the building skin resilience. Yet, there are two fundamental problems in the literature addressing such approach: the fragmented body of knowledge on the evolutionary approach in the built systems and the shortage of research to support devising of resilience strategies in real-world contexts.

Based on such research problems, four objectives were defined for this investigation (1) to propose a theoretical framework based on a comprehensive literature review to adapt the conceptual underpinnings of the evolutionary resilience approach in the house-building sector; (2) to propose the operationalisation of the evolutionary resilience framework through a set of core requirements for the building skin; (3) to devise a set of surrogates (indicators) to assess the requirements; and (4) to investigate the proposed model, exemplifying their use in a real case and demonstrating their viability and usefulness.

In the fields of both risk management and urban planning, the resilience concept is gaining attention. It is emerging quickly and has become widespread in cities policymaking, and several academic fields (industrial risk management, engineering, ecologic science, social aspects, for examples). Resilience is related to the way systems deal with adversity, changes and shocks. Through the literature review, it was detected different views about what is considered to be resilient. While some definitions interpret as the ability of a system to return to its original equilibrium state (engineering resilience), some recent approach incorporates elements as transformability and the capacity to learn (evolutionary resilience). In this last concept, there is not an equilibrium state.

The theoretical framework of this thesis assumes the evolutionary conceptualisation of resilience, where a system is resilient when it presents the learning capacity, besides, as suggested in the context of socio-ecological systems, the abilities of transformability, adaptability and persistence. It embraces the complex of socio-ecological systems, rejecting the existence of equilibria and stability, and is evidenced through evolutionary development absorbing shocks, minimising short-term damages besides speedy recovery; fundamentally dealing with a changing and uncertain context.

This theoretical position introduces the underpinnings for a comprehensive view of a housing building resilience framework. This perspective assumes that the EWEs can and will happen and requires abilities through a variety of simultaneous and complementary measures. The abilities of survivability, reconfigurability, adaptability and learnability summarise the main points of this measures. They introduce the ideas of building with maintainability, buildings that are more flexible and with adaptable and intelligent features, while closely link those abilities through meaningful information to all building sector stakeholders.

These abilities set out a perspective that could support the development of the practice-oriented requirements that will together finally assess the resilience of a system. The second objective, propose the operationalisation of ERB framework, and its development was narrowed for the building skin system. The aim here was to bring resilience to real-life. Based on the semi-structured interviews with the experts, this research explored each one the abilities searching for practical requirements. The semi-structured interviews were carried out considering three group of experts: technical, social and environmental viewpoints. Either one of the groups provided with important requirements. Although the focus was varied, those views are considered complementary on the aim of resilience. The results provided were richer and more holistic that if would consider just one group.

The set of surrogates (indicators and appraisal rating scale) to assess the requirements, plays a key role in the definition of which strategies can be used to achieve resilience. The indicators collected through the semi-structured interviews insights and the literature, provides a model to create resilient buildings. Also, provides a stronger performance-based approach using an appraisal rating scale for assessing the requirements, recognising the performing assets and fostering innovation. The ERB model helps to deliver and validate the resilience perspective for the housing building sector. The appraisal rating system reflects the performance achieved by a building, also enabling comparability between projects. Additionally, it helps decision makers to manage and mitigate extreme weather risks through demonstrating resilience during planning, design, construction and in-use phase.

The ERB model was verified in a focus group discussion with experts and practitioners. Participants gave their insights. Finally the fourth aim was to investigate the proposed model, exemplifying their use in a real case and demonstrating their viability and usefulness. The application showed that the holistic view is necessary for the ERB model implementation. Through the case study, it was observed that was needed to obtain information with different stakeholders (architect, site engineer and users). Which means that there is information loss through the process and poor communication among the stakeholders. Different stakeholders have different interests. However, information and communication is a real gap in the building sector nowadays, the model application shows that a better communication and information system sharing promotes effective long-term relationships, being fundamental to improve resilience.

This investigation advances both the theoretical and practical development of the resilience principle in building the housing sector. It adds the evolutionary perspective, which is then applied to new buildings development, bringing a more transformative and evolvable approach. On the other hand, it contributes to the discussion of the inclusion of the users with a fundamental role in this scenario. It does not assume the development and maintenance housing to be exclusive of technicians and as a governmental responsibility. However, any of the stakeholders is exempt from responsibilities. As such, it focuses on the interactions between formalised stakeholders (architects, engineers, investors, constructors, govern, and suppliers), and the informal actions of dwellers and other societal actors.

Recent advances on the Brazilian construction sector regarding to standards *(the Building Performance standards (ABNT NBR 15.575), the Renovation of buildings - management systems of building renovation standard (ABNT NBR 16280); the standard of maintenance of buildings (ABNT NBR 5674); and the standard, guidelines for the preparation of manuals for the use, operation and maintenance of buildings - Requirements for the development and presentation of contents (ABNT NBR 14037))* are part of a modernisation of the housing sector. Those standards identify construction stakeholders and assigning responsibilities, being the user an important actor, indicating great advances. However, it is still needed a better interaction and information sharing, besides users training, in order to improve building resilience.

The interactions between the different stakeholders are thus central to the housing sector, risk management and overall resilience approaches. Not only is important to consider the full network, but also their interactions. By that, the users start to play an important role, not just in dealing with the building maintenance but to manage their natural risks themselves. If users are expected to maintain their houses against risk, they should be better supported in doing so. Therefore, government, through regulations, providing technical assistance, the academia, and all the stakeholders should promote the empowerment of dwellers. Learnability is a fundamental concept here and indispensable for sharing responsibilities, as it can activate the users to perceive risks.

At the same time, the building system should allow the empowerment too. A novel paradigm that leads towards reconfigurability, to generate a new system should be pursued. The ability to adapt will require more dynamic systems. Technology plays a paramount role in shaping the horizon of the housing sector. New materials, new building systems, communications and digital assets will be part of disruptive innovations that will certainly, shape the future of the construction sector. The building should be prepared for that too.

Finally, strategies could be developed based in this model is fundamental to design and manage resilient buildings, but also the model could set the rules for the creation of innovative building systems. Additionally, the results of this work are useful starting points to discuss new building codes, regulations and standards or even a certification system for resilience improvement.

Considering as a result, for a building system, the resilience will depend on the network (building+users) learning capacity to survive, be able to adapt, be reconfigurable to, finally, be innovative. This premise is applied in this research only in the scale of an individual unit. However, it is not the idea to build islands of resilience. The individual scale should be the means to subsequently built cities more resilient in the face of climate change

Finally, a new kind of housing system should be pursuit: one that privileges the adaptable over the firm; the context based over the generic; the customised over the homogeneous; the evolvable over the rigid. The future is wide open.

8.1 SUGGESTIONS FOR FUTURE RESEARCH

The innovative character of exploratory researches means that the number of new questions raising, more than questions are answered. Many issues discussed will have to be examined in greater depth in further researches efforts. Some suggestions for future studies that could build into resilient buildings are presented as follow:

a) This investigation proposes a framework with a set of requirements that should be considered by the development of housing in devising resilience approach. Although an initial sequence for defining those requirements and indicators were proposed, future studies should implement the framework in different cases to refine such list, in order to produce an empirically grounded model.
b) Some key challenges can be addressed in the future, firstly, it will be necessary to determine the relative weight or importance of the four dimensions (abilities) in different risk scenarios. Secondly, it is required the understanding of how the strategies can be related and depend upon each other. On a third level, the relation between each one of the strategies with the required performance for any particular geographical area could to be addressed.
c) In order to embrace sustainability, studies should compare the evolutionary resilience framework proposed to an environmental assessment tool. Life-Cycle assessment can be used, in order to quantify environmental impacts that more resilient requirements could present.
d) Life-Cycle cost analysis could also be used to analyse the economic impacts of the design decisions of the proposed resilient buildings. Following the environmental, economic and resilient results should be integrated in an assessment model, in which those perspectives can be compared over the building lifespan.
e) Although the requirements and indicators proposed address the EWEs, others demands as the social needs, sustainability future demands, and construction sector requests of innovation should be considered in defining a resilience strategy. In order to answer the question resilient to what? Area-specific frameworks could be developed as subsequent research endeavours.
f) Another theme for future investigation is to further explore the relationship among resilient building and their users and the implications that one may have on the other, evaluating if a co-evolutionary process is possible.
g) Although the framework addresses the houses and the model explores requirements on the building skin, it is not assumed that the house should cope with all the risk alone. Extend the investigation over other scales, as the neighbourhood, cities, hydrographic basin, and even a national strategy of resilience should be an avenue for further researches.

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APPENDIX A – Semi-structured interview scripts

This section presents the scripts used to guide the semi-structured interviews divided on Technical, Social and Environmental groups

Roteiro da Entrevista Semiestruturada - Social

Objetivo Geral: Identificar indicadores para as características de resiliência definidos.		
Nome:		
Formação:		
Idade:		
Objetivos Específicos	Eixo Norteador Ad: Adaptabilidade Man: Manutenibilidade Tr: Transformabilidade HA: Habilidade de aprender	Perguntas
Conhecer a prática do profissional entrevistado	Questões pessoais	1. Como iniciou sua prática profissional?
		Quantos anos de experiência?
		Como é atualmente sua prática profissional?
Identificar possíveis abordagens sobre a temática de desempenho, risco e resiliência de edificações	Questões gerais	2. Considerando ameaças de eventos extremos naturais. Que tipos de riscos você acredita que deveria ser considerado no momento de lidar com uma população de uma determinada localidade?
	Questões gerais	3. Com relação às mudanças climáticas, você considera que seus impactos são fatores que podem afetar o uma comunidade urbana? De que forma?
	Questões gerais	4. De que maneiras essas comunidades poderiam estar preparadas para as mudanças climáticas ou eventos naturais extremos como exemplo tempestades, inundações? Ou eventos imprevisíveis?
	Questões gerais	5. O que você entende por resiliência?
	Questões gerais	6. O que você entende por comunidade resiliente?
	Questões gerais	7. Você poderia avaliar se uma residência poderia ter essas características?
	Questões gerais	8. Como os residentes de uma edificação poderiam ser resilientes a esses eventos naturais extremos?
Identificar estratégias de projeto e soluções construtivas que possam servir de indicadores para resiliência de edificações	Em um cenário de inundações, alagamentos ou vendavais e tempestades, as edificações, especialmente as residenciais são muitas vezes a primeira proteção das pessoas. Tendo esse cenário em mente	
	AD	9. Você acredita que as pessoas podem adaptar suas residências a determinados eventos naturais extremos?
	AD	10. Você poderia descrever situações, estratégias que a pessoas usaram para que essa adaptação pudesse acontecer? *
	AD	11. Você acredita que sistemas inteligentes, smart systems podem facilitar a geração de edificações mais adaptáveis?
	AD	12. Como esses sistemas inteligentes podem ser viáveis para aplicação nas edificações?
	Em um cenário de eventos naturais extremos, a facilidade e rapidez de recuperação dessas residências é um fator importante. Considerando isso:	
	MAN	13. Considerando nossa realidade nacional, você acredita que as famílias fazem a manutenção de suas residências considerando uma possibilidade de evento natural extremo?
	MAN	14. Você conseguiria pensar em estratégias ou situações em que essas manutenções pudessem ser facilitadas ou incentivadas?
	MAN	15. Essas estratégias e soluções poderiam favorecer também as atividades de recuperação após a edificação sofrer os impactos de eventos naturais extremos

	Considerando eventos imprevisíveis e a dificuldade de previsões confiáveis com relação a eventos naturais extremos.	
	TR	16. Considerando uma situação de evento natural extremo, na qual, por exemplo, partes ou a totalidade da fachada de uma residência foi danificada, que sistemas construtivos você considera melhor em critérios de custo e rapidez para reconstrução?
	TR	17. Você considera que sistemas desmontáveis e modulares podem facilitar a auto reconstrução e auto reforma? Além de facilitar a reconstrução?
	HA	18. Como você acredita que essas estratégias e as informações que sobre a residência poderiam ser transmitidas mais facilmente para os moradores? Que tipo de informações deveriam ser passadas?
Fechamento	GERAL	19. Que estratégias poderiam ser utilizadas para facilitar a reconstrução? O que poderia ser feito diferente na maneira como se constrói atualmente?
	GERAL	20. Que outro tópico ou assunto dentro deste tema não foi discutido nesta entrevista e você acredita ser importante abordar?

Roteiro da Entrevista Semiestruturada – Técnico (engenharia e arquitetura)

Objetivo Geral: Identificar indicadores para as características de resiliência definidos.		
Nome:		
Formação:		
Idade:		
Objetivos Específicos	Eixo Norteador Ad: Adaptabilidade Man: Manutenibilidade Tr: Transformabilidade HA: Habilidade de aprender	Perguntas
Conhecer a prática do profissional entrevistado	Questões pessoais	1. Como iniciou sua prática profissional em relação a edificações?
		Quantos anos de experiência?
		Como é atualmente sua prática profissional?
		2. Como você busca informações sobre atualização/inovações na construção?
Identificar possíveis abordagens sobre a temática de desempenho, risco e resiliência de edificações	Questões gerais	3. Que partes das edificações são mais vulneráveis em situação de eventos extremos:
	Questões gerais	4. Que tipos de riscos você acredita que deveria ser considerado no momento de projeto?
	Questões gerais	5. Com relação às mudanças climáticas, você considera que seus impactos são fatores que afetam o desempenho das edificações? De que forma?
	Questões gerais	6. De que maneira uma edificação poderia estar preparada para as mudanças climáticas ou eventos naturais extremos?
	Questões gerais	7. Com relação a riscos relacionados a eventos naturais extremos, você considera importante desenvolver estratégias de projeto ou estratégias de manutenção visando a proteção da edificação?
	Questões gerais	8. Como uma edificação pode estar preparada para eventos de alagamentos?
	Questões gerais	9. Como uma edificação pode estar preparada para eventos de tornados/ciclones?
	Questões gerais	10. O que você entende por resiliência?
	Questões gerais	11. O que você entende por edificação resiliente?
	Questões gerais	12. Que requisitos de desempenho (exemplificar) você considera no momento de projeto e ou inspeção de uma edificação/estrutura?
	Questões gerais	13. Como você classificaria esses requisitos que você citou por ordem de importância?
Identificar estratégias de projeto e soluções construtivas que possam servir de indicadores para resiliência de edificações	Em um cenário de inundações, alagamentos ou vendavais e tempestades, as edificações, especialmente as residenciais são muitas vezes a primeira proteção das pessoas. Para que as edificações possam enfrentar esses eventos sistemas que se adaptam rapidamente a essas condições têm sido desenvolvidos, visando proteção das aberturas. Para situações de temperaturas sistemas inteligentes que variam abertura e fechamento de janelas e brises já possuem mais aplicações reais. Tendo esse cenário em mente	
	AD	14. Você acredita que as edificações podem ser adaptáveis a determinados eventos naturais extremos?
	AD	15. Você poderia descrever situações, estratégias de projeto ou soluções construtivas em que essa adaptação pudesse acontecer? *
	AD	16. Você acredita que sistemas inteligentes, smart systems podem facilitar a geração de edificações adaptáveis?

	AD	17. Você acredita que esses sistemas inteligentes podem ser viáveis para aplicação nas edificações atuais? Estão tecnologicamente desenvolvidos e com tempo de maturidade suficiente para aplicação? Em quanto tempo poderiam vir a ser incorporados?
	Estratégias de projeto e escolha de materiais podem facilitar a realização de manutenções preventivas, corretivas ou ações de recuperação. Considerando isso:	
	MAN	18. Considerando uma situação de evento natural extremo, qual sua opinião a respeito da maneira que a edificação se comportaria considerando as ações/ boas práticas de manutenção realizadas hoje? Como poderia se avançar nesta questão
	MAN	19. Você conseguiria citar estratégias de projeto ou soluções construtivas que poderiam baixar o custo ou aumentando a rapidez das atividades de manutenção ou conservação, mantendo ou melhorando o desempenho inicial?
	MAN	20. Essas estratégias e soluções poderiam favorecer também as atividades de recuperação após a edificação sofrer os impactos de eventos naturais extremos
	Considerando as tendências de industrialização da construção e possíveis tecnologias de montagem e desmontagem de sistemas construtivos	
	TR	21. Considerando uma situação de evento natural extremo, na qual, por exemplo, partes ou a totalidade da fachada de uma edificação foi danificada, que sistemas construtivos você considera melhor em critérios de custo e rapidez para reconstrução? E com relação a serem menos ambientalmente impactantes?
	TR	22. Na mesma situação mencionada, você acredita que partes da edificação podem ser reutilizadas ou recicladas na reconstrução da própria edificação? Caso sim, que soluções construtivas poderiam facilitar a reutilização ou reciclagem?
	TR	23. Você considera que sistemas desmontáveis e modulares podem facilitar a auto reconstrução e auto reforma?
	TR	24. Você considera que sistemas desmontáveis e modulares podem ser mais rápidos e com menor custo em situações de recuperação e reconstrução?
	TR	25. Que características esses sistemas devem possuir para facilitar a montagem e desmontagem?
	HA	26. Como você acredita que essas estratégias e as informações que foram mencionadas podem ser gerenciadas durante o uso da edificação?
	HA	27. Você considera que o BIM pode ter um papel importante na manutenção e recuperação de uma edificação que precisa enfrentar os riscos relacionados e eventos naturais extremos? De que forma?
	HA	28. De que forma as ferramentas de gestão da informação da edificação pode auxiliar em um contexto de eventos naturais extremos? Que tipo de informações deveriam ser armazenadas e sistematizadas?
Fechamento	GERAL	29. Que estratégias poderiam ser utilizadas para facilitar a reconstrução? O que poderia ser feito diferente na maneira como se constrói atualmente?
	GERAL	30. Que outro tópico ou assunto dentro deste tema não foi discutido nesta entrevista e você acredita ser importante abordar?

Roteiro da Entrevista Semiestruturada - Ecologia

Objetivo Geral: Identificar indicadores para as características de resiliência definidos.		
Nome:		
Formação:		
Idade:		
Objetivos Específicos	Eixo Norteador Ad: Adaptabilidade Man: Manutenibilidade Tr: Transformabilidade HA: Habilidade de aprender	Perguntas
Conhecer a prática do profissional entrevistado	Questões pessoais	1. Como iniciou sua prática profissional?
		Quantos anos de experiência?
		Como é atualmente sua prática profissional?
Identificar possíveis abordagens sobre a temática de risco e resiliência	Questões gerais	2. Que tipos de riscos você acredita que podem ser previstos e mensurados a probabilidade?
	Questões gerais	3. Com relação às mudanças climáticas, como lidar com eventos imprevisíveis? De que forma?
	Questões gerais	4. De que maneiras um ambiente natural/edificação poderia estar preparado para as mudanças climáticas ou eventos naturais extremos como exemplo tempestades, inundações? Ou eventos imprevisíveis?
	Questões gerais	5. O que você entende por resiliência?
	Questões gerais	6. O que você entende por ambiente ou edificação resiliente?
	Questões gerais	7. Que estratégias um sistema sócio ecológico resiliente necessita?
Identificar estratégias do ambiente natural que possam servir de indicadores para resiliência de edificações	Em um cenário de inundações, alagamentos ou vendavais e tempestades, tanto o ambiente natural quando os construídos apresentam diversas vulnerabilidades. Para que as edificações possam enfrentar esses eventos, sistemas que se adaptam rapidamente a essas condições têm sido desenvolvidos, visando por exemplo, proteção das aberturas. Tendo esse cenário em mente	
	AD	8. Como o ambiente natural se adapta ao construído?
	AD	9. Como o ambiente construído deveria se adaptar ao natural?
	Em um cenário de eventos naturais extremos, a facilidade e rapidez de recuperação do ambiente construído é um fator importante. Estratégias de projeto e escolha de materiais podem facilitar a realização de manutenções preventivas, corretivas ou ações de recuperação. Considerando isso:	
	MAN	10. Qual seria a melhor forma de convivência entre o ambiente natural e o ambiente construído durante o ciclo de vida da edificação?
	Considerando eventos imprevisíveis e a dificuldade de previsões confiáveis com relação a eventos naturais extremos.	
	TR	11. Você já teve a experiência de ver um ambiente natural/edificação se recuperar depois de um grande desastre? Como ocorreu essa recuperação? Teve algum processo transformativo?
	HA	12. Que tipos e informações/essência um ambiente natural precisa preservar para se recuperar depois de um desastre??
Fechamento	GERAL	13. Que outro tópico ou assunto dentro deste tema não foi discutido nesta entrevista e você acredita ser importante abordar?

APPENDIX B – Requirements table presented at the focus group discussion

The table used during the Focus group is presented. It is important to highlight that this is no the final model. Changes were made based on the focus group discussion.

Estratégias de Resiliência	Requisitos para o envelope (sistema de vedação vertical externo e sistema de coberturas)	Indicadores (critérios de avaliação) 1	2	3	4	5
CAPACIDADE DE SOBREVIVÊNCIA **(SURVIVABILITY)** É a habilidade na qual pelo menos alguns elementos do sistema persistem frente aos estresses contínuos ou agudos. No presente modelo, essa habilidade é atingível através da presença de elementos robustos e manutenção preventiva sistemática facilitada. Estresses crônicos	**Origem e disponibilidade dos elementos (tecnologias à disposição)** Acredita-se que a menor distância associada a maior abundância e disponibilidade dos elementos constituintes envelope é fundamental para a rapidez e facilidade para a manutenção e eventual necessidade de substituição. Dessa forma, o projeto do sistema deve considerar o uso preferencialmente de materiais locais.	1: Elementos disponíveis apenas por importação;	2: Elemento produzido nacionalmente, porém escasso;	3: Elemento produzido nacionalmente e abundante;	4: Elementos produzidos em uma distância de até 800 km, porém escasso;	5: Elementos produzidos em uma distância de até 800 km e abundante.
	Otimização de elementos O projeto do sistema deve ser solucionado com um menor número de diferentes elementos para sua montagem. Um menor número de diferentes elementos gera menor quantidade de juntas além de facilitar a manutenção com elementos que não tenha exigências e características diferentes.	1: Acima de 20 elementos diferentes;	2: Até 20 elementos diferentes;	3: Até 10 elementos diferentes;	4: Até 5 elementos diferentes;	5: Até 4 elementos diferentes.
	Utilização de Tecnologia Social (TS) Devem ser previstos sistemas construtivos cuja manutenção possa ser mais facilmente realizada pelo usuário, com baixo custo e cuja técnica possa ser multiplicada entre os diferentes usuários.	1: Pelo menos aberturas passiveis de substituição por autoconstrução;	2: Pelo menos a cobertura passível de autoconstrução;	3: Pelo menos as aberturas e coberturas vertical passível de autoconstrução;	4: Pelo menos algum elemento da vedação, aberturas e cobertura passível de autoconstrução;	5: Todo envelope passível de autoconstrução.
	Plano para uso e manutenção Deve ser previsto um plano para gestão da informação da manutenção de modo que sejam favorecidas inspeções e efetivado um plano para manutenção. A inspeção é fundamental para a continuidade e duração do sistema, sem inspeção não existem informações durante a vida útil. Nesse caso, torna-se a estratégica para manter os dados da edificação e facilitar as operações de manutenção.	1: Não possui plano de manutenção;	2: Possui plano de manutenção, mas não é seguido;	3: Não existe plano de manutenção, mas ela é realizada esporadicamente;	4: Existe plano de manutenção ela é realizada, mas não existe inspeção periódica;	5: Existe plano de manutenção e inspeção e são realizadas conforme, e possuem acompanhamento técnico periódico e treinamento dos usuários.
	Elementos robustos e confiáveis Devem ser buscados elementos que apresentem menor probabilidade de falha e maior tolerância as mesmas. Para tanto, os elementos do sistema devem ser especificados para atender a durabilidade levando em conta os condicionantes locais e mesmo em estado esteticamente degradado devem manter a função.	1: Uso de elementos que atendam aos prazos de garantia definidos;	2: Uso de elementos que tenham vida útil comprovadamente estendidos;	3: Uso de elementos que tenham vida útil comprovadamente estendidos e que considerem condicionantes locais;	4: Uso de elementos que tenham vida útil comprovadamente estendidos e considerando condicionantes locais e eventos extremos;	5: Uso de elementos que tenham vida útil comprovadamente estendidos, considerem condicionantes locais e eventos extremos e que mantenham desempenho mesmo em estado degradado.
	Prover acessibilidade para inspeção e manutenção em todo sistema Para uma adequada manutenção todo o sistema deve favorecer condições de acesso para a inspeção e manutenção. Esse requisito pode ser atendido provendo maior número de possibilidades para acessibilidade aos componentes do sistema para manutenções preventivas. Ainda, de forma ideal, os próprios elementos não necessitariam de manutenção preventiva. Ex: vidros auto limpantes.	1: É possível acesso, mas nenhum foi planejado;	2: Existem acessos planejados, porém os suportes e equipamentos devem ser contratados externamente;	3: O sistema prevê condições de acesso ou suporte e fixação de andaimes e balancins;	4: É previsto fácil acesso a outras instalações, sem necessidades de equipamentos externos	5: É previsto fácil acesso a outras instalações, sem necessidades de equipamentos externos, além da utilização de alguns elementos que se auto mantém, exigindo nenhuma ou baixíssima manutenção preventiva.

Estratégias de Resiliência	Requisitos para o envelope (sistema de vedação vertical externo e sistema de coberturas)	Indicadores (critérios de avaliação) 1	2	3	4	5
ADAPTABILIDADE **(ADAPTABILITY)** É a habilidade de um sistema absorver e ser flexível aos distúrbios externos. Neste modelo essa habilidade é atingível através da existência de sistemas alternativos que permitam a escolha entre alternativas eficientemente. Indicando a agilidade com que o sistema pode se adaptar à nova necessidade, visando a adaptação em tempo real.	**Adaptação a inundações e alagamentos** Neste modelo a adaptação a inundações pelo sistema de envelope acontece de duas maneiras: evitando a entrada de água e mitigando seus efeitos minimizando danos e reduzindo e tempo para reocupação do imóvel.	1: Tecnologias de barreiras desmontáveis e temporárias no perímetro e nas aberturas gerenciáveis e instaladas pelo usuário;	2: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas, gerenciáveis e acionadas mecanicamente pelo usuário;	3: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas, acionadas pelo usuário, associado a um sistema com leitura de dados ambientais e alerta;	4: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas, acionadas de forma autônoma, associado a um sistema com leitura de dados ambientais e alerta;	5: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas, acionadas de forma autônoma, associado a um sistema com leitura de dados ambientais e alerta. Uso de materiais e componentes no sistema que permitam rápida secagem e/ou substituição.
	Adaptação a temperaturas extremas O sistema de envelope deve promover condições de abrigo e segurança e conforto térmico interno, quando submetidos a temperaturas extremas de frio ou calor, visando preferencialmente reduzir a necessidade de climatização artificial e gasto energético. Para tanto o sistema deve mais rapidamente se adaptar às variações de temperatura, podendo ser atingível por dispositivos que controlem ventilação e raios solares.	1: Sistema de dispositivos de ventilação gerenciáveis pelo humano (ex. janelas que possam abrir e fechar);	2: Sistema de dispositivos gerenciáveis de ventilação e controle de raios solares pelo humano (ex. janelas que possam abrir e fechar e persianas com possibilidade de barrar raios solares);	3: Sistema de dispositivos gerenciáveis de ventilação e controle de raios solares pelo humano associado a sistema com leitura de dados ambientais para monitoramento e alerta;	4: Sistema com leitura de dados ambientais e automação programável de alguns dispositivos de ventilação e controle solar;	5: Sistema com capacidade de monitoramento, armazenamento e aprendizagem de parâmetros chaves internos e externos e adaptação e acionamento de dispositivos em tempo real, através de estratégias Machine to Machine (M2M).
	Adaptação a condições de ventos extremos Este requisito visa uma maior facilidade e rapidez para adaptação a ventos extremos. Para ventos de menores velocidades sistemas de barreiras para as aberturas apresentam-se como solução de adaptação rápida. Para eventos destrutivos materiais e componentes que permitam mais rápida substituição devem ser utilizados sempre associados a sistemas de segurança e alerta para garantir a segurança dos usuários.	1: Tecnologias de barreiras desmontáveis e temporárias nas aberturas gerenciáveis e instaladas pelo usuário;	2: Tecnologias de barreiras pré-instaladas e temporárias nas aberturas gerenciáveis e acionadas mecanicamente pelo usuário;	3: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas acionadas pelo usuário, associado a um sistema com leitura de dados ambientais e alerta;	4: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas acionadas de forma autônoma, associado a um sistema com leitura de dados ambientais e alerta;	5: Tecnologias de barreiras pré-instaladas e temporárias no perímetro e nas aberturas acionadas de forma autônoma, associado a um sistema com leitura de dados ambientais e alerta. Associado à utilização de componentes que permitam rápida substituição. Recomenda-se uso de refúgios.
	Adaptação a crises energéticas O sistema de envelope deve auxiliar a adaptação da edificação a possíveis crises e faltas de energia, geradas por eventos naturais extremos ou outra natureza. Esse requisito visa proporcionar condições de iluminação e ventilação naturais adequadas pelo maior período do dia possível, bem como a possibilidade de associação de geração de energia, visando uma maior adaptabilidade a variações de disponibilidade energética.	1: Prevê condições para climatização e iluminação natural em todos os ambientes;	2: Prevê condições para climatização e iluminação natural em todos os ambientes, associados com sistemas que controlam intensidade e necessidade de iluminação artificial, visando uma melhor gestão do consumo energético;	3: Prevê condições para climatização e iluminação natural controláveis em todos os ambientes, associados com sistemas que controlam intensidade de iluminação e climatização artificial, visando uma melhor gestão do consumo energético;	4: Prevê condições para climatização e iluminação natural controláveis em todos os ambientes, associados com sistemas que controlam intensidade de iluminação e climatização artificial. Adicionalmente, a produção de energia (solar ou eólica) suficiente para emergências temporárias;	5: Prevê condições para climatização e iluminação natural controláveis em todos os ambientes, associados com sistemas que controlam intensidade de iluminação e climatização artificial. Adicionalmente, produção de energia (solar ou eólica) suficiente para auto suficiência.
	Adaptação a condições severas de cargas Para condições severas de cargas (fogo, explosões, terremotos, deslizamentos e enxurradas) e a para movimentações gerados por estresses contínuos (movimentações térmicas, higroscópicas e da própria acomodação da estrutura) os sistemas de envelopes devem apresentar: 1) Capacidade de suportar e adaptar a pequenas deformações, 2) Capacidade de adaptação para cargas horizontais, 3) Projetadas para a capacidade de "tombar" em pé.	1: Ter pelo menos uma das características apresentadas;	2: Tenho duas das 3 características apresentadas;	3: Tenho todas as 3 características apresentadas;	4: Tenho todas as 3 características e programa constante de inspeção e monitoramento;	5: Tenho as três características e sistemas ativos de compensação, monitoramento de parâmetros chaves através de sistemas cognitivos e comunicáveis como Internet of Things (IoT) para alerta e evacuação.

Estratégias de Resiliência	Requisitos para o envelope (sistema de vedação vertical externo e sistema de coberturas)	Indicadores (critérios de avaliação)				
		1	2	3	4	5
RECONFIGURAÇÃO (RECONFIGURABILITY) **É a habilidade de facilidade de transformação do sistema. Para este modelo o sistema de envelope deve possuir maior facilidade de adicionar, substituir ou remover componentes do sistema, ainda pela possibilidade de expansão ou redução vertical e/ou horizontal.** **Estresses agudos**	**Guia para reconfiguração** Gerar e armazenar todas as informações do método para desmontagem, com a possiblidade de rastrear elementos e informações a respeito dos mesmos.	1: Projeto detalhado;	2: Passo a passo ilustrado da montagem com os encaixes e conexões;	3: Manual completo com instrumental e procedimentos para desmontagem (passo a passo), com todos os elementos etiquetados;	4: Manual completo com instrumental e procedimentos para desmontagem (passo a passo), com todos os elementos etiquetados permanentemente com informações sobre, manutenções, trocas e substituições;	5: Manual completo com instrumental e procedimentos para desmontagem (passo a passo), com todos os elementos etiquetados permanentemente com informações sobre manutenção e troca dos elementos possíveis de serem enviadas por sensores e via Internet.
	Elementos e conexões robustos e confiáveis Os elementos do sistema devem ser projetados com o uso de materiais que permitam maior número de remontagens. Assim, estes devem ser robustos e com uso de materiais que não se deteriorem em montagens e desmontagens.	1: Possibilita desmontagem, porém sem possibilidade de uso posterior;	2: Possibilita a desmontagem com possibilidade de reuso de alguns elementos;	3: Possibilita pelo menos uma desmontagem e remontagem;	4: Possibilita múltiplas desmontagens e remontagens com necessidade de pequenos reparos;	5: Possibilita múltiplas desmontagens e remontagens sem danos.
	Facilidade para desacoplamento Utilizar conexões de fácil desacoplamento sem causar danos aos elementos. A maior facilidade de desmontar os elementos do sistema sem danos, engloba também, a facilidade e acessar e identificar o local das conexões.	1: Fixações químicas passíveis de desmontagem;	2: Fixações químicas passíveis de desmontagem sem danos, com fácil identificação das conexões;	3: Fixações por pregos, com fácil identificação das conexões;	4: Fixações por parafusos com fácil identificação, com menor diversidade de tipo e utilização de ferramenta de uso comum para todos;	5: Todas conexões por encaixe e em menor número possível e com fácil identificação.
	Componentes em escala ergonômica Usar componentes e elementos em escala humana com fácil desacoplamento por equipamentos de uso comum. Esses princípios irão diminuir a intensidade de trabalho facilitando renovações e desmontagens.	1: Mais de um elemento não possui escala ergonômica e não é possível de desmontagem apenas com uso de força humana, sem comprometer sua sáude e segurança;	2: Apenas um elemento do envelope não é desmontável com utilização apenas de força humana, sem comprometer sua saúde e segurança;	3: Todos os elementos possuem peso que não compromete a saúde e segurança, porém há a necessidade de equipamentos especiais para desmontagem de alguns elementos;	4: Todos os elementos podem ser desmontados utilizando força humana e possuem peso que não compromete a saúde e segurança, necessita de maquinário de pequeno porte;	5: Todos os elementos possuem peso que não compromete a saúde e segurança do trabalhador e são facilmente desacopláveis com uso ferramentas simples e força humana.
	Modularidade Os elementos devem ter dimensões adequadas para a possibilidade de trocas e substituições conforme demanda acoplando e desacoplando as partes interessadas, possibilitando também a flexibilidade de uso e relocação entre componentes e elementos.	1: Utilização de apenas parte dos elementos com medidas modulares;	2: Utilização de todos elementos com medidas modulares;	3: Utilização apenas de elementos com medidas modulares e normatizadas;	4: Coordenação modular de todos elementos com possibilidade de substituição, porém, sem possibilitar a troca de posição entre eles;	5: Coordenação modular de todos elementos com possibilidade de troca de posição entre os mesmos.
	Estrutura robusta e independente Projetar o sistema estrutural de modo separado do sistema de envelope. Separar a estrutura do envelope de fechamento irá permitir um aumento da flexibilidade para separação dos elementos não estruturais. Uma estrutura mais robusta irá permitir a escalabilidade.	1: O envelope é o sistema estrutural e projetado para ampliação vertical de pelo menos um pavimento;	2: O envelope está integrado ou fisicamente aderido e não pode ser trocado. O sistema estrutural é projetado para ampliação vertical de pelo menos um pavimento;	3: Estrutura integrada no envelope, fácil de manter e com baixo custo. O sistema estrutural é projetado para ampliação vertical de pelo menos um pavimento;	4: Poderia substituir elementos do envelope sem afetar a estrutura. O sistema estrutural é projetado para ampliação vertical de pelo menos um pavimento;	5: Poderia perder o envelope sem afetar a estrutura. O sistema estrutural é projetado para ampliação vertical de pelo menos um pavimento.

Estratégias de Resiliência	Requisitos para o envelope (sistema de vedação vertical externo e sistema de coberturas)	Indicadores (critérios de avaliação) 1	2	3	4	5
GESTÃO DA INFORMAÇÃO **(INFORMATION MANAGEMENT)** É a habilidade que promove o aprendizado. É atingível através de coleta, armazenamento e gestão da informação, além de eficiente comunicação entre todos os intervenientes.	**Requisito dos usuários** As necessidades e requisitos dos usuários devem ser fontes de informações para o desenvolvimento do projeto e recomenda-se que estas sejam atualizadas durante a vida útil. Essas informações são importantes para orientar e delimitar as estratégias utilizadas para manutenção, adaptação e transformação.	1: Desenvolver briefing considerando necessidades de usuários padrão;	2: Desenvolver briefing considerando e consultando as necessidades e conhecimentos dos usuários reais;	3: Desenvolver briefing considerando e consultando as necessidades e conhecimentos dos usuários reais além de necessidades futuras;	4: Desenvolver briefing considerando e consultando as necessidades e conhecimentos dos usuários reais além de necessidades futuras, e realização de pelo menos uma Avaliação Pós Ocupação;	5: Desenvolver briefing considerando e consultando as necessidades e conhecimentos dos usuários reais além de necessidades futuras, e realização Avaliação Pós Ocupação e inspeções técnicas anualmente.
	Mapeamento de riscos e condicionantes ambientais As informações relativas ao entorno, somado aos possíveis riscos associados devem ser mapeados. A vulnerabilidade do sistema também pode ser monitorada durante eventos extremos através de sensores e trasmitidos através de conceitos como a Internet das Coisas, monitorando parâmetros ambientais chaves que indicam falhas eminentes e possam gerar alertas aos usuários.	1: Mapeamento das vulnerabilidades e ameaças do local;	2: Mapeamento de riscos do local;	3: Mapeamento de riscos considerando previsões futuras de riscos	4: Mapeamento de riscos indicando possíveis necessidades futuras de reconfiguração;	5: Mapeamento constante durante o ciclo de vida da edificação através de monitoramento automatizado de riscos prevendo e gerando alertas para sinais de falhas eminentes.
	Informações de projeto Gerar maior qualidade e acessibilidade de informações sobre os sistemas, componentes e materiais utilizados no envelope. Todas as decisões de projeto, os cálculos e os resultados de simulações devem ser gerados e armazenados de modo que possam ser compatibilizados e acessados durante toda a vida útil da edificação.	1: Projetos arquitetônico, estrutural e instalações em 2D;	2: Projetos arquitetônico, estrutural e instalações em 2D somado a projetos executivos detalhados e memoriais descritivos;	3: Projetos arquitetônico, estrutural e instalações 2D, compatibilizados e projetos executivos detalhados e memoriais descritivos;	4: Utilização de 3D BIM para geração das características geométricas e físicas da edificação e seus componentes e toda documentação;	5: Utilização de 3D BIM para geração das características geométricas e físicas da edificação e seus componentes e toda documentação, além da geração de de ambientes virtuais e simulações de uso.
	Informações de construção As informações geradas durante a obra devem ser armazenadas e utilizadas para consulta durante toda a vida útil da edificação. Qualquer alteração de especificação de projeto que se fizer necessária deve ser documentada também como forma de lições aprendidas.	1: Projeto arquitetônico ou/e as -built;	2: Projeto arquitetônico ou/e as -built, informações organizadas a respeito dos orçamentos e fornecedores;	3: Projetos executivos ou/e as -built, informações organizadas a respeito dos orçamentos e fornecedores e cronograma da obra;	4: Organização de toda a informação da construção no conceito BIM (4D BIM (tempo de construção e cronograma) + 5D BIM (custos);	5: Organização de toda a informação da construção no conceito BIM (4D BIM (tempo de construção e cronograma) + 5D BIM (custos) além armazenamento e organização de arquivo com lições aprendidas.
	Informações durante a fase de uso Informações para a fase de uso e operação devem ser geradas e armazenados antes da construção e durante a fase de uso indicando e orientando os processos de manutenção, recuperação e possível transformação dos sistemas.	1: Manual do usuário;	2: Manual do usuário e orientações detalhadas de manutenção;	3: Manual do usuário e plano de manutenção e inspeção detalhados;	4: Organização das informações de projetos, manual do usuário e planos de inspeção e manutenção em plataforma 6D BIM (gestão do ciclo de vida);	5: Organização das informações de projetos, manual do usuário e planos de inspeção e manutenção em plataforma 6D BIM (gestão do ciclo de vida), além de arquivo organizado com lições aprendidas para ser abastecido durante a vida útil da edificação.

APPENDIX C – Final requirements table for ERB model

The next tables present the Final list of requirements, indicators and the appraisal rating scale to each one of the ERB abilities.

SURVIVABILITY

REQUIREMENTS	INDICATORS	
Easily obtainable building materials	**Distance and availability of components and materials**	
	1	The system has some components or materials produced in abundance but the purchased can happen only on importation;
	2	The system has some components or materials produced nationally but far from 800 Km and scarce with few suppliers;
	3	The system has some components or materials produced nationally far from 800 km in large quantities and amount of suppliers;
	4	All the components and materials are produced in an 800 km radius, but scarce with few suppliers;
	5	All the components and materials are produced in an 800 km radius in large quantities and amount of suppliers;
Standardisation: minimise the use of different elements' material	**Number of different elements' material**	
	1	More than 20 different elements' material;
	2	Up to 20 different elements' material;
	3	Up to 15 different elements' material;
	4	Up to 10 different elements' material;
	5	Up to 5 different elements' material.
Provide the possibility of use of Social Technology	**Number of replicable self-building elements**	
	1	Presence of replaceable roofing through self-maintenance;
	2	Presence of windows and doors that allow self-maintenance
	3	Presence of roofing, windows and doors that allow self-maintenance;
	4	Presence of roofing, windows and doors and any part of the vertical opaque elements, that allow self-maintenance;
	5	The entire building skin allows self-maintenance
Provide an inspection plan system	**Level of inspection and frequency**	
	1	Basic routine inspection undertaken by the orientated user;
	2	Basic routine inspection undertaken by the orientated user with systematic feedback to a suitable qualified professional;
	3	Basic routine inspection undertaken by the orientated user with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by a professional building inspector;
	4	Basic routine inspection undertaken by the orientated user with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by a professional building inspector at times specified in the maintenance manual;
	5	Training of its users to do a routine inspection with systematic feedback to a suitable qualified professional and general visual inspection of main elements made by an professional building inspector at times specified in the maintenance manual, plus full inspection of the building skin not exceeding a five year period.
Provide access to the parts of the building quickly and without barriers	**Accessibility**	
	1	Some entry points are viable to some system's parts, besides not planned and not to all system;
	2	Planned access points are present providing access conditions after disassembling some entities; but there are not panned access point to all system;
	3	Planned access points are present providing access conditions and easy access provision for regular cleaning of components;
	4	Direct access to all system and his components after disassembling one or more entities and easy access provision for regular cleaning of components;
	5	Direct access to all system and his components, easy access provision for regular cleaning of components and easy access to other critical (hydraulic, electric, etc.) systems’ parts.
Selection of durable components using precautionary principle	**Durability of the components' material**	
	1	Components where maintenance is acceptable at short intervals, typically two to five years, for either protective or decorative purposes;
	2	Components where the first maintenance is envisaged to be at about five to ten years;
	3	Components where the first maintenance is envisaged to be at about ten to twenty years;
	4	Components that will not be maintained during the design life of the building;
	5	Components that will not be maintained during the design life of the building considering local variables and the risks and uncertainties of EWEs, preserving minimal performance when damaged.

ADAPTABILITY

REQUIREMENTS	INDICATORS	
Flood adaptability	**Level of agility to handle flooding protections.**	
	1	Temporary flood protection system formed by flood barriers on the doors that are wholly installed by the users during flood event (e.g. Sandbags);
	2	Temporary technology of removable and demountable flood barriers positioned on the doors that are supplied with pre-anchors for the barriers, installed by the user;
	3	Pre-installed barriers positioned around the envelope, activated manually (e.g. flip-up barriers);
	4	Pré-installed barriers positioned around the envelope activated by a push button or automatically triggered by sensors (e.g. flip-up barriers or drop-down);
	5	Self-closing technology of pre-installed flood barriers positioned around the building skin, automatically raise the barrier, coupled with an environmental data gathering and warning system;
Storms adaptability	**Level of windows protection system autonomy**	
	1	Technology of detachable and temporary barriers on windows installed by the user (e.g. plywood)
	2	Technology of detachable and temporary barriers on windows installed with permanent anchor systems, installed by the user;
	3	Pre-installed permanent protective barriers on the windows, activated and operated by the user (e.g. shutters);
	4	Pre-installed permanent protective barriers activated remotely;
	5	Pre-installed automatic permanent barriers, coupled with an alert system of environmental data collection and impact rated laminated glazed systems.
Extreme temperatures adaptability	**Level of ventilation and radiation controlling.**	
	1	The opaque elements of the building envelope should have high thermal storage capacity, and user-managed ventilation systems (opening and closing windows, for instance);
	2	The opaque elements of the building envelope should have high thermal storage capacity, and user-managed system of sunlight control and ventilation (opening and closing windows and shutters to block sunlight);
	3	The opaque elements of the building envelope should have high thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing;
	4	The opaque elements of the building envelope should have high thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing and ventilation controlling;
	5	The opaque elements of the building envelope should have high thermal storage capacity and the façade should be able to react and vary themselves in response to the changing outdoor climate and indoor comfort, applied to the amount of radiation passing, ventilation controlling. The system should have monitoring, storage, and learning capabilities, also able to learn key internal and external parameters. Presence of real time device activation, using Machine-to-Machine (M2M) strategies.
Energy crisis adaptability	**Level of user's comfort during energy crises and energy production sufficiency**	
	1	Natural lightning and internal comfort conditions in all building rooms;
	2	Natural lightning and internal comfort conditions in all building rooms associated to solar water heating systems;
	3	Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid;
	4	Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid and solar-battery system to storage generation enough for temporary emergencies;
	5	Natural lightning and internal comfort conditions in all building rooms associated to photovoltaic energy production connected to the public power grid and solar-battery system to storage generation enough for later use and self-sufficiency.
Severe loading condition adaptability (fire, explosion, earthquakes, landslides and flash floods) a) Ability to support and adapt to small deformities; b) The structural components has the ability to withstand horizontal pressure; c) Independence between structural and non-structural.	**Total of the severe loading condition adaptable characteristics presented by the building skin.**	
	1	At least one of the characteristics is present on the building skin design;
	2	Having 2 out of the 3 characteristics present on the building envelope design;
	3	Having all 3 characteristics on the building envelope design;
	4	The building envelope has all 3 characteristics, with constant monitoring and inspection procedures;
	5	The building envelope has all 3 characteristics, and ensure the monitoring of key parameters through cognitive and communicative systems such as Internet of Things (IoT) to share signs of imminent failure and evacuation alerts.

RECONFIGURABILITY

REQUIREMENTS	INDICATORS	
Provide adequate reconfiguration documentation	**Level of reconfiguration information guide**	
	1	Detailed design and construction documents;
	2	Graphic instructions with illustrated step-by-step for the dismantling process for components and connections;
	3	Complete manual with tools and disassembly procedures (step-by-step), with labelled components;
	4	Complete manual with tools and disassembly procedures (step-by-step), with permanent labelled components with information about their materials composition and properties;
	5	Complete manual with tools and disassembly procedures (step-by-step), with permanent component tags built into them, which all information can be organised in databases and with wireless technology be sent through the internet.
Robust components and connections	**Number of possible and disassembled and reassembled**	
	1	The building skin system allows disassembly, but without possibility for later use or reassembly;
	2	The building skin allows disassembly with the possibility of some elements (e.g. windows, roof tiles) being re-used doing some repair;
	3	All the elements of the building skin allows at least one disassembly and reassembly cycle with some repair needed;
	4	All the building skin allows multiple disassembly and reassembly cycles, with some repairs needed;
	5	All the building skin allows multiple disassembly and reassembly cycles, without damage and no repairs needed.
Disassemblability of the connections	**Complexity of the equipment needed for disassembly the connections**	
	1	The connections between the components of the building skin can be disassembled using more than one type of electric equipment;
	2	The connections between the components of the building skin can be disassembled using one type of standard electric equipment ;
	3	The connections between the components of the building skin can be disassembled using non-standard manual equipment;
	4	The connections between the components of the building skin can be disassembled using standard manual equipment;
	5	The connections between the components of the building skin can be disassembled with no need of equipment.
Human-scale components	**Number of workers needed disassembled each element**	
	1	More than one element does not have human-scale components and need a worker team and equipment for handling and moving them;
	2	At least one element does not have human-scale components and need a worker team and equipment for moving;
	3	At least one element does not have human-scale components and need just worker team for moving;
	4	All the building skin elements have human-scale components and are easily and moved with no need of equipment, and the components weight is not too heavy safely manual handle by at least two workers;
	5	All the building skin elements have human-scale components and are easily moved with no need of equipment, and the components weight is not too heavy safely manual handle by one worker.
Components Modularity and Interchangeability	**Level of interchangeable possibilities**	
	1	The components do not use modular measures; however, the components with the same function has the same dimensions;
	2	Using some components with modular measures, it is possible to change for others new but not interchange with others components of the building skin;
	3	All the components follow modular measures and are coordinated and interchangeable, but not among different elements;
	4	All the components are modular, coordinated, labelled for traceability and there is the possibility of interchange all components and elements of the systems.
	5	All the components are modular, coordinated, labelled for traceability using IoT appliances and sensors and there is the possibility of interchange all components and elements of the systems.
Independency of other building systems	**Level of independency between the systems**	
	1	The building skin is projected as a monolithic load bearing walls, but at least the hydraulic and electric systems are independent or easily accessed;
	2	The building skin is integrated to the structured or physically adhered and cannot be changed, but it is independent of all the others functional systems;
	3	The building skin is integrated to the structure, however, it is easy to maintain and low cost and independent of the other systems;
	4	Elements of the building skin can easily be changed without affecting the structure and the remains systems;
	5	All the building skin could be replaced without affecting the structure and others systems.

LEARNABILITY

REQUIREMENTS	INDICATORS	
User's requirements information	**Level of user's requirement knowledge**	
	1	Development of briefing considering user's needs, but such building are not designed in response to any particular user;
	2	Development of briefing considering the specific client/users' needs and knowledge;
	3	Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements;
	4	Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements additionally should be carried out regular post-occupation analysis;
	5	Development briefing considering the specific client/users' needs and their knowledge, and also providing room for possible future requirements additionally should be carried out regular post-occupation analysis and technical inspections.
Risks and environmental constraints mapping	**Level of environmental risk knowledge**	
	1	Develop the inventory of all the EWEs that occurred in that specific region. This inventory, can be obtained by governmental agencies, media collection or any other source of information;
	2	Point one, plus mapping the susceptibility of EWEs happening in that local;
	3	Point one and two plus mapping of local vulnerabilities and threats for the human activities. This mapping could be done with the help of the local population;
	4	Risk mapping indicating possible future reconfigurations;
	5	Risk mapping indicating possible future reconfigurations; plus, constant mapping during the building's lifecycle, through automated monitoring of risks, generating alerts in case of imminent failure through IoT systems.
Design Information	**Level of development of the design phase information**	
	1	General architectural Projects, 2D drawing and CAD developed;
	2	Architectural, structural and installations projects, using 2D drawings and detailed construction documentation with descriptive guides;
	3	Use of 3D model BIM, with LOD 300 - A accurate model building with precise quantity of elements, size, shape and location. Non-graphic information should be attached to the model;
	4	Use of 3D model BIM, LOD 350 - A accurate model building with precise quantity of elements, size, shape and location, and the interfaces among the building systems should be represented. Non-graphic information should be attached to the model;
	5	Use of 3D model BIM, LOD 400 - A accurate model building with precise quantity of elements, size, shape and location, with detailing construction and assembly information. Non-graphic information should be attached to the model. Additionally, all its documentation, prototyping virtual reality and simulations should be provided.
Construction Information	**Level of development of the construction phase information**	
	1	As-built drawings - revised set of 2D drawings (architectural);
	2	As-built drawings - revised set of 2D drawings (architectural, structural and installations);
	3	As-built drawings - revised set of 2D drawings (architectural, structural and installations). In addition, a list of suppliers should be attached.
	4	As-built BIM Model (4D BIM (construction time and schedule) – LOD 500 – Model with a field verified representation of size, shape, location, quantity and orientation as constructed for maintenance and operations.
	5	As-built BIM Model (4D BIM (construction time and schedule) – LOD 500 – Model with a field verified representation of size, shape, location, quantity and orientation as constructed for maintenance and operations. Non –graphic information should be added as time for construction, schedule and suppliers lists. In addition, an organized file with lessons learned in the construction phase should be provided.
Operation and Maintenance Information	**Level of development of the use and operation phase information**	
	1	Provide a building manual with easy and accessible information for management and use, and the summary of the building;
	2	Provide a building manual with easy and accessible information for management and use, the summary of the building; key reference suppliers, and information about energy management and conservation;
	3	Provide a building manual with easy and accessible information for management and use, the summary of the building; key reference suppliers, and information about energy management and conservation. In addition, a specific and detailed operation and maintenance manual, providing training that include an introduction to the maintenance of the building system, in case of emergency, (for instance fire alarm) and energy and water saving;
	4	Point 3 plus, organization of all project information, user guide, inspection and operation and maintenance plans inside a BIM platform;
	5	Point 3 plus, organization of all project information, user guide, inspection and operation and maintenance plans inside a BIM platform, being managed and fed with new information and learned lessons during the building lifecycle.