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BREAKTHROUGH OF THE RESEMBLANCES AND CORRESPONDENCES BETWEEN RESILIENCE AND SUSTAINABILITY IN CIVIL INFRASTRUCTURES

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Abstract.

Sustainable construction has become a growing trend among researchers and stakeholders. Simultaneously, resilience and risk assessments for civil Infrastructures have flourished in terms of importance among researchers, economic sectors, and society. Nevertheless, there is no abundant research that correspond to both approaches, despite that, there are massive similarities and shared characteristics between both investigation branches. Distinctively, this year has demonstrated that sustainable development is directly obstructed by different extreme events that trigger risks and vulnerabilities in civil Infrastructures. These extreme events require a deep and complex study to minimize the impacts they may cause in society and economy, two main factors considered in the study of sustainability. Therefore, when a risk and resilience assessments are conducted, it is already analyzed as a sizable part of sustainability. Consequently, there exists a possibility to create a methodology that examines and assesses four categories of civil infrastructure sustainability: Technical, environmental, social, and economical. The aim of this paper is to demonstrate the need of a comprehensive approach between sustainability, risk, and resilience assessment, compiling and comparing the existing methodologies for assessing the impacts on civil infrastructures, showing that both present resemblances and none can be omitted, being necessary for the decision-making.

Keywords: Civil critical infrastructures, extreme events, resilience assessment, risk assessment, sustainable construction.

1. Introduction

World population has increased dramatically in the last decades, with a difference of 6 billion people between only one century. This exponential increment of population results on an excessive use of primary resources in order to fulfill their needs, being this one of the explanations towards the climate change problem we are currently facing [1, 2]. As a result of this worldwide problem, in the late 70s, reports began to appear concluding that if the population growth and its consumption of resources are not controlled, the world would not withstand the pressure on its resources, giving birth to the term of "Sustainable Development" [3]. Nowadays sustainability is a common concept in research that has been the focus of multiple studies, these investigations usually determine the development of humanity in the interconnection of three dimensions, the economic dimension, which is the most widespread over time, the environmental dimension, and the social dimension [3, 4]. Also, it is clearer now that the sustainable development is occasionally obstructed by new risks and vulnerabilities, such as terrorist attacks or diseases, as we are currently facing the new SARS-CoV-2 [5]. As emphasized in the United Nations Agenda 21, there are some risks, designated as systemic risks, that are arising actively (e.g. diseases, terrorism, natural disasters due to climate change), facing them in a never-ending challenge loop [5].

Today, critical infrastructure systems face an increased number of hazards, such as: natural (earthquakes, floods, fires), technological (operational failures in systems), and human (fires, cyber-attacks, or terrorism), that can intervene in the functionality of these systems. The malfunction of these systems can cause a cascading effects through the community that produce social, economic, and functional disruption [6, 7]. Therefore, there is the need to identify the new upcoming risks that may affect infrastructures, so at the time needed, governments address hazards within a comprehensive management and understanding of the complexity of civil infrastructures. Risk management models and resilience assessments are the best solution to assess and find solutions for planning, mitigation, and recovery for civil infrastructures under extreme events, where the consequences of damage and losses are quantified for decision making [7]. In this context, risk and resilience analysis play an important role, as it provides information that help decision makers to develop risk mitigation plans and strategies, taking into account that the economic development of a country strongly depends on its level of infrastructures [8]. In consequence, these concepts should be brought into a comprehensive approach that leads towards a sustainable development of infrastructures [5].

The aim of this paper is to demonstrate the need of a comprehensive approach between sustainability and risk and resilience assessment, compiling and comparing the existing methodologies for assessing the impacts on civil infrastructures, showing that both present resemblances and none can be omitted, being necessary for the decision-making. Thus, this paper seeks to establish the theorical foundation for a future approach that combines and evaluates the concepts of resilience, risk, and sustainability of civil infrastructures simultaneously using quantitative and qualitative methods. As this is of high importance for stakeholders, authorities, and industries in the decision making for civil infrastructures, under any hazard and the impacts that it would incur in social, economic, environmental and functionality terms.

This paper is mainly developed in 5 chapters. The first chapter consists on a brief introduction, which includes a general framing of the topics, the definition of the objectives of the work and a presentation of the structure of the article. In the second chapter, it is introduced the concept of sustainable development, as it is necessary to understand the context in which it emerged, as well as its historical evolution, then a short display of the most known methods at international level for sustainability in construction are presented, showing their characteristics and some examples of the indicator measures are introduced. In the third chapter it is addressed the beginning of risk and resilience analysis, recalling on some of the worst recent events that impacted infrastructures and society, that at the time, pointed out the necessity of this studies to be born, then a brief explanation is given upon this topic. On the fourth chapter is approached the main topic of this paper, that is the convergence between sustainability and risk and resilience concepts in civil infrastructures, where is presented the current situation of research within these two areas, through a brief state of the art focused towards civil infrastructures, emphasizing on the necessity to fill this research gap and stating some key points that the creation of a methodology that addresses sustainability, risk and resilience for civil infrastructures must have. The last chapter are the conclusions, where the authors summarize the key points obtained from the research.

2. Sustainable Construction

2.1. History, definition, and application

Climate change has been increasing in recent years, being the result of the existence and the multiple activities conceived by Humanity. Among these activities, specifically, there is one of those that produce the greatest impact, which is the construction industry. This industry currently uses about 40% of the fossil fuels, 30% of the raw materials and 25% of the water consumed annually in the world. Additionally, it consumes about 30% of electricity and generates 30% of greenhouse gas emissions [4], [9]. However, this industry has the potential to generate large reductions with small changes in the way buildings are designed and used, which could achieve savings of up to 30% in energy consumption, a 35% reduction in CO_2 emissions, and a reduction in water consumption of up to 50% [3, 4, 9].

This brought the attention to the international community to focus on the construction sector and its impacts began to emerge in the early 1970's when the First United Nations Conference on Environment and Development was held in Stockholm, giving rise to the United Nations Environment Program, with the aim to promote the appropriate use and sustainable development [3, 4]. Then, in 1988, in the report of the World Commission on Environment and Development named "Our Common Future", defined sustainability as "the attempt to meet the needs of the present without compromising the ability of future generations to meet their own needs". Thus, it was only by the year 1992 that international principles for sustainable development were established, during the United Nations Conference on Environment and Development in Rio de Janeiro, where Agenda 21 was elaborated, a document that systematized a plan of oriented actions creating the minimum necessary conditions for new constructions, both for developed and undeveloped countries [3, 10]. This Rio conference has been continued with the versions of Rio+10 in 2002 in Johannesburg and Rio+20 in 2012 in Rio de Janeiro, to reaffirm the Rio-92 goals and to include clean energy and corporate responsibility in the debate and also to focus on the green economy, being capable of generating jobs with low impact on the environment and efficient use of natural resources [3, 11]. After these world conferences, the need to develop methods and tools to study the sustainable performance of buildings emerged, because the countries that were implementing projects with better environmental performance had no ways to verify their improvements, obtaining situations where green buildings consumed more energy than conventional ones. Accordingly, it was necessary to develop methodologies to standardize building sustainability in a global way, allowing the analysis and comparison of various solutions to further improve the environmental performance of buildings [3].

2.2. Methodologies to assess sustainability

Currently there are tools that are not legally required, but they raise awareness and help to promote sustainability in construction entities. Countries such as United States, Canada, France, Japan, among others have already implemented tools for assessing the sustainability of buildings, as a support for project design and at the same time assessing their post-occupancy.

Some of the first certifications of the sustainability level of buildings began to emerge through the use of methods such as BREEAM in the United Kingdom, HQE certification (Haute Qualité Enviromentale) in France, LEED certification in the United States and GBTool (Green Building Assessment Tool) in some of the EU member states and adapted towards each state's necessities [3, 4][3]. Some of these methods are briefly explained down below.

2.2.1. Leadership in energy and environmental design (LEED) [3]

Developed by the U.S. Green Building Council in 1994, in the United States of America. In this method, the environmental performance of the building is evaluated holistically, throughout its life cycle, i.e., in the design, construction, operation and maintenance phases. This tool applies to various types of buildings, such as residential, commercial, and school buildings, among others. For a building to be evaluated it must meet a minimum required criterion, a pre-selection with a series of requirements. After this verification, the building becomes eligible, and the stage of analysis and evaluation of its performance begins. This is a points-based system, awarding points for specific criteria in five different categories: Sustainable Sites; Water Efficiency; Energy and Atmosphere; Materials and Resources; and Indoor Environmental Quality. These categories in total add up to 100 points, but there are two additional categories as a bonus, the Innovation in Design category, with 6 points, and the Regional Priority with 4 points. The points of the evaluation can only be assigned if the building complies with the requirements of the system; in the end, with the sum of these points, a classification can be assigned to the building, among four possible certifications, basic, silver, gold, and platinum.

2.2.2. Building Research Establishment Environmental Assessment Method-BREEAM [3]

The BREEAM method was developed in the early 1990s in the UK by researchers. The assessment with this tool considers the following sustainability categories: water, energy, materials, health and well-being, management, transportation, waste, contamination, and land use; each performance is verified by comparing them with pre-established benchmarks, thus obtaining the building's assessment. BREEAM can be used for virtually any type of building, such as offices, industrial plants, residential buildings, and hospitals. Thanks to the multiple existing versions of this tool, each one specifically developed to suit the building under assessment. In each of the categories mentioned above, requirements are defined, giving credits to the building, which are added as the building complies with them. On the other hand, in each category, specific weights are fixed, indicating their relevance, and depending on the type of building being evaluated. In this way, the set of credits and weights of the categories conform an environmental performance index for the building, which can obtain a value between zero and 100 for the Environmental Performance Index (EPI). According to the obtained EPI, six levels of certification are attributed, "Excellent", "Great", "Very Good", "Good", "Approved", and "No classification", each one depending on the total points obtained in the environmental performance index.

2.2.3. Sustainable building tool Portugal - SBTool PT [3, 4, 11]

. This methodology follows four steps: (i) Quantification of building performance at the level of each indicator; (ii) Parameter normalization; (iii) Parameter aggregation; (iv) Sustainability score calculation and overall assessment. The overall rating of the building depends on the weighting of the different criteria, considering benchmarking practices reference practices that are set at the national level (Portuguese level). This weighting is done by comparing the performance of the building with national reference practices: the best practice, which has a value of 1.0, and the conventional practice, with a value of 0.0. The value of this normalization is within a range between -0.2 and 1.2. Subsequently, with the performance of each indicator and its corresponding weight, the performance of the category to which it belongs is calculated. Finally, with the performances of each category and their respective weights, the results for each dimension are calculated, thus obtaining in the end an overall sustainability level for the building chosen for the case study.

3. Risk and resilience analysis in critical infrastructures

The growing number of catastrophic events and their implications, such as 9/11 in the United States, or the terrorist events in Madrid on March 11, 2005, have prompted Europe and other nations around the world to take steps to prevent these events from leading to high consequences that can be reduced or prevented. In June 2004, the European Council called for a strategy to protect critical infrastructure, which had a response on October 20, 2004, in a statement in which the Commission described the actions being taken to protect critical infrastructure and proposed additional measures to strengthen existing instruments and meet the mandates of the European Council [12]. Later, on November 17, 2005, the Commission adopted a Green Paper on a European Programme for Critical Infrastructure Protection, stating that the main scope of the European Programme for Critical Infrastructure Protection (EPCIP) is the need to increase the capability to protect Critical Infrastructures (CI) in Europe and to help reduce vulnerabilities related to CI [13].

The first step in protecting CI involves identifying and assessing the factors that may negatively influence its operations, defining a systematic, analytical approach to prioritizing resilience measures for CI. This analysis should include an assessment of the impacts of CI disruption by pre-established criteria. Several approaches are used in OECD countries [14]. In terms of criteria, the European Commission defines a minimum set for the assessment of critical infrastructure, including public impacts, economic impacts, environmental impacts, interdependence, political impacts, and psychological impacts. Identifying weaknesses allows prioritizing where to focus resilience efforts in existing infrastructure systems: on points of failure that would have the most severe consequences. This prioritization can be a decisive variable in decision making, such as which infrastructure should be hardened or relocated, or which CI should receive priority restoration after a disaster to ensure rapid recovery [12, 14].

Infrastructures must be designed and built to serve adequately over longer life terms without major deterioration or reaching collapse. With the current technology of materials, analysis, design, and construction, it should be possible to specify a bigger design life in new infrastructure projects. This leads towards a broader perspective which indicates that risk and resilience assessments are part of the general decision support to plan, to design and produce new infrastructures that are economically efficient, reliable, safe, secure, and sustainable [15].

4. Integrated approach for civil infrastructures

Recent literature has discussed the importance to go beyond the sustainability assessment of single buildings and to enlarge the assessment scale to communities and cities to meet all the different aspects of sustainability [9]. This chapter is divided in two main parts, the first part, where are presented some of the tools used to assess sustainability in infrastructures, and the second part, present diverse studies that integrate risk or resilience assessments with at least one dimension of sustainability's assessment (environmental, social, or economic).

4.1. Sustainability in Infrastructures

Sustainability assessment tools for civil infrastructures are less frequent rather than the existing tools to evaluate buildings, however, some researchers have already progressed in this topic. Following are showed some of their studies.

- Pardo-Bosch et. Al. [16], presented the multicriteria decision system MIVES. This decision model is divided into 4 steps. i) identification of the problem; ii) development of the decision tree, a diagram that organizes and structures the concepts that will be evaluated; iii) defining the relative weight of each of the aspects that are to be considered in the decision tree using Analytical Hierarchical Process; and iv) establishment for indicators of value function that in each case reflects the appraisal of the decision-maker [16]. It prioritizes with technical accuracy public infrastructure projects that one administration must finance with only one budget in a developed country, helping to minimize the subjectivity in the entire decision-making process.
- Rosasco et. Al. [8], show a study under a program named "Regional Strategic Intervention Program" (P.R.I.S), which objective is to guarantee the social protection of citizens that reside according to the Italian law about the expropriation of private real estate for the construction of public work projects. Within the framework of this program, the authors developed a mass appraisal estimation model that quantifies the indemnities values through a multi-parameter model of residential and commercial units within the area affected by the public work project. This multi-parameter estimation model uses a survey evaluated on the real estate units that are in the studied area; Seven main features were selected, which are: 1. Dimension (sqm); 2. age of building; 3. type of building; 4. maintenance state; 5. floor level; 6. lift (or not); 7. accessibility. This estimation model was applied in a new infrastructure project located near the city of Genoa, in Italy, the results show that the acceptance percentages of the indemnities estimated present a high degree of satisfaction, although the indemnities partially compensate all the inconvenience suffered. The authors conclude that these economic indemnities contribute to the achievement of that social sustainability of the infrastructures, and it can guarantee reasonable transfer alternatives for both residence and economic activities.
- Jones et. Al [17], considered the holistic nature of water infrastructure development in terms of rural areas in developing countries, through an outcome-based assessment method using Life-Cycle Analysis (LCA). This method uses the LCA framework to supply a holistic set of sustainability indicators, these indicators are grouped into three categories including metrics for technical (performance), environment, and economic (market-based) aspects. All the metrics are employed at community level to indicate the current state of the system. Finally, this method should provide the socio-economic impacts generated. The authors applied the method on a generic example of arsenic water-treatment in Bangladesh.

4.2. Risk-resilience and sustainability in civil infrastructures

The evaluation of resilience should not only consider technical but also environmental, organizational, social and economic dimensions [9]. Despite this, there is limited number of previous studies that integrate them with critical infrastructure sustainability. Few authors have worked onto developing a comprehensive approach that unites sustainability and risk-resilience analysis as it could provide synergies and clearer results about the overall role and needs of civil infrastructures.

- Markert et. Al. [15], presented a method for risk and sustainability analysis of complex hydrogen infrastructures, this model is based on a high level risk assessment, that are complemented with other decision support tools such as GIS, LCA and Life Cycle Cost (LCC). Providing a novel and comprehensive study as it enables the possibility to obtain spatial analysis with the GIS system, for both, the risk assessment approach, and the sustainability approach, easing the identification of vulnerable elements and high-risk zones, in addition to the environmental and economic aspects.
- Bocchini et. Al. [18], concluded that sustainability and resilience have a great deal of similarities and common features, as i.e. both integrate structural analysis with social and economic aspects, and both seek to enhance an infrastructure in terms of structural design, used materials, maintenance, management strategies, and impacts on society. Therefore, the authors proposed an approach established on a risk assessment, using the concepts of probability of occurrence and risk, to address resilience and sustainability at the same time. Despite the differences between sustainability and resilience targets, both converge on seeking to perform a service level to society during and after the occurrence of an extreme event and recover to the optimal functionality at great pace. For this, the proposed approach must be rigorous, quantitative, and unified, being able to assess numerous events and compare them. These events are weighted using Eq. 1 to quantify their probability of occurrence.

$$I = \sum_{e \in E_r} P_e I_e + \sum_{e \in E_s} P_e I_e \tag{1}$$

  Where I, is expected life-cycle impact of the infrastructure under analysis on the community (in monetary terms), and are the domains of events addressed by resilience and sustainability, respectively; is the probability of occurrence of the event e, and is the predicted impact on the community of the event e, this result is nondimensional. Eq. 1 can be used at the individual scale of an infrastructure (e.g. a Bridge), or at a global scale.
- Mejia et. Al. [19], defined three performance measures for the long-term investment in energy and transport infrastructures, which are: cost, sustainability and resiliency. The authors defined sustainability as the period where the infrastructure system satisfies operational and environmental requirements, and resilience as the cost from a pre-contingency state of the infrastructure to a post-contingency due to an occurrence of an extreme event. In addition, the authors used four input factors to quantify the resilience, cost, and sustainability performance of the system: the system of interest; the expected demand; projected events, and the expected actions. This quantitative approach was demonstrated in a case study of an integrated energy and transportation system in the United States.
- Marinella Giunta [20] proposed an integrated approach of resilience and sustainability to identify the most efficient alternative of road infrastructure rehabilitation after an extreme event based on life cycle costs. The author addressed that the main difficulty of this kind of approach is to do an evaluation of the sustainability and resilience using quantitative indicators. To overcome this issue, she articulated the approach in three main steps:
  1. Identify the rehabilitation alternatives considering technical, economical, and time aspects.
  2. Quantify the life cycle cost of each alternative. For each alternative it is quantified the Life Cycle Assessment (LCA) and the Life Cycle Cost Analysis (LCCA).
  3. Resilience assessment of the infrastructure for each rehabilitation alternative, based on economic aspects. It is done by the estimation of the costs to restore functionality, and the time needed for the reconstruction.

The result of this unified approach is a best solution of rehabilitation based on the lowest sum of the costs of sustainability and resilience.

4.3. Conclusions

This paper provided a broad analysis of the characteristics of different tools, methodologies and applications for the identification and evaluation of risks, resilience, and sustainability in civil infrastructures, as an opening towards developing an integrated and multidisciplinary methodology that allows to assess simultaneously to serve adequately over longer life terms without major contingencies.

It was observed in the literature from the most relevant articles related to risk and resilience assessment, that there is a possibility to create a multidisciplinary methodology that includes sustainability as it directly involves the economical and societal consequences that any disruptive event might bring. In this way, the aspects associated with sustainability and resilience assessment are considered simultaneously and in a process of mutual interaction, opening the possibility to be used for planning and development of new cities, industries, and facilities as this comprehensive analysis is important for their continues optimization. The development of this kind of research seems to push designers and administrators in a similar direction, as it is a useful source of information for stakeholders at the local level, as the assessment methods and tools may comprehensively support sustainable choices that are also the basis for the sustainable pursuit of civil infrastructures.

Risk, resilience, and sustainability are complementary characteristics for civil infrastructure. While sustainability addresses the time-continuous impacts on the economy, society, and environment that the infrastructure certainly will distribute over its entire service life, resilience, and risk focus on the big impact that the service failure of the infrastructure can have in the case of extreme events. The combination of these approaches will provide a truly comprehensive assessment of the quality of the infrastructure.

A possible big obstacle for the integrated assessment of both sustainability and resilience is the computation of truly quantitative metrics. The resilience research is more advanced in terms of quantitative analyses and indicators for civil infrastructures. Instead, sustainability assessment systems have promoted a culture of qualitative assessment.

Finally, it is essential to continue investigating and improving the way of collecting and processing these methodologies. Hence, future studies are needed to conduct to validate the usefulness and reliability of a comprehensive methodology described to evaluate the resilience and sustainability of civil infrastructures. Additionally, it is vital to realize applications on case studies embracing different scenarios for each characteristic.

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