Overview of resilience: a concept to assess healthcare infrastructure preparedness against disasters. Evaluation of existing models and applicability to HVAC systems.

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Abstract. Healthcare infrastructures are critical and have elements which are likely to fail or to get collapsed in disaster scenarios (earthquakes, pandemics, etc.). There are many parameters and factors to evaluate their preparedness, but resilience has outstood in recent investigations. Hospitals must not only be prepared for disasters to come, but also to reach the nominal operation in the aftermath as soon as possible, as these infrastructures play a critical role in modern societies. The aim of the study is to evaluate and assess different insights into resilience, as well as marking possible improvements, providing a deeper understanding about the topic and concepts that surround the definition of resilience. The result is the constitution of a new assessment tool based on semi-quantitative and quantitative models. The model can be scaled and applied to internal systems in healthcare infrastructure such as HVAC facilities.

1. Introduction

Healthcare infrastructures are one of the main pillars of the welfare state, as they provide numerous and specialized types of medical services. These infrastructures -especially critical areas- are vulnerable when they are stricken by a disaster of a considerable magnitude [1]. These areas include intensive care units, high risk and conventional operating rooms and various emergency services. Besides, they require special hygiene and environmental conditions, as well as a larger basic supplies consumption such as electricity and water [2].

Critical zones may become singularly vulnerable during a catastrophic scenario, as a minimum change in the boundary conditions may modify the normal operation [3]. Moreover, Heating Ventilation and Air Conditioning systems (HVAC) are crucial to maintain the strict requirements of these zones, and henceforth an optimization and preparedness analysis is justified to be applied. Therefore, a necessity arises from this premise regarding the capacity of the healthcare infrastructure to overcome various unfavourable situations that may disrupt the normal operation of the infrastructure. These unfavourable states may entail economic, social and even human losses, so prevention and preparedness analysis are justified with this regard [4]. Risk management strategies have been trying to reduce both the likelihood of adverse scenarios to happen and their consequences. Concerning this, predictive maintenance in hospitals HVAC systems is a key aspect [5]. Protection, prevention and prophylactic measures are considered with regard to this issue, and there is a concept which has outstood in recent literature and has become quite trendy: resilience [6].
The original term of resilience refers to the ability of a generic material to spring back to an original form after having been exposed to some external forces. Similarly, the concept of resilience may be extrapolated to hospitals and healthcare infrastructure considering the capacity of the healthcare system to return to the normal state after a disruption occurs [7]. Apart from this, resilience can also be defined as the intrinsic ability of a system to adjust its functionality in the presence of a disturbance and unpredicted change. Taking this into account, Zhong et al. [8] proposed a model to identify the underlying main factors of the resilience. In this vein, the same authors, Zhong et al. [4] proposed a validation of a framework to assess this concept, as a basis on resilience had to be settled.

Resilience is a scalable concept since it can be applied to various and independent fields and facilities. R. J. Fairbanks [9] links resilience with monitoring, anticipation, response and feedback processes. Resilience can be assessed through different domains with regard to buildings, facilities and infrastructures, including organizational, social, economic and engineering domains. The latter is the one that concerns this study. According to B. D. Youn et al. [10], the definition of resilience from this perspective involves the sum of the passive survival rate (reliability) and proactive survival rate (restoration) of a system.

Another interesting concept that derives from this definition is the resilience engineering, adopted by Dinh et al. [11], which tries to understand both the normal functioning of a technical system and the way it fails. Besides, and according to Hollnagel et al. [12], resilience can be defined as the ability of a system to sustain external and internal disruptions without any discontinuity of performance or to fully recover if the function is disconnected. On this line, resilience is susceptible to being related to preparedness and preventive design disciplines.

The objective of this study is to provide a wide, holistic and comprehensive definition of parameters involved in preparedness, prevention and resilience, as well as the eventual applicability of the concepts in systems of multiple characteristics. Additionally, this study aims to dig deep in relevant studies, marking their respective strengths and potential weaknesses and take items to build a new suitable model to assess the resilience of systems.

2. Methodology

The modus operandi of this study lied on selecting the adequate concepts to study and evaluate the preparedness and preliminary measures concerning healthcare infrastructures and its elements' response to disaster and adverse scenarios. Then, existing references were extracted and assessed, pointing out the most relevant articles and selecting the analysis that have been carried out in them. By searching keywords such as 'hospital', 'health', 'HVAC', 'infrastructure' and 'resilience' in scientific websites such as Scopus, WOS and Google Scholar, a compound of 12 articles and their relative references were assessed and evaluated, as most relevant models were supposed to be exposed there. The overall literature review is evaluated throughout the study.

The next step was providing an insight of the topic from the engineering point of view, completing existing qualitative analysis and trying to approach the measures to quantifiable and numerical scales. The models were filtered and classified according to their approach on resilience analysis, relevance, characteristics and interest of the authors. Then, differences among models sorted in the same group were also pointed out, specifying the main outlines and features among them.

Finally, a resulting model was proposed to evaluate not only overall systems, but individual subsystems which define larger ones, focusing on HVAC facilities. The results were focused on the following questions: "what can go wrong?", "what is the probability of the unfavourable scenarios?" and "what are the consequences?". The answers to these questions are uncertain and depend on multiple factors. Evaluating these parameters was one of the main motivations to carry out this research.
3. Results
A compilation of huge on extensive bibliographic revisions about terminology and several approaches from the engineering point of view have also been taken as a reference. In this reference, several models are extracted and classified according to the domain they belong to, the journal where and the year when they were published [6]. This data extraction is helpful to select candidate models in order to create a new model to evaluate the resilience of several items. A variation from Hosseini’s [6] classification is shown in figure 1:

Figure 1. Classification of resilience assessment models. Adapted from [6]

3.1. Qualitative models
Making use of conceptual frameworks may be helpful to assess and evaluate the resilience of a system. Alliance [13] evaluation process is described in figure 2:

Figure 2. Steps of the conceptual framework for qualitative models

Defining, understanding and limiting the system under study
Identifying the appropriate scale in which the resilience is evaluated
Identifying the system drivers as well as the external and internal disturbance
Identifying the main stakeholders in the system
Developing conceptual models for identifying necessary recovery activities
Implementing results to inform the policymaker
Incorporate the findings and feedback

Apart from this, some key concepts are related to this topic, as this evaluation is not only applicable to healthcare infrastructure, but also to generic systems. The capacity of the system to generate stocks and reserves, risk assessment, robustness, consequence mitigation and the consequent planning evaluation are items inherent to this process [8].
3.2. Semi-quantitative models

These models may be based on qualitative models, but they introduce discrete tools such as Likert scales or percentage rankings. With the help of these items, subdivision and identification of key parameters and linearly independent composing factors of healthcare infrastructure is more likely to be achieved. Semi-quantitative models are often associated with questionnaires and divide the evaluation into different sub-indices such as economy, infrastructure, human resources or capability among others. This characteristic allows the user to identify important aspects which are involved in healthcare infrastructures. In addition, semi-quantitative models are not only valid to hospitals, but also to other engineering disciplines and fields, such as supply chains.

Different studies and surveys have been carried out with models in regard to hospitals and healthcare systems [14]. Although in this reference the concept of resilience is barely mentioned, the approach to disaster preparedness is reasonable. From 140 studies, a filtered list based on the COSMIN criteria for evaluating these tools shows the best candidates to fit best the requirements that are needed to perform an effective resilience study, evaluation and assessment [15].

3.3. Quantitative models

Quantitative models can be sorted depending on whether the resilience evaluation provides a determined system performance (general measures), or they describe boundary conditions and internal layouts to optimize the system (structural-based models) [6].

3.3.1. General measures

General models can be assessed through both a deterministic and a probabilistic perspective [6]. However, they lead to a performance loss which can be represented by scaled graphics. One of the models that have been considered in this study is the one developed by Bruneau et al. [16], in which a performance loss can be observed. In this model, the concepts of community resilience, robustness of the system, redundancy of elements, resourcefulness and rapidity are applied on a specific unfavourable scenario: an earthquake whose effects last from \( t_1 \) to \( t_2 \) as it is shown in figure 3.

A more simplified model corresponds to Zobel's triangle, elaborated by Zobel [17], which proposes the percentage of the total possible loss over a considerable time interval, including a time frame between \( T \) as the end of disruption, and \( T^* \) as a security time. The beginning of the disruption is marked as \( t_1 \) as it is shown in the figure 4:

![Figure 3. Generic performance loss. Adapted from [16]](image1)

![Figure 4. Zobel's Triangle model. Adapted from [17]](image2)

In both the first and the second model an instantaneous degradation of performance can be observed. There are some models which include a vulnerability stage where the performance loss is not discrete, but it decreases during a certain amount of time. Henry and Ramirez-Marquez [18] constitute their model based on this idea and point out all the required stages to recover the nominal operation. In Henry and Ramirez-Marquez model, the importance of the vulnerability
stage is linked to the evaluation of the performance in facilities during the aftermath of the disruption state, as they can be a key indicator in a resilience study, as it is shown in figure 5:

**Figure 5. Stages of performance recover over a disruption [18]**

![Figure 5](image)

Another model that has been investigated and that includes several original ideas is Rose [19] model, as it considers a variance in resilience over a certain period of time. Rose differentiates static resilience from dynamic resilience and considers that the recoverability of the system is tied to stepped recoveries of performance. On the one hand, and regarding the static resilience, Rose [19] establishes a comparison between the level of performance referred to status quo where there is no disruption, there is an expected degraded performance level and the worst-case scenario, as shown in figure 6.

On the other hand, dynamic resilience is obtained from the difference between time-dependent variables constituted by a string of step functions. Those two variables correspond to situations where protocols with hastened conditions are applied or not and can be observed in figure 7, obtained from Rose's model [19]:

**Figure 6. Percentage performances of static resilience [19]**

![Figure 6](image)

**Figure 7. Dynamic resilience representation [19]**

![Figure 7](image)

3.3.2. Structural-based models

The structural-based approaches evaluate how the system is constituted and its relationship with the resilience, as well as the expected behaviour [6]. The main drawback of these models is the difficulty to transform the obtained results from the model to real conditions, since structural-based models are often based in different types of simulations, including optimization models,
discrete events and scenarios simulations and fuzzy logic routines, which cannot be easily linked to reality.

However, due to their nature, a large amount of simulations can be executed, by modifying parameters that are fixed and discussed in general measures models. Making use of tools like Random Number Generators (RNG), Monte Carlo methods, optimization processes and decision-problem solvers, a quite accurate output can be achieved [20]. With this idea, several simulations can be executed within a single study, providing different outputs with the same problem. This could lead to solutions and protocols concerning the multiple unfavourable situations which can affect the systems.

4. Discussion

Although qualitative models provide a flexible insight of a system resilience and allows the user to identify relevant domains and subdomains in regard to the evaluation, it may become vague and somewhat inaccurate, as they lack direct quantification. The purpose of general optimization and orientation of resources may be accomplished, but if a higher sensitivity of the system is required, qualitative models may not be the best option.

One of the main advantages of semi-quantitative models with respect to qualitative models is the possibility of identifying and partially quantitating the extracted parameters, so that priorities can be established among different components of the healthcare systems. However, the evaluation is not fully objective, as an expert panel is likely to be needed if the decisions are meant to be contrasted. Plus, qualification, experience and feedback from previous incidents are required for the committee, not only to provide the most feasible and truthful choices in the decision-making process, but also to draft the questions to address the most relevant topics.

The advantages of quantitative models are the provided theoretical results which can be translated into direct solutions whose output is bound to be objective. However, these models have a few drawbacks that prevent them from outstand compared to semi-quantitative models. Undoubtedly, the output results of the resilience study are objective, as the result is the combination of different mathematic models. Nevertheless, the input data and the way to evaluate the probabilities of the different scenarios, the loss of performance as well as the expected recoverability curve are based on the same premises as the semi-quantitative models: an expert panel. Besides, the time scale is also an important point, because the period between the disruption origination and the final time linked to a recovered state is undefined. This is also a measure to be evaluated and assessed by the expert panel.

The suitable items that could be used to assess the preparedness, capacity and resilience of HVAC systems are semi-quantitative approaches, as these models are suitable for identifying and characterizing the components of systems and subsystems and they have already been proven to be effective in questionnaires [15]. Plus, several disaster scenarios can be easily implemented, evaluating the different responses of the facility against multiple events. Nevertheless, non-exclusive characteristics from quantitative models can also be applied, providing an expected performance loss. For instance, multiple simulations of certain HVAC systems using conceptual models, Monte Carlo methods and varying the boundary conditions may provide several performances in different scenarios according to the design conditions and the impact of the disaster in the elements of the facility.

This combined model can be applied to HVAC systems, calculating the resilience of the individual elements and the relationships among them, considering the capacity of the facility to maintain the required set parameters in critical areas and the multiple disaster scenarios that may happen depending on the health infrastructure location. This resilience assessment provides an expected performance loss, which can guide the elaboration of protocols and the resource management strategies to ensure a correct and optimal operation. Besides, the study can be applied not only considering disaster situations, but also regarding maintenance and surveillance.
5. Conclusions
The importance of basic and critical systems in modern societies like healthcare infrastructure, and the reason why failure and preparedness are capital with regard to HVAC systems and conditions maintenance has been justified. Plus, the concept of resilience has been studied through several approaches, including different models to evaluate how the resilience is related and thereby transformed into a system performance alteration. The importance of defining different subdomains and identifying key factors has also been pointed out, as shown in the examples.

A revision has been carried out, assessing the different types of models applicable to resilience evaluation concerning HVAC systems, their components and eventual relationships among them. The advantages and drawbacks of the types of models has been noted, as well as the contrast between relevant ideas. As a final idea, a recap has summed up the objectives of the study, which is provide a wide and comprehensive understanding of the term resilience as well as a comparison between qualitative, semi-quantitative and quantitative studies that have been published with this regard.

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