Robust and resilient buildings: A framework for defining the protection against climate uncertainty

Amin Moazami1,*, Salvatore Carlucci2, and Stig Geving2

1 NTNU Norwegian University of Science and Technology, Department of Ocean Operations and Civil Engineering, Ålesund, Norway
2 NTNU Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, Trondheim, Norway
* amin.moazami@ntnu.no

Abstract. The design of high-performance buildings has been questioned for their actual performance in operation, where the impact of external perturbations such as occupant behavior and climate has proved to be prominent. These sources of variability, called aleatory uncertainties, are inherent variations of nondeterministic systems and are irreducible. Therefore, one of the main approaches to deal with these uncertainties is to consider them as noise during the design phase. The goal of the design is hence achieving a solution whose performance is least sensitive to the noise. This specific design process is called robust design. In this study, a prospect of climate conditions that a building might face during its lifespan is identified. However, although robust design can support the design of building variants whose performance is insensitive to typical climate conditions and also predictable extreme climate conditions, these building variants cannot be considered protected in case of unforeseeable extreme events. During such events, another property called resilience is required, which focuses on withstanding and recovering during and after the occurrence of the event. This study reviews the concepts of robustness and resilience and organizes them into a framework that clarifies their relationships in the protection of buildings against climate uncertainties.

1. Introduction

The first step towards protection against climate uncertainty is to identify the climate conditions that a building might face during its lifespan. The following definitions provided by World Meteorological Organization (WMO), Intergovernmental Panel for Climate Change (IPCC) and United Nations Office for Disaster Risk Reduction (UNISDR) can provide a platform for depicting this prospect. Climate normals as defined by WMO are “averages of climatological data computed for the following consecutive periods of 30 years: 1 January 1981 to 31 December 2010, 1 January 1991 to 31 December 2020, etc.” IPCC defines climate change as “A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.” Furthermore, IPCC defines climate extreme as “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable”.

Although nowadays, decision-makers are provided with data on climate normals and also projections of climate changes according to generated data by climate models [1], there are climate conditions that occur far beyond observed or expected ranges. These extreme events are unforeseeable and can lead to disaster impacts. Disaster impacts are defined by UNISDR as “the total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event..."
or a disaster. The term includes economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being”.

Based on the above definitions, in the following sections, a prospect of climate conditions and their impacts on buildings are described and examples are provided.

1.1. Climate normal and typical climate conditions
The WMO has been providing climate normals at monthly scale for the last 82 years. They first calculated climate normals for the period of 1901-1930 and updated them every 30 years [2]. As they are meant to be, these data provide decision makers and stakeholders a representative image of climate conditions in a given location. The climate normals are based on a stationary assumption of climate. Stationarity assumption is considering that natural systems fluctuate within an unchanging envelope of variability [3]. However, the observed climate change has shown that the assumption of stationarity for climate cannot be taken for granted and climate normals do not provide a complete image of possible future climate for a location [3].

1.2. Climate change and foreseeable extreme conditions
As stated by IPCC [4], the mean (i.e. the climate normals) and the variability of climate is changing over time, therefore, in any decision-making process, it is important to account for these changes over several decades to come. Apart from long-term patterns of climate change, the short-term changes that induce climate extremes have to be considered. Observations show a more frequent and more intense occurrence of climate extremes [5].

1.3. Unforeseeable extreme events
Climate extremes can become unforeseeable extreme events with disaster impacts through two mechanisms:

**Mechanism 1:** Cities are complex systems, and, during an extreme event, some functionalities disrupt as a result of a chain of small events. An example is the failure of a power grid during a heat wave. This failure is typically the result of several smaller events:
1. Extremely high temperatures can last from days to weeks. This cause peak loads to be much higher both in magnitude and duration [6].
2. Extremely high temperatures cause reduction of the thermal capacity of the transmission lines that applies more stress on the power grid [7].
3. Heat waves are usually accompanied by stationary high-pressure zones, resulting in light winds at the surface and, therefore, reduced wind generation by wind turbines [7].
4. Increased air temperature has a derating effect on gas-turbines, which causes a reduction in capacity and the efficiency of these systems [8].
5. During heat wave 2003, French nuclear power plants operated at much lower capacity due to very low river water levels and also high temperature of the water leaving cooling towers exceeded environmental safety levels [9].

This chain of events and high demands for a period of time implies high stress on the grid, which can lead to unforeseeable failure of the grid system and thus:
6. No electricity leaves thousands of buildings without any means of mechanical cooling, potentially causing a fatal situation for the elderly, very young, or chronically ill people, as it occurred during the 2003-heat wave in Europe when thousands of people died [10].

The climate extremes experienced during the summer of 2003 led to disaster impacts with a high number of heat-related deaths in France [11] and in Switzerland [12] including Geneva.

The Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) provides climate indicators to communicate how climate is changing: hot days are defined as “days in which the temperature rises above 30 °C”, frost days are defined as “days on which the temperature dips below 0 °C”, and tropical nights are defined as “days on which the temperature does not dip below 20 °C”. Table 1 shows the numbers of hot days and tropical nights for the city of Geneva according to climate normals and three climate extreme summers extracted from data provided by MeteoSwiss. The table reveals how the average processing of calculating climate normals misses important information on climate extremes.
### Table 1. Comparison of the number of hot days and tropical nights for Geneva.

| Type of data               | Period      | Number of hot days | Number of tropical nights |
|----------------------------|-------------|--------------------|---------------------------|
| Climate normals            | 1961–1990   | 10.4               | 0.1                       |
|                            | 1981–2010   | 14.7               | 0.4                       |
| Observed climate extremes  | Summer 2003 | 51                 | 4                         |
|                            | Summer 2017 | 30                 | 4                         |
|                            | Summer 2018 | 33                 | 1                         |

It is interesting to note that, although there is a substantial difference in number of hot days between the summer of 2003 with those of 2017 and 2018, the scale of the impacts was much higher than this difference, in other words, during the 2003 heatwave, the extreme conditions were coupled with other small events that in a domino effect ended to a disaster impact. Climate extremes increase the probability of disaster impacts, but it is almost impossible to predict which outcome will occur due to a number of involved factors characteristic of each urban system.

**Mechanism 2:** Climate extreme can also cause disaster impacts as they occur in an unpredictable scale of magnitude for a given location. An example of this failure mechanism is the hurricane Maria that made landfall on Puerto Rico on Wednesday, September 20, 2017. It caused several casualties and estimated damage of $ 90 billion [13]. On the island of Puerto Rico during 48 hours of the event, it was recorded a maximum wind speed of 61.2 m/s and a maximum precipitation rate of 163.6 mm/h [14]. To provide a benchmark, the American Meteorological Society classifies a precipitation rate above 7.6 mm/h as **heavy rainfall** [15]. Thus, the peak value of the precipitation rate in Porto Rico during the hurricane Maria was more than twentyfold what is expected to be heavy rainfall.

1.4. Organization of the paper

After identifying the different climate conditions, a framework is conceptualized to represent the building’s protection against all identified climate conditions. After reviewing the two concepts of robustness and resilience through the definitions provided in section 2, the framework is presented and discussed in section 3. Finally, the conclusions are drawn in section 4.

2. Conceptual approaches for protection against climate change

2.1. Robustness

Designing under the presence of aleatory uncertainties is not a new concept and has been in discussion in other fields of industry for a long time. The basic idea is that rather eliminating the source of uncertainty, this source is treated as **noise** during the design phase, and the goal is to achieve a design solution whose performance is least sensitive to the presence of noise. This process is called **robust design** and was introduced first by Taguchi in the 1940s. Taguchi defined **robustness** as “the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user’s environment) and aging at the lowest unit manufacturing cost” [16].

2.2. Resilience

Although climate robust buildings provide a performance that is insensitive to typical and predictable extreme conditions, these buildings cannot be considered as protected against the unforeseeable extreme events. Protection against such events requires a different approach, this concept in the literature is mainly referred to as **resilience**. It is the capacity of a system to withstand and recover during and after the occurrence of an extreme event. For a better understanding, table 2 provides the commonly discussed concepts of robustness and resilience in buildings design.
The measure by which the indoor environment of a building lives up to its design purpose when it is used by occupants in a real-life situation.”

“Insensitivity” of the building performance to the presence of those uncertainties. For the case of robustness, the considered uncertainties are “uncertainties during operation” and the main focus is on aleatory uncertainties such as occupant behavior and actions and climate.

Focus is on “major disruptions or shocks”, which can be the unforeseeable extreme events described in section 1.3. These types of events, as mentioned earlier, can lead to disaster impacts. For this reason, the required attributes can be summarized as “withstand, absorb and recover”. Thus, if a building is robust, it is likely that it will withstand and absorb the shock better than a non-robust building. However, an unforeseeable extreme event can still cause the building to fail. For the aforementioned matters, the following two definitions are provided in this work.

Definition 1: A robust building is a building that, while in operation, can provide its performance requirements with a minimum variation in a continuously changing environment.

Definition 2: A resilient building is a building that not only is robust but also can fulfill its functional requirements (withstand) during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts.

The functional requirements define what a building has to do, and the performance requirements determine how well a functional requirement has to be done [28].

Table 2. Definitions provided in literature for the concepts of robustness and resilience.

| Ref. | Definition                                                                 | Ability                        | Source of Uncertainty            |
|------|---------------------------------------------------------------------------|--------------------------------|----------------------------------|
| [17] | “The measure by which the indoor environment of a building lives up to its  | Lives up to its design purpose | Occupants in a real-life situation |
|      | design purpose when it is used by occupants in a real-life situation.”    |                                 |                                  |
| [18] | “The sensitivity of identical performance indicators of a building design  | Insensitivity                   | Errors in the design assumptions  |
|      | for errors in the design assumptions.”                                    |                                 |                                  |
| [19] | “A building that shows little variation in performance despite of          | Little variation                | Occupant’s behavior              |
|      | variable occupant’s behaviour.”                                           |                                 |                                  |
| [20] | “A building that is not negatively affected by changes in operation       | Not negatively affected         | Changes in operation parameters  |
|      | parameters.”                                                              |                                 |                                  |
| [21] | “Robust solution is insensitive to climate change uncertainties.”         | Insensitivity                   | Climate change uncertainties     |
| [22] | “Buildings whose performances show little variations with alternating     | Little variations               | Occupant behavior patterns       |
|      | occupant behaviour patterns.”                                              |                                 |                                  |

3. Positioning robustness and resilience in a framework for protection against climate change

Table 2 allows identifying two aspects for both robustness and resilience concepts: (1) the nature of their considered uncertainties, and (2) the required attributes for the protection against these uncertainties. In the case of robustness, the considered uncertainties are “uncertainties during operation” and the main attribute is the “insensitivity” of the building performance to the presence of those uncertainties. For buildings, the main focus is on aleatory uncertainties such as occupant behavior and actions and climate. In the case of resilience, although the considered uncertainties are “uncertainties during operation”, the focus is on “major disruptions or shocks”, which can be the unforeseeable extreme events described in section 1.3. These types of events, as mentioned earlier, can lead to disaster impacts. For this reason, the required attributes can be summarized as “withstand, absorb and recover”. Thus, if a building is robust, it is likely that it will withstand and absorb the shock better than a non-robust building. However, an unforeseeable extreme event can still cause the building to fail. For the aforementioned matters, the following two definitions are provided in this work.

Definition 1: A robust building is a building that, while in operation, can provide its performance requirements with a minimum variation in a continuously changing environment.

Definition 2: A resilient building is a building that not only is robust but also can fulfill its functional requirements (withstand) during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts.

The functional requirements define what a building has to do, and the performance requirements determine how well a functional requirement has to be done [28].
Following these definitions and considering the prospect of climate conditions for the built environment that were identified in section 2, a framework can be realized for representing the protection of the built environment against all mentioned climate conditions (figure 1).

Figure 1. Framework for the protection of the built environment against all climate conditions.

Figure 1 demonstrate that the buildings that are designed based on typical conditions can function as expected during such conditions, but their performance will be significantly challenged during extreme foreseeable conditions. This is due to their sensitivity to outdoor conditions. These buildings are even at risk of complete failure of functionality during unforeseeable extreme events with no possibility for reoccupying them after the event (end of service). Robust buildings perform with low sensitivity under typical and foreseeable conditions but their functionality is at risk during unforeseeable extreme events. Resilient buildings on the other, not only have to withstand the unforeseeable extreme events but also be able to recover to acceptable performance level and continue their service.

4. Conclusions
While in other industries, the design against uncertainty is a consolidated procedure, in the building sector it is not a common approach. Focusing on the aleatory uncertainty represented by the climate acting on the built environment, in this paper, a framework for the protection of the built environment against typical climate conditions, and foreseeable and unforeseeable extreme climate conditions is presented. Based on the reaction of the built environment to the foreseeable and unforeseeable extreme climate conditions, univocal and coordinated definitions are provided for the terms robustness and resilience. Finally, a graphical representation of these two terms is drawn in regards to the capacity of the built environment to provide acceptable levels of the performance and functional requirements.

References
[1] Moazami A, Nik VM, Carlucci S and Geving S. Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions. 2019 Appl. Ener. 238 696-720.
[2] Arguez A and Vose RS. The Definition of the Standard WMO Climate Normal: The Key to Deriving Alternative Climate Normals. 2011 BAMS. 92(6) 699-704.
[3] Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP and Ronald JS. Stationarity Is Dead: Whither Water Management? 2008 Sci. 319(5863) 573-4.

[4] Field CB, Barros V, Stocker TF and Dahe Q. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of IPCC. 2012 CUP.

[5] Fischer EM, Knutti R. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. 2015 Nature Clim Change. 5 560.

[6] Lu N, Wong P, Leung L, Scott M, Taylor T, Jiang W and Correia J. The impact of climate change on US power grids. 2009 CCTC.

[7] Ke X, Wu D, Rice J, Kintner-Meyer M and Lu N. Quantifying impacts of heat waves on power grid operation. 2016 Appl. Ener. 183 504-12.

[8] Najjar YSH. Efficient use of energy by utilizing gas turbine combined systems. 2001 Appl. Ther. Eng. 21(4) 407-38.

[9] De Bono A, Peduzzi P, Kluser S and Giuliani G. Impacts of summer 2003 heat wave in Europe. 2004 UNEP (Retrieved from https://www.unisdr.org/files/1145_ewheatwaveen.pdf).

[10] Robine JM, Cheung SLK, Le Roy S, Van Oyen H, Griffiths C, Michel JP and Herrmann FR. Death toll exceeded 70,000 in Europe during the summer of 2003. 2008 Comp. Rend. Bio. 331(2) 171-8.

[11] Vandentorren S, Suzan F, Medina S, Pascal M, Mailpoix A, Cohen JC and Ledrans M. Mortality in 13 French Cities During the August 2003 Heat Wave. 2004 Public Health. 94(9) 1518-20.

[12] Grize L, Huss A, Thommen O, Schindler C and Braun-Fahrlander C. Heat wave 2003 and mortality in Switzerland.2005 Swiss medic. weekly. 135(13-14) 200-5.

[13] Kishore N, Marques D, Mahmud A, Kiang MV, Rodriguez I, Fuller A, et al. Mortality in Puerto Rico after Hurricane Maria. 2018 medic. 379(2) 162-70.

[14] National Aeronautics and Space Administration (NASA), Maria (Atlantic Ocean). (accessed on March 23rd, 2019. https://www.nasa.gov/feature/goddard/2017/maria-atlantic-ocean)

[15] Glossary, Meteorology. "American Meteorological Society." (Accessed on 23rd March 2019. http://glossary.ametsoc.org/wiki/Rain).

[16] Taguchi G, Chowdhury S and Taguchi S. Robust engineering: learn how to boost quality while reducing costs & time to market. 2000 McGraw-Hill Prof. Pub.

[17] Leyten JL and Kurvers SR. Robust indoor climate design. 2011 ICIAQC.

[18] Hoes P, Hensen JLM, Loomans MGLC, de Vries B, Bourgeois D. User behavior in whole building simulation. 2009 Ener and Build. 41(3) 295-302.

[19] Fabi V, Buso T, Andersen RK, Corgnati SP and Olesen BW. Robustness of building design with respect to energy related occupant behaviour. 2013 IBPSA.

[20] Palme M, Isalguie A, Coch H and Serra R. Energy consumption and robustness of buildings. 2010 CESB.

[21] Chinazzo G, Rastogi P and Andersen M. Robustness assessment methodology for the evaluation of building performance with a view to climate uncertainties. 2015 IBPSA.

[22] Buso T, Fabi V, Andersen RK and Corgnati SP. Occupant behaviour and robustness of building design. 2015 Build. and Envir. 94 694-703.

[23] Bosher L. Introduction: the need for built-in resilience. 2008 Hazar. and the Built Envir. 21-37.

[24] Faller G. The resilience of timber buildings. 2013 SEMC Taylor & Francis - Balkema.

[25] Champagne CL and Aktas CB. Assessing the Resilience of LEED Certified Green Buildings. 2016 ICSDEC. 1452016 380-7.

[26] Desouza KC and Flanery TH. Designing, planning, and managing resilient cities: A conceptual framework. 2013 Cities. 35 89-99.

[27] Pearson LJ, Pearson L and Pearson CJ. Sustainable urban agriculture: stocktake and opportunities. 2010 Agri. Syst. 8(1-2) 7-19.

[28] Wilde Pd. Building Performance Analysis. 2018 Wiley-Blackwell.