WOODHEAD PUBLISHING SERIES IN CIVIL AND STRUCTURAL ENGINEERING

ADAPTING THE BUILT ENVIRONMENT FOR CLIMATE CHANGE

DESIGN PRINCIPLES FOR CLIMATE EMERGENCIES

Edited by
FERNANDO PACHECO-TORGAL
CLAES-GÖRAN GRANQVIST

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Woodhead Publishing Series in Civil and Structural Engineering

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Design Principles for Climate Emergencies

Edited by

Fernando Pacheco-Torgal
C-TAC Research Centre, University of Minho, Guimarães, Portugal

Claes-Göran Granqvist
Ångström Laboratory, Uppsala University, Sweden

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WOODHEAD
PUBLISHING
An imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

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ISBN: 978-0-323-95336-8 (print)
ISBN: 978-0-323-95337-5 (online)

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Publisher: Matthew Deans
Acquisitions Editor: Gwen Jones
Editorial Project Manager: Emily Thomson
Production Project Manager: Anitha Sivaraj
Cover Designer: Miles Hitchen

Typeset by MPS Limited, Chennai, India

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List of contributors

Iftekhar Ahmed Department of Architecture, BRAC University, Dhaka, Bangladesh

Shady Attia Department of Urban and Environmental Engineering, University of Liege, Liège, Belgium

İdil Ayçam Faculty of Architecture, Department of Architecture, Gazi University, Ankara, Turkey

João C. Azevedo Centro de Investigação de Montanha, Instituto Politécnico de Bragança, Bragança, Portugal

Cristina Baglivo Department of Engineering for Innovation (DII), University of Salento, Lecce, LE, Italy

Ivar Björnsson Division of Structural Engineering, Lund University, Lund, Sweden

Cristina S.C. Calheiros Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Novo Edifício do Terminal de Cruzeiros do Porto de Leixões, Matosinhos, Portugal; Institute of Science and Environment, University of St. Joseph, Macao, P.R. China

Faith Chan School of Geographical Sciences, Faculty of Science and Engineering, University of Nottingham, Ningbo, P.R. China; School of Geography, University of Leeds, Leeds, United Kingdom; Water@Leeds Research Institute, University of Leeds, Leeds, United Kingdom

Jinxin Chen State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, P.R. China

Ali Cheshmehzangi Department of Architecture and Built Environment, Faculty of Science and Engineering, The University of Nottingham, Ningbo, P.R. China; Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima, Japan

Innocent Chirisa Administration, Ezekiel Guti University, Bindura, Zimbabwe; Department of Urban & Regional Planning, University of the Free State, Bloemfontein, South Africa

Paolo Maria Congedo Department of Engineering for Innovation (DII), University of Salento, Lecce, LE, Italy

Rojina Ehsani Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

Rijalul Fikri Department of Civil Engineering, Syiah Kuala University, Banda Aceh, Indonesia

Davide Forcellini Department of Civil and Environmental Engineering, University of San Marino, Serravalle, San Marino

Alessandra Gandini TECNALIA, Basque Research and Technology Alliance (BRTA), Parque Tecnológico De Bizkaia, Derio, Spain

Leire Garmendia Mechanical Engineering Department, School of Engineering in Bilbao, University of the Basque Country (UPV/EHU), Bilbao, Spain

Dániel Honfi Transport Department, City of Stockholm, Stockholm, Sweden

Mingyang Hong Civil and Transportation School, South China University of Technology, Guangzhou, P.R. China

Junyi Hua School of International Affairs and Public Administration, Ocean University of China, Qingdao, P.R. China

Oskar Larsson Ivanov Division of Structural Engineering, Lund University, Lund, Sweden

Jonas Johansson Division of Risk Management and Societal Safety, Lund University, Lund, Sweden

Sara Kalantari Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

Alalea Kia Department of Civil and Environmental Engineering, Imperial College London, London, United Kingdom

Erik Kjellström Rossby Centre, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

Lei Li School of Geography, University of Nottingham, Nottingham, United Kingdom; School of Geographical Sciences, Faculty of Science and Engineering, University of Nottingham, Ningbo, P.R. China

Sheng Liu School of Architecture, Southwest Jiaotong University, Chengdu, P.R. China; Faculty of Architecture, The University of Hong Kong, Hong Kong, P.R. China

Michael V. Martello Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, United States

Domenico Mazzeo Department of Engineering for Innovation (DII), University of Salento, Lecce, LE, Italy; Department of Mechanical, Energy and Management Engineering (DIMEG), University of Calabria, Rende, CS, Italy

Thembani Moyo Department of Urban & Regional Planning, University of Johannesburg, Johannesburg, South Africa

Amro Nasr Division of Structural Engineering, Lund University, Lund, Sweden

Tariro Nyevera Development Governance Institute (DEGI), Harare, Zimbabwe

Fernando Pacheco-Torgal C-TAC Research Centre, University of Minho, Guimarães, Portugal

Pinar Pamukcu-Albers Department of Geography, University of Bonn, Bonn, Germany

Sofia I.A. Pereira Universidade Católica Portuguesa, CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Porto, Portugal

Laura Quesada-Ganuza Mechanical Engineering Department, School of Engineering in Bilbao, University of the Basque Country (UPV/EHU), Bilbao, Spain

Chao Ren Faculty of Architecture, The University of Hong Kong, Hong Kong, P.R. China

Pelin Sarıcıoğlu Faculty of Architecture, Department of Architecture, Gazi University, Ankara, Turkey

Fariborz M. Tehrani Department of Civil and Geomatics Engineering, California State University, Fresno, CA, United States

Francesca Ugolini Istituto per la Bioeconomia—Consiglio Nazionale delle Ricerche, Sesto Fiorentino, Italy

Andrew J. Whittle Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, United States

Jianguo Wu School of Life Sciences, School of Sustainability, Arizona State University, Tempe, AZ, United States

Tianyu Xie School of Civil Engineering, Southeast University, Nanjing, P.R. China

Shi Yin Faculty of Architecture, The University of Hong Kong, Hong Kong, P.R. China; School of Architecture, South China University of Technology, Guangzhou, P.R. China

Xinyu Zhao State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, P.R. China

Adriana Zuniga-Teran School of Geography, Development & Environment, Udall Center for Studies in Public Policy, University of Arizona, Tucson, AZ, United States

Resilient cooling of buildings to protect against heatwaves and power outages

11

Shady Attia
Department of Urban and Environmental Engineering, University of Liege, Liège, Belgium

11.1 Introduction

Resilience is a central feature of the United Nations (UN) Sustainability Development Goals (SDGs) and is reflected in a range of SDG targets (Jacob et al., 2018). According to the UN General Assembly Resolution 71/276 (United Nations, 2017), the term "resilience" describes "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform 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 through risk management."

The need for resilient building design and construction is urgent to anticipate climate change and disruptions caused by weather extremes, increasing carbon emissions, and resource depletion (Attia, 2020). Our well-being depends on reducing the carbon emissions in our built environment and other sectors (Attia et al., 2021). While solving the root-cause problem of climate change, we need to address its effects. Avoiding excessive temperatures induced by overheating is one of the most critical challenges that the building industry will face worldwide in the coming decades (Gupta et al., 2017; Kjellstrom et al., 2009).

Increasing electricity demand during heat stresses can lead to blackouts and grid failures. This can leave buildings out of thermal comfort range and threaten the lives of vulnerable people at risk, as happened during the 2003 Europe heatwave (De Bono et al., 2004). As building disruptions may have severe and long-term economic impacts, resilient building cooling solutions are an essential strategy to mitigate threats to occupants (Gupta & Kapsali, 2016). There is an urgent need for resilient cooling solutions in buildings to keep comfort despite extreme weather events due to climate change (Holzer & Cooper, 2019). Meanwhile, fuel-intensive mechanical cooling should be reduced to slow climate change (IEA, 2018). Greenhouse gas emissions from buildings' air conditioning stand at around 210−460 gigatonnes of carbon dioxide equivalent (GtCO2e) over the next four decades, based on 2018 levels (Anderson et al., 2020).

It is important to define buildings' resilient cooling to maintain indoor environmental quality against unexpected events, for example, extreme weather conditions,

Adapting the Built Environment for Climate Change. DOI: https://doi.org/10.1016/B978-0-323-95336-8.00014-7

heat waves, and power outages. However, the definition of resilience and resilient cooling is challenging and complex (Kelman et al., 2016). Research on resilience associated with human–nature interactions is still in an explorative stage with few practical methods for real-world applications (Carpenter & Folke, 2006; Liao, 2012).

This chapter presents the main concepts of resilience. It proposes a definition of resilient cooling of buildings based on the discussion taking place in the International Energy Agency (IEA)—Energy in Buildings and Communities Programme research project "Annex 80: Resilient Cooling of Buildings" (Holzer & Cooper, 2019). The essence of this chapter is to define resilience against overheating and power outages. It seeks to answer the following research questions:

1. What are the existing concepts of resilience in the built environment?
2. How to define resilient cooling of buildings?

This chapter presents a definition framework based on reviewing almost 90 studies of resilience, including RELi 2.0 Rating Guidelines for Resilient Design and Construction (USGBC, 2018). One of the challenges of this study is to define resilience on the building scale beyond what is present in literature, which mainly addresses the definition of resilience on an urban scale. This reinforces the importance of resilient cooling as an integral approach for building design and operation concerning comfort (including indoor environmental quality), carbon neutrality, and environmental friendliness (Attia et al., 2021).

11.2 Methodology

The qualitative research methodology relies on literature review, focus group discussions, and follow-up discussions with individuals.

11.2.1 Data collection

A literature review aimed to define resilience against different climate change-associated disruptions in the built environment worldwide. The publications included scientific journal chapters, books, and building rating systems. Our initial Scopus and Web of Science research resulted in almost 90 publications relevant to resilience and resilience criteria in the built environment. To examine the definitions of resilience and the associated resilience criteria, such as vulnerability, resistance, robustness, and recoverability, we surveyed resilience in ecology, resilience in engineering, and resilience in psychology.

11.2.2 Data processing

The content of the full text of every identified article was analyzed, and an analysis protocol and coding schema were developed to record its content attributes. The entire text of the full chapter was read multiple times as the coders (authors) completed the search for coding words. Coding is a way of indexing or categorizing the text to establish a framework for its themes (Gibbs, 2007). We used the framework method commonly used to manage and analyze qualitative data in health research (Gale et al., 2013; Lacey & Luff, 2001).

11.2.3 Development of a definition

For the definition development, we used the framework method, which is the most commonly used technique for managing and analyzing qualitative data in health research (Gale et al., 2013; Lacey & Luff, 2001). The framework method allows systematic analysis of the text data to produce highly structured outputs and summarized data. It can also compare and identify patterns, relevant themes, and contradictory data (Gale et al., 2013). We categorized the codes (resilience concepts) by theme. Our classification resulted in four concepts that define the resilient cooling of buildings.

11.2.4 Focus group and follow-up-discussions

Qualitative research is primarily a subjective approach to understanding human perceptions and judgments. However, it remains a solid exploratory scientific method if bias is avoided. The suggested definition was validated through focus group discussions to provide reliable and consistent results. Several validation measures were implemented, including member checking, memo logs, and peer examination following the work of Attia et al. (2021). The study validation allowed emphasizing credibility and strengthening the study’s relevance and results. Focus groups were convened during IEA Annex 80 first expert meeting in Vienna, Austria (October 21, 2019) and during its second expert meeting, held online (April 21, 2020). Each focus group comprised 15 people. The invited experts for the focus-group discussion represented the scientific and professional experts in the field of building performance assessment and comfort. An IEA Annex 80 participants list can be found on the Annex website (Holzer, 2019). The goal of the focus group discussions was to validate the suggested definition and main associated criteria.

Follow-up discussions with RELi steering committee members and UN resilience experts helped articulate and validated the framework and included the detailed elaboration of some criteria. The follow-up discussions took place between the first authors and some of the coauthors via teleconference and emails.

11.3 Results

11.3.1 Resilience against what?

One critical prerequisite for a comprehensive definition and assessment of resilience is identifying threats (shocks) or disruptions to the stability of these systems. An essential question to answer is “resilience against what?.”

As shown in Table 11.1, several types of disruptions or emergencies can lead to the systemic failure of buildings to be resilient—for example, air pollution, fires, and earthquakes. Disruptions are increasingly presented by unexpected phenomena outside or inside the building (De Wilde & Coley, 2012). The rate and pace of disturbances that the built environment faces have accelerated significantly over the past three decades (Bull-Kamanga et al., 2003). Understanding and identifying the phenomena that disrupt a building and threaten the well-being of its occupants is fundamental.

For our study, we decided to identify heat waves and power outages as the major disruptions that can influence occupant indoor environmental quality conditions on the building scale (Attia et al., 2021). This chapter is focused on the definition of resilient cooling of buildings as part of the IEA Annex 80 activities that aim to define resilience. Crawley (2008) identified heat waves as the significant climate change disruption in buildings. Baniassadi et al. (2018) identified the frequency and duration of power outages as a significant cause of disruption for buildings in the near future. Both studies confirmed that the increase of mean outdoor temperatures and the frequent and intensive nature of heatwaves disrupt power and degrade comfort.

Disruptions are shocks or events that have an origin, nature, incidence, scale, and duration. Therefore we define disruptions in buildings as shocks that degrade the indoor environment and require resilient cooling strategies and technologies to maintain it (De Wilde & Coley, 2012).

11.3.2 Resilience: at which scale? And for how long?

The resilience of a system cannot be studied without examining the scale of the system and the relation between the shock cause and its effect(s). Resilient systems function through the interaction of complex processes operating at different scales and times frames (Bull-Kamanga et al., 2003). Therefore it is essential to characterize the scale of the system that is expected to be resilient in a time-bound way. The definition of resilience should always reflect whether the disturbance affects the performance or operation of a single building element, building service, or the entire building (Crawley, 2008). As shown in Fig. 11.1, the definition of resilience should always characterize the resilience to disturbance of a system concerning its scale within a specific time frame for the disturbance.

For our study, we define heat waves and power outages as the primary disruptive events addressed by resilient cooling for buildings. Our proposed definition considers the indoor environmental conditions on the building scale for long periods. Climate scenarios represent historical and future outdoor conditions and consider short-term and long-term heat waves. Resilience in the building engineering field is strongly associated with long-term climate projections that encompass the increase in the average temperature due to a global warming effect and a further temperature rise due to the urban heat island effect (Palme et al., 2017).

Defining and identifying disruptions and specifying their associated events that impact healthy and comfortable buildings is the first step to determining a building's resilience. As shown in Fig. 11.1, heat waves and power outages are events that may impact the thermal conditions in buildings. The identification of heatwave

Table 11.1 Different types of disruptions affecting the built environment.

	Description
Air Pollution	- *Outdoor air pollution* refers to the air pollution experienced by populations living in and around urban and rural areas. Air pollution derives from poor combustion of fossil or biomass fuels (e.g., exhaust fumes from cars, furnaces, or wood stoves) or wildfires. Buildings require efficient air filters and ventilation systems that mitigate the impact of air pollution.
Fire	- *Wildfires* are sweeping and destructive conflagrations, especially in a wilderness or a rural area, that cause significant damage. Most building codes address common fire hazards with mandatory fire-resistant stairwells, fire-resistant building materials, and proper escape methods.
Earthquakes	- *Earthquakes* are the most common disruptions covered in all building codes. Trembling of the ground is caused by the passage of seismic waves through the earth's rocks. This natural disaster can damage a building by knocking it off its foundations and harming the occupants. Seismic testing should be used on components of buildings to determine their resilience to earthquakes.
Wind storms hurricanes	- *Hurricanes* have the potential to harm lives and property via storm surge, heavy rain, or snow, causing flooding or road impassibility, lightning, wildfires, and vertical wind shear.
Flooding	- *Flooding* is the inundation of land or property in a built environment, particularly in more densely populated areas, caused by rainfall overwhelming the capacity of drainage systems, such as storm sewers.
Heatwaves	- *Heatwaves* are a period of excessively hot weather, which may be accompanied by high humidity. They cause overheating in the building and intensify the urban heat island effect. This event can potentially risk the health and lives of occupants if no measures are taken.
Power outages	- *Power outages* and blackouts are common occurrences that can be caused by natural disasters cited earlier, like floods or hurricanes. It can lead to overheating in buildings when air conditioners do not operate.
Water shortages	- *Water shortage* is the lack of freshwater resources to meet water demand. Lack of water significantly impacts irrigation and urban use, degrading food security, public health, and overall stability.
Pandemic	- *Pandemics* can impact the built environment of societies is how spatial and social aspects are intertwined to constitute everyday lives mutually. Minimizing the risk of disease spread in buildings during active outbreaks starts with keeping people out of them. For those who occupy a building, increasing the ventilation and filtration of the inside air is essential.

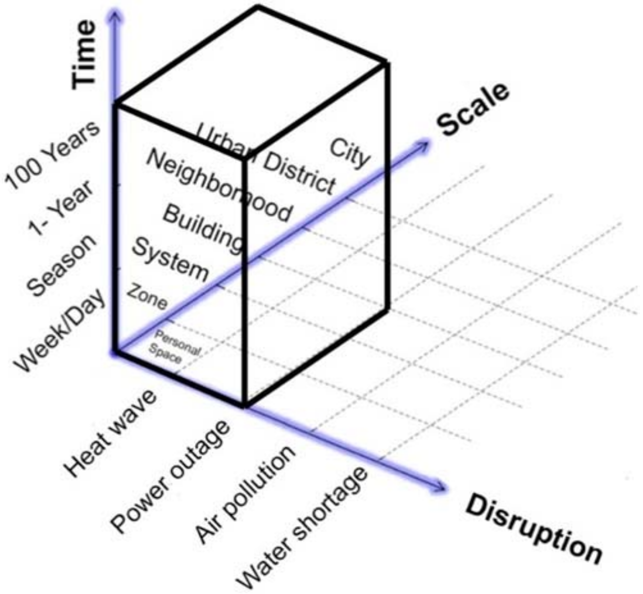


Figure 11.1 Time, Scale and Disruption as boundary conditions for systems' resilience.

events is based on their intensity, duration, and frequency coupled with power outages (Laouadi et al., 2020). A building with a resistant cooling design (strategy) is expected to withstand short and extensive heat waves. A building with a robust cooling design can withstand short, intense, and prolonged lengthy heatwaves. The performance of a building with a resilient cooling design could surpass that of a robust building by reacting to power outages and longer intensive heat waves. The literature review confirms that resilience must be associated with a response to system failure (Gale et al., 2013). A system is robust when it can continue functioning in the presence of internal and external challenges without a system failure. However, a system is resilient when it can adapt to internal and external challenges by changing its method of operations while continuing to function. The ability of the building to recover after disruptive events is a fundamental feature of resilience. Therefore the ability to model the occurrence and consequences of discrete heatwave events is crucial to preparing the building for the response.

The interviewed experts agreed that climate change should be defined as a long-term disruptive event and that heatwaves and power outages should be designated short-term disruptive events. Based on our literature review and following Fig. 11.2, we distinguish four major events categories that can challenge resilient cooling (Laouadi et al., 2020):

Event 1: Observed and future extreme weather conditions (extended, spanning years).
Event 2: Seasonal extreme weather conditions (long, spanning months).
Event 3: Short extreme weather conditions (short, spanning days).
Event 4: Power outages (spanning hours).

Across the literature, several studies identified extended and long climate change-associated temperature increase events (events 1 and 2) (Hamdy et al., 2017; Moazami et al., 2019). Other studies investigated the impact of short-term heat waves and power outages on thermal conditions and cooling systems' resilience (MacKenzie & Barker, 2012; Sailor, 2014). For example, the RELi rating system requires thermal safety during emergencies (events 3 and 4) by maintaining indoor air temperature at or below outdoor air temperature for up to 7 days (Gale et al., 2013). Schünemann et al. (2022) investigated the heat resilience (overheating intensity) and energy efficiency (cooling demand) of two representative apartment buildings in Germany and Korea. Through thermal zoning and modeling, designers need to demonstrate that the building will maintain safe temperatures during a blackout that lasts four days. During a power outage, buildings must provide backup power to satisfy critical loads for 36 hours.

We define four major event categories that need to be tested and addressed in any resilience assessment for comfort in buildings. The following section provides a further detailed explanation for Fig. 11.1 associated with Fig. 11.2.

11.3.3 Definition of "resilient cooling for buildings"

Resilient cooling is used to denote low-energy and low-carbon cooling solutions that strengthen the ability of individuals and our community as a whole to withstand and also prevent the thermal and other impacts of changes in global and local climates—particularly concerning rising outdoor temperatures and the increasing frequency and severity of heatwaves (Burman et al., 2014).

Resilient cooling for buildings is a concept that was not approached thoroughly in previous studies. Therefore we developed the following definition based on the

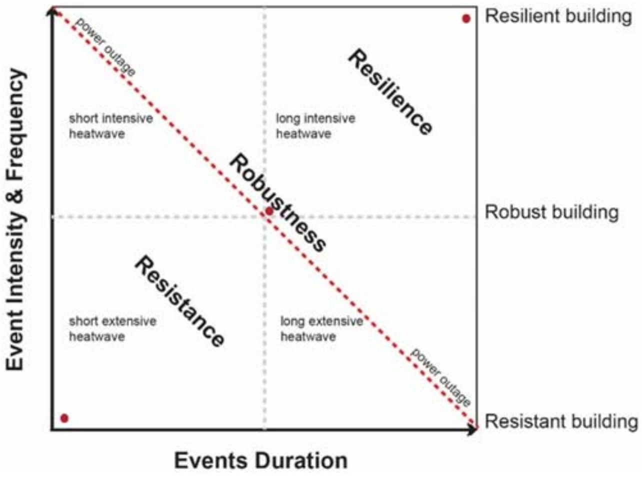


Figure 11.2 The difference between resistance, robustness and resilience in relation to disruption events intensity and frequency.

literature review and validated it through the focus group discussion with members of IEA Annex 80:

The cooling of a building is resilient when the capacity of the cooling system integrated into the building allows it to withstand or recover from disturbances due to disruptions, including heat waves and power outages, and to adopt the appropriate strategies after failure (robustness) to mitigate degradation of building performance (deterioration of indoor environmental quality and /or increased need for space cooling energy (recoverability).

Resilience is a process that involves several criteria, including vulnerability, resistance, robustness, and recoverability (Martin & Sunley, 2015). Therefore we include those four criteria in the definition formulation shown in Fig. 11.1. The vulnerability involves the sensitivity or propensity of the building's comfort conditions to different disruptions. It is vital to define disruptions at this stage, as discussed in Section 3.1 (see Figs. 11.1 and 11.2).

A resilient building must be conceived based on a vulnerability assessment that considers future climate scenarios and prepares the building system, including occupants, to adapt against failures. The vulnerability assessment should test the building's performance against long-term disruptions using average weather conditions, extreme weather conditions, future weather conditions, and worst future weather conditions. It should also test the building against short-term disruptions, including brief heat waves and power outages. A vulnerability assessment stage should be part of the design process. A building cooling system is prepared for different disruption scenarios engaging different thermal conditions.

The building cooling system should withstand short-term and long-term disruptive events. As shown in Fig. 11.3, resistance involves the ability and the depth of reaction to the shock. Under disruptive events, the building may use performance dropbacks to achieve the predefined minimal thermal conditions. After the failure of the building cooling system, the building's resilience process moves to the most

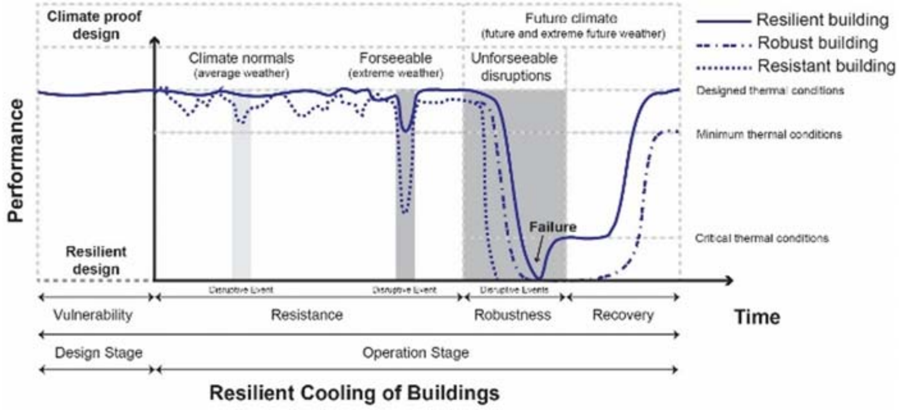


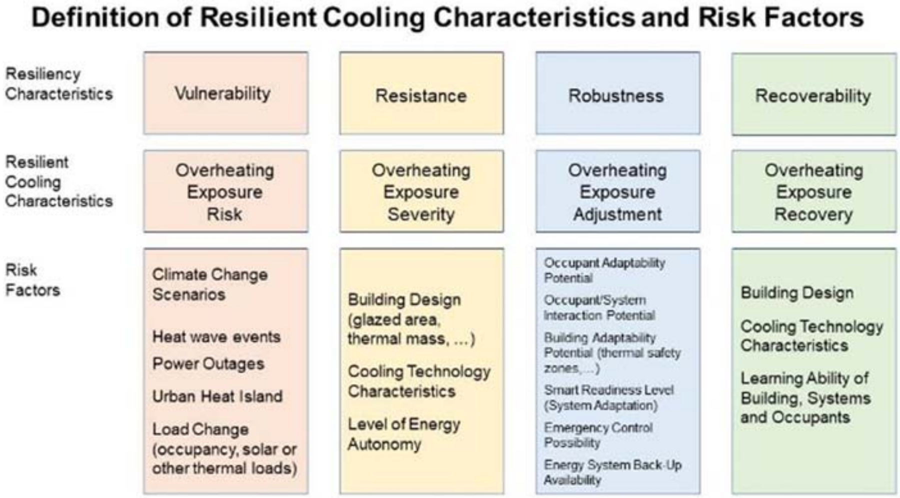
Figure 11.3 The buildings resilience timeline and performance (for higher resolution, see Attia, 2020).

crucial stage—robustness, meaning reaction to failure. Robustness requires the building to be prepared to survive an otherwise-fatal shock by adapting its performance. The survivability of the system relies on its ability to ensure the critical thermal conditions to maintain the functional activities of occupants during a crisis. As shown in Fig. 11.3, a robust building will first fail and then adapt its performance conditions to meet critical or minimum thermal requirements to achieve a degree of survivability for occupants depending on the vulnerability assessment decisions made during design. The significant distinction between a resistant building system and a robust building system is that the latter is prepared to adapt based on a backup plan and ecosystem. Robustness involves how the building, including its services and occupants, adjusts and adapts to shocks.

The final stage of resilience involves the recoverability of the system. Recoverability consists of the extent and nature of occupants and the building's services to recover and returns to its equilibrium state and its speed to come back. As shown in Fig. 11.3, recovering has a duration, performance, and learnability. The necessary speed for recovery and the recovery performance curve should be planned during the vulnerability assessment stage. The ability of the users, buildings, and systems to learn from the event is an integral part of this stage.

While the diagram in Fig. 11.3 is linear, the resilience process is cyclic and iterative. Resilient cooling of buildings is a continuous process involving the commissioning and retro-commissioning of building elements and systems over the building's life cycle. It also includes the continuous education of occupants and the preparation for adaptive measures during unforeseeable disruptions.

Fig. 11.4 provides a complementary definition framework that includes the main resilience criteria. It presents an example of the factors that influence building



Resiliency Characteristics	Vulnerability	Resistance	Robustness	Recoverability
Resilient Cooling Characteristics	Overheating Exposure Risk	Overheating Exposure Severity	Overheating Exposure Adjustment	Overheating Exposure Recovery
Risk Factors	Climate Change Scenarios Heat wave events Power Outages Urban Heat Island Load Change (occupancy, solar or other thermal loads)	Building Design (glazed area, thermal mass, ...) Cooling Technology Characteristics Level of Energy Autonomy	Occupant Adaptability Potential Occupant/System Interaction Potential Building Adaptability Potential (thermal safety zones,...) Smart Readiness Level (System Adaptation) Emergency Control Possibility Energy System Back-Up Availability	Building Design Cooling Technology Characteristics Learning Ability of Building, Systems and Occupants

Figure 11.4 Influencing factors of resilient cooling of buildings (for higher resolution, see Attia, 2020).

cooling performance under the four resilience criteria. Depending on the overheating definition and exposure risk, a resilient cooling design for buildings assures that the designed indoor environmental conditions are secured before the disruption. The risk factors should be identified during the design stage to assess vulnerability. Examples of risk factors include climate change scenarios, heat waves combined with power outages, or urban heat island effects. As shown in Fig. 11.4, the resistance stage depends mainly on the building's design features and technologies and their ability to keep the building performing under severe overheating exposure until reaching failure. The failure is the essential disruption to start the third stage of resilience, namely robustness. The robustness of the cooling system the building must adapt to cover the critical thermal conditions temporarily until reaching the recovery stage. The ability to respond, in an adaptive way, that implements fundamental changes to the original thermal conditions involved occupants and systems adaptability. The energy system backup and an emergency control possibility are part of the building's robustness. This is finally followed by a recovery stage and a shift in the building performance to achieve before designed thermal conditions that adapt to the normal.

11.4 Discussion

The review of the main concepts of resilient cooling for buildings and the proposal for a definition and assessment framework indicates the complexity of the idea. We found varying and inconsistent definitions of resilience in the context of building comfort and in the context of the overall built environment. The following sections discuss possible questions that we answered in this study.

1. What are the existing concepts of resilience?
2. How to define resilient cooling for buildings?

Few studies and case studies succeeded in defining resilience and applying its principles on a building scale. Across our review, we found some studies that focus mainly on robustness as a proxy for resilience (Homaei & Hamdy, 2020, 2021; Kotireddy et al., 2018; Miller et al., 2021). However, none of those reviewed studies embraced a multicriteria approach for resilience that involves vulnerability, resistance, robustness, and recoverability. Therefore based on our literature review and focus group discussions, this study's suggested definition and framework are a step forward. The following recommendations can be helpful for designers and building operators that seek to achieve resilient cooling of buildings in a holistic way:

1. Any definition of resilience must be based on identifying a specific shock or disruption. In the case of resilient cooling of buildings, heat waves and power outages are considered the main shocks (extreme events). Designers should prepare buildings against those shocks.

2. Any definition of resilience should specify and distinguish, at the same time, the resistance and robustness conditions against heat waves and power outage events. The resistance period involves the building's ability to resist shock(s) with the same preshock operation conditions. However, robustness requires failure and adaptation after failure. The robustness mechanism involves building users and building systems adaptation and their ability to adjust after a shock.
3. Thus the definition of resilient cooling for buildings involves four critical criteria, mainly vulnerability (preparation), resistance (absorption), robustness (adaptation after failure), and recovery (remedy). The building design, construction, and operation processes should address these criteria.
4. Resilient and passive cooling design is an urgent requirement for future-proof buildings (Silva et al., 2022). Weather extremes must be anticipated to assume well-being. The choice of comfort models is elementary in preparing buildings. Resilient cooling design involves the combination of passive and active cooling design measures (Zeng et al., 2022), on-site renewable production, and coupling to storage capacities. Our suggested definition for resilient cooling of buildings can help to develop future resilience performance indicators that account for the impacts of global warming for long and short assessment periods. This can allow comparing the carbon emissions and primary energy use at different stages of the building life stages. As part of the activities of IEA—Annex 80, there is a need to assess the performance of conventional and advanced cooling technologies. Without a multistage definition, it will be challenging to develop universal indicators that assess the active and passive cooling technologies listed above.
5. Building operation systems and building management systems will play a significant role in applying the adaptation strategies and risk mitigation plans in collaboration with buildings users. HVAC systems and envelope features are a prime target for real-time optimization for resilient cooling. Different dynamic control strategies with predictive algorithms should be embedded in building operation systems using a deeply coupled network of sensors. The smart readiness of buildings is part of resilience because it considers that buildings must play an active role within the context of an intelligent energy system (Märzinger & Österreicher, 2019).
6. Resilience is a process, and its criteria should be addressed following a circular, iterative approach. Extracting learned lessons and integrating user experience during shocks is essential to increase the emergency learnability and feed the preparedness loop.

11.5 Conclusion

A definition of resilient cooling for buildings is developed and discussed in this chapter as part of the IEA Annex 80 research activities. The definition's main concepts and criteria are based on qualitative research methods. This chapter presents a set of recommendations to adopt the definition in practice and research. Future research should build on our findings and create more consistent frameworks (Rahif et al., 2022) with useful quantifiable indicators (Zhang et al., 2021), quantitative metrics, and performance threshold limits. Additional definitions of overheating and modeling of overheating events are required for different building types and climates. The research should be extended to identify benchmarks and case studies (Sun et al., 2021) with reference values and threshold ranges and seek tools and reporting mechanisms for the resilient cooling of buildings. The suggested framework should evolve as research and experience build a greater understanding of resilient and sustainable buildings.

Acknowledgments

The Walloon Region partially funded this research under the call "Actions de Recherche Concertées 2019 (ARC)" and the project OCCuPANt, on the Impacts Of Climate Change on the indoor environmental and energy PerformAnce of buildiNgs in Belgium during summer. The authors would like to gratefully acknowledge the Walloon Region and Liege University for funding.

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Claes-Göran Granqvist is a senior professor of solid-state physics at the Ångström Laboratory of Uppsala University in Sweden. He is an active member of The Royal Swedish Academy of Sciences and The Royal Swedish Academy of Engineering Sciences.

ISBN 978-0-323-95336-8

9 780323 953368

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