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Implementing resilience in sustainable building design: Testing selected resilience criteria in a case study

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Abstract. Climate change is causing unprecedented changes in precipitation, extreme temperatures, and weather-related threats. Without effective intervention, these changes are expected to escalate in the coming years, potentially causing substantial damage to buildings. Paradoxically, the buildings themselves possess the potential to both exacerbate and alleviate climate change. To achieve a balance, the design of the building must adhere to minimal sustainability standards, taking into account resilience. Popular building rating systems, currently skewed towards sustainability, often neglect resilience principles. This paper aims to assess five selected resilience criteria from a new module incorporated into an existing building certification system, SBToolCZ. Validation occurs through a multi-residential building case study in Prague, evaluating the effectiveness of the criteria in terms of feasibility, accuracy, consistency, and time/data requirements. The results of this criteria test determine the clarity, achievability, and informativeness of the selected criteria. If gathering information and meeting benchmarks within a specific time frame proves challenging, adjustments to the criteria may be necessary for attainability and specificity. Integrating resilience features into sustainability rating systems, typically used in the early stages of design, can encourage designers to incorporate resilience into their projects. This proactive approach could lead to long-term reductions in environmental, social, and economic impacts, especially during weather-related hazards.

Keywords: resilience design, rating systems, resilience assessment, survivability, preparedness, risk assessment.

1. Introduction

A changing pattern of precipitation, extreme temperatures, and other weather-related hazards is becoming recurrent evidence of climate change, reaching unprecedented levels [1]. Without effective actions, these changes are expected to intensify in the coming years, with more serious global consequences [2,3]. Extreme weather events can seriously impact the built environment which, at the same time, can become a valuable contributor to mitigating climate change, by remarkably reducing GHG emissions, and implementing an adaptive strategy by increasing the resilience [4].

Building design should adhere to minimum sustainability standards while also considering the resilience to future threats. In recent years, there has been a huge debate about these two concepts in the construction industry: Do they share a common ground? [5]

Across global regions, including Europe, numerous public authorities have formulated adaptation plans, yet only a limited number have been implemented [6,7]. The primary factor that hinders rapid implementation is the absence of an integrated framework and robust digital planning tools capable of seamlessly incorporating resilience and sustainability indicators in the evaluation of design and renovation measures [8].

2. Background

Existing building rating systems, such as Leadership in Energy and Environmental Design (LEED) or Building Research Establishment Environmental Assessment Methodology (BREEAM), are primarily focused on sustainability assessment with less attention paid to resilience principles [8]. Therefore, some studies (e.g., Roostaie et al. [9] and Felicioni et al. [5]) are exploring the opportunity to embed resilience principles within already existing rating systems to foster their adoption by architects, designers and planners who already use these tools in shaping the built environment of the next decades.

The purpose of this paper is to test the selected resilience criteria developed as part of a resilience module, which could be implemented into already existing sustainability rating systems, and to validate them in a building case study. This work is part of a 4-year PhD project focused on finding the balance between sustainability and resilience in buildings through the implementation of a set of resilience criteria and indicators in the Czech national building rating system SBToolCZ [10], which has been chosen for this research as a case study tool. This work aims to highlight the efficacy of the use of criteria to assess resilience by determining their feasibility, precision, and consistency, as well as the amount of time and data needed to complete them.

3. Materials and Methods

The research began with an analysis of what has already been addressed by SBToolCZ [10] in terms of resilience, in particular in the multi-residential building version of the system that comprises 45 criteria divided into environmental, economic, societal and site-related groups [8]. After completing this phase, a resilience module consisting of five macro-categories was drafted considering what already existing resilience assessment tools for buildings, taking as a starting point the outcome of previous work [5].

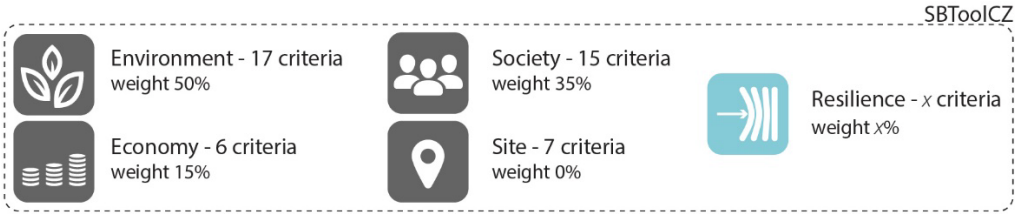

Figure 1. Overview of SBToolCZ categories plus the additional new resilience module [8].

Hence, Figure 2 shows the linear diagram of this process, starting from gathering information from the international background to the validation of the criteria in case studies (the scope of the article) and the final implementation of the resilience module in the rating system.

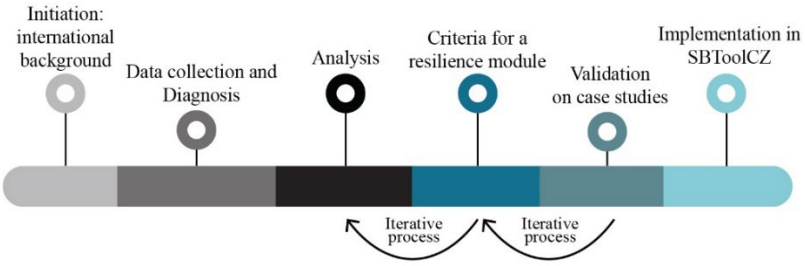

Figure 2. Linear diagram for the design of the resilience module.

The module's effectiveness must first be evaluated and validated by building case studies to identify any potential weaknesses. Indeed, the development of criteria is an iterative process that is influenced by the results of the validation of case studies – see Figure 2. Therefore, these criteria will be redefined and properly adjusted to ensure that they accurately reflect the desired result. The accuracy, reliability, and validity of the values obtained from the five criteria are considered part of the investigation.

3.1 Resilience calculation tool

As part of the PhD research, a method has been developed to develop a new criteria module focused on resilience in multi-residential buildings. Subsequently, this method was adapted into an MS Excel tool for enhanced usability and convenience. This adaptation aligns with the overarching approach of the SBTool rating systems, which rely on manuals where the method of assessment is described and can then be used to assess for building case studies using MS Excel tools (e.g., [11,12].

The Resilience calculation tool allows for the easy input of data, as well as the ability to quickly analyse and present the results. Furthermore, Excel is widely available, making it an accessible solution for many users.

Indeed, all criterion sheets are converted into dedicated Excel sheets, one for each criterion, containing information concerning the name of the criterion, its purpose, a brief description of its benefits if achieved, the indicator – qualitative or quantitative – and the evaluation modules. Each module consists of a list of items to which amount of points are assigned if implemented successfully.

Depending on the significance that the item would have to the building in terms of safety, the number of points per item may vary. Each item, and therefore its points, may be simply summed up in some cases; in others, a single item may be selected from the list, in which case the final score of the module is determined by the number of points of that item.

Following the calculation of each module, based on the method of evaluating the criterion, which is usually a sum of modules' scores, the final value of the criteria can then be normalised in a range of 0 (minimum number of points achievable from the item list) to 10 (maximum number of points achievable from the item list) by linear interpolation. The final results will then be multiplied by the weight assigned to each criterion. A panel of experts in the field of building and urban resilience expressed a proportion preference according to the pre-set module structure.

3.2 Resilience Criteria

The criteria of the new add-on module include both qualitative and quantitative indicators. These evaluation criteria are formulated as interrogative statements, necessitating the corresponding responses and supporting documentation. Illustrative examples of evaluation criteria include:

- Yes/No: Verification of the implementation of a specific action or attainment of a particular outcome (e.g., incorporation of antiflood measures in the project).
- Target: Specification of a particular outcome with identifiable and quantifiable benchmarks (e.g., maintenance of indoor temperature below 27 degrees Celsius).
- Accomplishment: Executing a process with a broad or unspecified outcome (e.g., completion of a rapid site assessment).

Each criterion consists of a list of items to which points are assigned if implemented successfully. Due to the point-based nature of the system, the number of points awarded for the achievement of an item depends on the level of safety that it would enhance within a building. The higher the level of safety, the more points it will receive. A brief description of the five representative criteria selected for this work is reported in Table 1.

Table 1. Five resilience criteria examined in this work.

Criterion	Category	Indicator	Typology
Site risk assessment	Preparedness	Likelihood of hazards to happen	Qualitative
Passive survivability	Redundancy	The absence / presence of passive systems for heating, cooling, ventilation, and lighting.	Qualitative/ Quantitative
Heat-wave-resistant building envelope and structure	Robustness	Readyness in terms of anti-extreme heat solutions implemented	Qualitative
Emergency power supply	Response Capability	Presence/absence of emergency power supply	Qualitative
Access to useful shared spaces	Community Cohesion	Number of available useful community areas	Quantitative

Each criterion is assigned to a distinct category within the module. The module comprises five different categories; each criterion is designed to elevate specific resilience levels corresponding to the category. For example, in the "Robustness" category, various criteria focus on fortifying the building in terms of proper design solutions and suitable materials to withstand climate-related hazards. In the next sub-chapters, a brief description of each criterion considered for this work.

3.2.1 Site Risk Assessment

The objective of this criterion is to identify the probability, intensity and time scale of potential hazards, such as floods, heavy rainfall, storms, heatwaves, subsidence, and drought, specific to a given location. These are the the hazards that are most likely to affect buildings, according to Appendix A of the EU Taxonomy [13].

Indeed, a fundamental lesson derived from the concept of resilience underscores its profound connection to the local context and regional dynamics. This highlights the need to follow an approach focused on the most relevant hazards to the specific location where a building is planned, rather than applying a uniform approach. It should be noted that a European climate risk assessment is currently being prepared and is scheduled to be completed in 2024 [14].

However, in initiating the creation of a site risk assessment, the expertise provided by the C40 Cities Climate Leadership Group has been considered. This approach employs a methodology that is accessible even to non-experts in the field, making it more convenient for architects or designers [15].

3.2.2 Passive Survivability

The purpose of this criterion is to ensure that a building can maintain crucial life support conditions during prolonged interruptions in power, heating fuel or water supply. This is achieved by incorporating passive survivability solutions during the design phase. The criterion consists of four distinct modules: passive solar heating, passive cooling, passive lighting, and thermal safety temperature.

The initial three modules primarily involve design strategies integrated into the building layout. For instance, daylighting spaces from multiple sides enhance even lighting, reduces glare around people and

objects. Additionally, solar-facing clerestory and sloped skylights contribute to increased privacy, shading of the solar facade, heating of deeper spaces, and spaces along other facades. This design approach helps to avoid direct sunlight on people and furniture, mitigating glare [16,17].

The last module focusses on determining the maximum daily calculated indoor air temperature in the hottest habitable room of the building or apartment. This calculation follows ISO 7730:2005 - Ergonomics of the thermal environment.

To meet the criterion, specific documentation must be provided, verifying that the building possesses passive survivability to some extent in the absence of power. For example, a report detailing calculations and drawings could serve as evidence.

3.2.3 Heat-wave-resistant building envelope and structure

The purpose of this criterion is to minimise extreme heat discomfort by ensuring the safety of the building and the well-being of users. Table 2 describes the hazard. As part of the Robustness category, this criterion is closely tied to the results of the Site Risk Assessment, as it identifies the most likely hazards that should be addressed during the early design stage.

Table 2. Overview of the hazard. Source: [18].

Heat wave	Extended period of exceptionally high temperatures in a specific location compared to the average
Origins	Trapped air circulation, high pressure system, heated, stagnant air
Issues	Lack of awareness, outdoor work-related tasks/jobs, health issues
Damaging components	High heat, extreme exertion on body, drought conditions

The proposed solutions to be implemented include the utilisation of light-coloured and reflective materials, green roofs, and vegetation on the sun-exposed sides to shade the building and mitigate its susceptibility to extreme heat. To address specific vulnerabilities, recommendations are outlined for various building components. For instance, to enhance openings, suggestions involve implementing sufficient insulation for windows, doors, and walls to impede the building's heat gain, along with the incorporation of solar shading for windows. Regarding building services, recommendations include the adoption of passive cooling and ventilation techniques and/or integration with a district cooling system to optimise energy efficiency [19,20].

Meeting this criterion requires the submission of documentation that highlights the solutions implemented. Since extreme heat protection measures are typically not included in standard project documentation, they must be explicitly specified in the project documentation on resilience assessment.

3.2.4 Emergency power supply

The purpose of this criterion is to validate the presence of sufficient emergency power to sustain crucial loads identified by the design team as essential for the building's operation for a minimum of a 96-hour period (four days) during a disruptive event. The criterion includes a list of potential power demands that the building may require, and it is imperative to include at least three of them in the building design to earn points in this category.

To successfully fulfil this criterion, documentation, including drawings illustrating backup power equipment, product data sheets clearly indicating power production capacity, and a roster of critical loads supported by the backup power system. Furthermore, calculations for the electricity demand in kWh based on the critical loads and their duration must be included.

3.2.5 Access to useful shared spaces

The purpose of this criterion is to provide building users with services and shared areas, fostering stronger social networks and connections among neighbours. This approach not only enhances material and spatial efficiency but also establishes meaningful social interactions.

The effectiveness of this strategy is exemplified by the residential complex Gleis 21 in Vienna (AT) [21]. A significant aspect of the Gleis 21 concept is its open ground floor, accessible to everyone in the neighbourhood. This design is intentionally permeable, creating a link between the promenade and the park. This open space functions as an extension of urban space and features a multifunctional room equipped for use as a theatre, cinema, or seminar room.

To meet this criterion, documentation with detailed descriptions and illustrations of shared spaces must be provided. The drawings should serve as proof of the incorporation of these communal areas, highlighting their role in improving social connectivity within the building.

3.3 Case study

These criteria were used in the analysis of a specific case study involving a multi-residential building located in Prague [CZ], known as X-LOFT [22] – Figure 3 and Figure 4. Chosen among a range of possible candidates, this building is particularly suitable for the scope of the study, already silver certified according to SBToolCZ [10] with the opportunity to explore if it also matches with resilient criteria. This choice was made to investigate whether a building certified as sustainable could also be considered, to some extent, as resilient. Furthermore, it aligns with the implementation of the resilience module as the initial step in the Czech national sustainable tool.

Figure 3. Photo of the building.

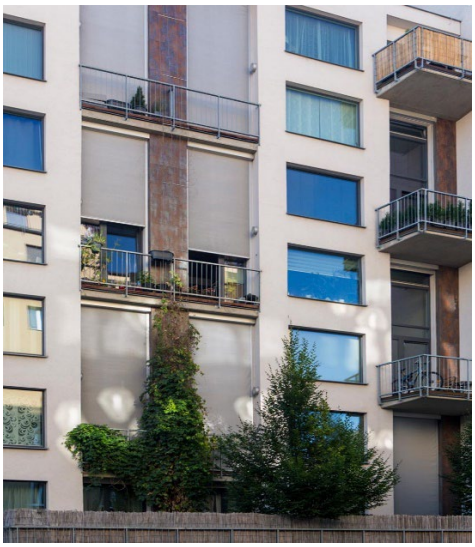

Figure 4. Photo of the building – focus on the sun-shade blinds.

Nevertheless, it is important to acknowledge that evaluating resilience based on the aforementioned five criteria is conducted on an already constructed building. Ideally, the module's original intent is to address resilience enhancements during the early design phase of the project, enabling adjustments to be made to the design to incorporate as many resilience-boosting solutions as possible.

The case study is located in an east-west direction within a former "brownfield" space, a traditional Prague suburb. The area was originally home to the Libeň brewery and now features a mix of residential apartment blocks from the 20th century, industrial structures, and a small suburban colony – Table 3 lists the main information of the building.

Table 3. Main information of the building case study.

Criterion	Category
Location	U Libeňského pivovaru, Prague
Year of construction	2011-2013
Residential unit	48
Floor	2 underground floors + 4 double-height floors
Total internal usable floor area in heated zones	4078 m^2
Annual energy consumption	81.2 kW/m2/y
Sustainability features	Solar collectors, reuse of harvested rainwater, accessibility to public transport

The building adapts to its surroundings by bridging the gap between industrial and residential structures and integrating elements from both typologies into its design. This integration is particularly evident on the facade, which features a mix of geometrically precise sections reminiscent of industrial architecture alongside more traditionally arranged windows. The roof design, inspired by 20th-century industrial architecture, further emphasises this integration while also accommodating the building's structural system.

The apartments are designed with a higher ceiling height of 4.9 meters to maximise natural light and sunlight. To optimise space utilization, apartment floor plans overlap toward the facade, allowing for expanded living areas.

Structurally, the building comprises two underground floors that house garages, cellars and technical facilities, while above ground it consists of four floors with 48 apartments and an attic. Each floor typologically follows a three-section layout, with a central vertical communication area flanked by basic housing units. These units feature spacious living areas with expansive glazed facades, while the layout broadens toward the facade to enhance the living space. Additionally, the upper floors benefit from roof terraces, and those on the ground floor facing east have direct access to front gardens.

The vertical load-bearing structures use a set of arrangement of lamellar reinforced concrete walls, rotated by 10° between apartment units on each floor. This rotation pattern is reversed on consecutive floors and influences the layout of windows. The facade itself serves as a heavy load-bearing perimeter shell.

In terms of sustainability, features such as triple glazing, solar collectors, rainwater retention for greenery irrigation, and the option for air recovery systems in apartment units are incorporated to meet the SBToolCZ evaluation criteria.

4. Results and Discussion

Criteria testing involved evaluating their clarity, the sufficiency of providing information, and the time invested in successfully obtaining the required material to meet the criteria and, subsequently, achieve the objective. If the collection of information and the meeting of the benchmarks prove impractical due to time constraints or insufficient data, the criterion may need to be rephrased to enhance achievability and specificity. The resilience module should ideally not require excessive time from a potential evaluator, as sustainability rating systems typically serve as guidelines for informed decision-making during the design stage.

However, since the building case study is an existing building and not an ongoing design, some criteria remained unmet because the building was not originally designed with resilience in mind in those specific aspects. Indeed, the module aims to be incorporated into an existing sustainability rating system tailored for new multi-residential buildings. Table 4 summarises the information necessary to meet each criterion.

Table 4. List of criteria and relative information needed.

Criterion	Information needed
Site risk assessment	Historical and future data
Passive survivability	Building drawings
Heat-wave-resistant building envelope and structure	Building drawings
Fundamental access to basic supply	Building drawings and technical supply
Access to useful shared spaces	Building drawings

4.1 Site Risk Assessment

To assess this criterion, a thorough analysis of historical and future data has been carried out to identify the most probable risks for the designated area. Specifically, databases and maps were consulted for this location, which included research on past occurrences of heatwaves, droughts, storms, and floods. This involved reviewing historical climate patterns and projecting future trends under various scenarios. The use of hazards maps has proven to be particularly effective in connecting climate science with areas susceptible to vulnerabilities.

Specifically, an examination was carried out on maps related to the city of Prague. A satellite image captured by NASA's ECOSTRESS instrument, which recorded ground temperatures in June 2022, revealed the hottest surfaces. The image also clearly depicted the cooling influence of parks, vegetation, and water [23]. However, the X-LOFT building case study is located in an area where the surface temperature ranges between 42 and 44 degrees Celsius. This underscores the intense hazard posed by extreme heat in that location, which emphasises the necessity for the implementation of adaptation measures.

The city has faced significant exposure from river floods, with a major flood occurring in 2002, requiring an expenditure of over 5 million CZK for the installation of flood shields (both fixed and mobile). The X-LOFT area remains unaffected by this hazard, as evidenced by the images of Bezpecnost.praha.eu [24]. These images even illustrate the floodplain in the event of a 100-year flood, confirming the absence of this threat in the vicinity of X-LOFT.

Ultimately, the new Excel tool designed for the resilience module allows the completion of the dedicated sheet for the Site Risk Assessment criterion. Points are assigned based on the achieved items, and these points are subsequently interpolated on a scale of 0-10. The resulting score reflects the total of points obtained for that criterion. In this particular case, since there has been no workshop with specific stakeholders to identify potential location hazards, only one item has been achieved, leading to the assignment of one point. Consequently, on a scale of 0 to 10, three points have been designated for this specific criterion – Figure 6.

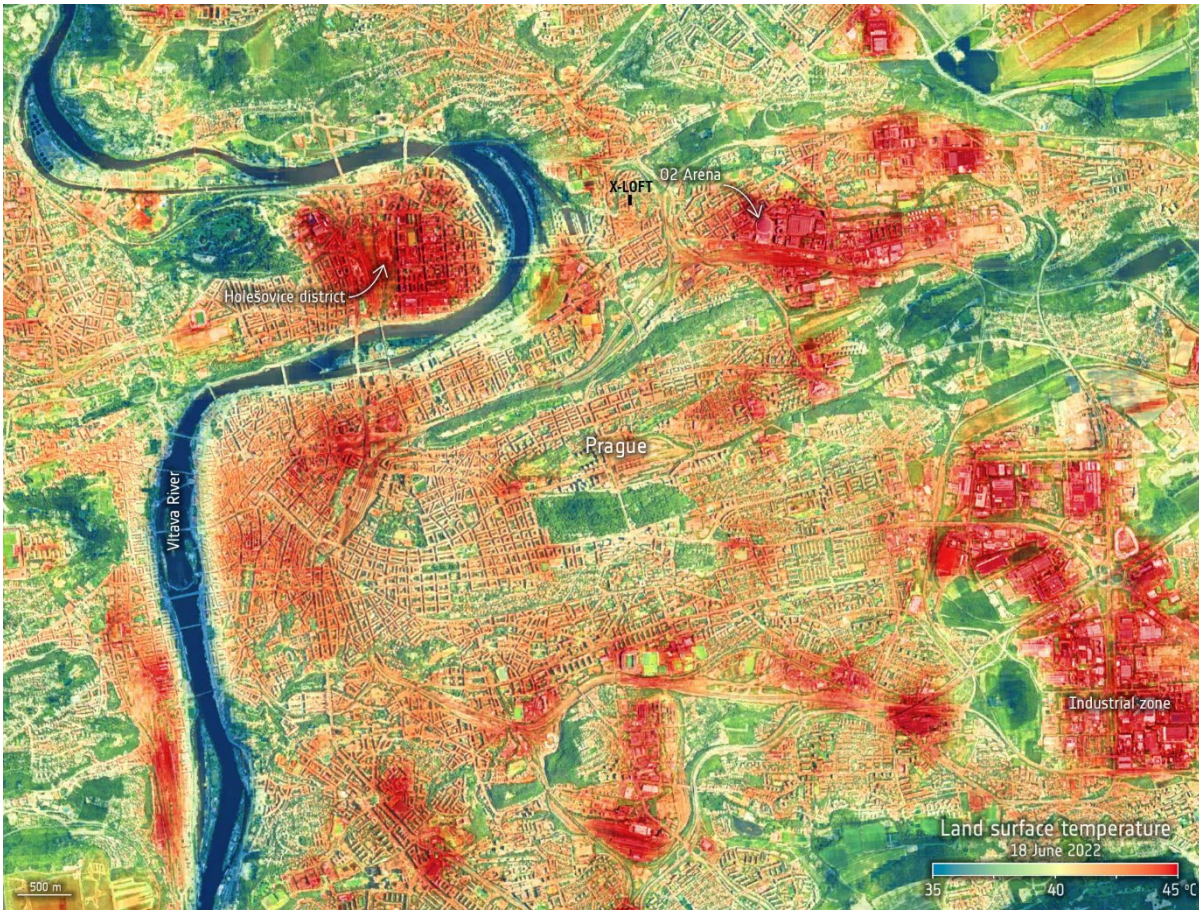

Figure 5. Land surface temperature in Prague on 18 June 2022. Source: [23].

PREPAREDNESS		
PRE.SA – Rapid site assessment		
Intent of the evaluation		
Identification of the probability, intensity, and timescale of the most likely happening hazards (floods, heavy precipitation and storm, heatwaves, subsidence, and drought) of a specific location.		
Description		
Several factors should be considered when characterizing the risks associated with climate change in a specific location, such as the climate threat, the geographical context (e.g., coastal area, mountain region), and the affected systems and sectors (e.g., people, infrastructure, properties, etc.) as well as the impacts on the most vulnerable groups. The purpose of site risk assessments is to determine the likelihood of future climate hazards occurring and the potential impacts on buildings and their users. Climate action and adaptation strategies must be prioritized based on this information.		
Indicator (qualitative)		
Assessment of exposure to specific hazards to identify those that are most likely to occur.		
Evaluation modules		
PRE.SA1 - Site Risk Assessment		
PRE.SA1 - Site risk assessment		
Item	YES/NO	pt
A - Perform an hazards assessment	YES	1
B - Perform the site risk assessment through a workshop	NO	0
Value KSA1	-	**1**
Overall evaluation		
$KPRE.SA = KPRE.SA_1$	**Total value K**	**1**
	pt	3
		min 0 - max 10

Figure 6. Extract from the Resilience calculation tool.

4.2 Passive Survivability

This criterion comprises four modules, each meticulously assessed. Regarding passive heating, the building shows strong performance with the installation of triple-glazed windows, effectively minimising heat loss and sound transmission. Additionally, thermal insulation consisting of a 14-cm thick layer of mineral wool further enhances energy efficiency.

Regarding passive cooling, the dual exposure allows for cross ventilation, facilitating natural airflow, and reducing indoor temperatures. To counteract excessive warmth, both external and internal blinds can be used to shade the large windows. Moreover, 2% of the building façade is covered with greenery which slightly improves the thermal efficiency.

In terms of passive lighting, the building benefits from its favourable orientation with main facades facing east-west, which helps minimise exposure to intense Southern sunlight. Tall windows extending from floor to ceiling enable ample natural light, creating well-illuminated spaces.

The fourth module involves determining the maximum daily calculated indoor air temperature in the hottest habitable room, following the ISO 7730:2005 standards. As the building is SBToolCZ-certified, information regarding the successful completion of this module was obtained from certification reports. Architectural drawings and on-site inspections proved instrumental in fulfilling the requirements of the remaining modules. As a result, eight points out of a possible ten were allocated to this criterion.

4.3 Heat-wave-resistant building envelope and structure

As identified in the Site Risk Assessment (see 4.1), the building and its surroundings are susceptible to the potential impact of heatwave hazards. An analysis of the building design, based on documentation and drawings, reveals the implementation of effective solutions to combat extreme summer heat, some of which were previously mentioned in the section on passive cooling (see 4.2).

Another notable feature of the building is the presence of a rainwater tank, which allows water collection from an underground reservoir for reuse. This practice helps reduce the demand for water for irrigation purposes during summer. The glazed areas facing the street and the courtyard façade are triple-glazed wood windows. The opaque surfaces are currently equipped with mineral wool with the best thermal technical properties at a thickness of 14 cm.

4.4 Emergency power supply

Heating and hot water provision is facilitated by two 90 kW gas boilers. Additionally, hot water preparation benefits from a roof solar collectors, which fully contributes to heating domestic hot water during the summer months.

For individual residential units, a residential recuperation unit was installed. This unit significantly reduces energy losses through ventilation and ensures that the carbon dioxide concentration remains below the permissible limit of 1200 ppm (classified as "C" according to ČSN EN 1752). Furthermore, it helps to maintain optimal relative humidity levels during both heating and transition periods within the range of 35% to 42%.

Nevertheless, the lack of a backup power source inhibits further examination of this criterion. Implementing solutions such as water pumps to ensure the availability of potable water, maintaining the operation of cable modems and wireless routers for online access, or utilising an accessible common room as a storage for emergency supplies could improve the building's resilience in the event of a prolonged blackout or other disruptive incidents.

4.5 Access to useful shared spaces

This criterion is achieved only partially in the specific building case study. In fact, there are common parking areas and bike storage as well as the essential connecting halls between apartments. It would have been compelling to plan shared areas given the substantial number of units and residents.

Allocating space for amenities such as a gym, laundry room, or multipurpose room (e.g., coworking space) would have been beneficial, especially considering the prevalence of relatively small apartments, suitable for single individuals or couples - 40 out of 48 apartments have a surface area below 50m².

However, the decision not to incorporate shared spaces within the building is influenced by the proximity to external amenities, such as sports facilities, located within a 5-minute walk. In the outdoor area, residents have unrestricted access to a shared courtyard and pergola. The information to meet this criterion arises from a review of the drawings and led to 2 out of the 10 available points.

5. Conclusion

This paper reports the outcome of the application five criteria proposed as part of a potential add-on module for an existing rating system, specifically within the SBTool family, aimed at evaluating the resilience level of buildings. The assessment was carried out using a case study of a multi-residential building located in Prague, Czech Republic, to determine the effectiveness of these criteria.

The analysis revealed that the Passive Survivability and Heat wave-resistant building envelope and structure criteria could encompass additional solutions and strategies beyond those currently included in the framework and Excel tool.

Additionally, the Site Risk Assessment criterion emerged as the most time-consuming to achieve, requiring extensive desk work involving historical and forecast data, including hazard map investigations.

The Emergency Power Supply criterion received limited investigation due to data scarcity. The building's age, constructed over a decade ago, lacked recognition of backup power systems for

prolonged operational sustainability. Furthermore, in the previous version of SBToolCZ, a criterion dedicated to building autonomy emphasised the importance of backup power sources and sustained consumption during power outages. However, this criterion was omitted in the latest SBToolCZ version to prioritise building quality and sustainability, despite the critical role of resilience.

The criterion regarding Access to useful shared space was the easiest to fulfil, as the time required to review documentation and examine floor plans to locate common areas was relatively short.

Finally, it was recognised that certifying an existing sustainable building does not necessarily indicate resilience in various aspects.

In conclusion, this new resilience module is primarily intended for application during the design phase, where adjustments to the drawings can be made to improve resilience to specific hazards. Integrating resilience characteristics into sustainability assessments during the early stages of design can encourage designers to incorporate resilience into their projects, ultimately minimising long-term impacts on the environment, society and economy, particularly during weather-related hazards.

Author Contributions

Conceptualization LF; methodology LF; formal analysis LF; investigation LF; writing-original draft preparation LF; writing-review and editing AL and JG; visualization LF; supervision AL and JG. All authors have read and agreed to the published version of the manuscript.

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