D6.1 Framework and rating system for resilient buildings

MULTICARE

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D6.1 Framework and rating system for resilient buildings

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Executive Summary

This deliverable outlines a framework for quantifying resilience scores of buildings, emphasizing the integration of impacts from various hazards: heat, earthquake, wind and flood. The document identifies multiple indicators to assess a building's resilience in terms of its ability to respond to and recover from these events. Special attention is given to formulating Resilience Readiness levels for both single and multi-hazard scenarios, adopting a multi-attribute decision-making approach to integrate diverse hazard impacts.

Authored by TU Delft, AMS Institute, UNIROMA1 and UTBV, the deliverable delineates the proposed methodology. As part of the project objectives, this approach will be integrated into a digital tool designed for early-stage design or retrofit selection, and extended to assess resilience scores for building archetypes in the demo sites.

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GLOSSARY

ACRONYM	FULL NAME
AHP	Analytic Hierarchy Process
EAL	Expected Annual Loss
HW	Heatwave
KPI	Key Performance Indicator
MADM	Multi-Attribute Decision-Making
MAFE	Mean Annual Frequency of Exceedance
NBS	New Building Standard
PML	Probable Maximum Loss
RR	Resilience Readiness
SET	Standard Effective Temperature
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

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1. Introduction

1.1. MULTICARE project

The built environment is ill-prepared for more frequent and increasingly intense climate-related extreme events. The current building stock is particularly vulnerable because it has limited or no capacity to adapt and recover from extreme events thereby leading to building failures that cause severe socio-economic losses and adversely affecting the health and wellbeing of people. Recent scientific and technological advances in the construction industry provide timely solutions for improving the resilience for specific single hazards (e.g. flood hazard or seismic hazard), but they are often not cost effective, rarely eco-friendly and nearly never address the multiple hazards present in many locations. This is hardly surprising because there is neither a clearly defined framework for quantifying the whole-life socio-economic-environmental impacts of extreme natural events nor tools for assessing the holistic climate resilience of buildings. Consequently, it is currently very challenging to develop/select optimal solutions for real-world multi-hazard scenarios.

MULTICARE will address this challenge directly by developing new multi-criteria decision-support frameworks and providing plug & play technological and digital solutions for improving the resilience of the built environment in a cost-effective, reliable and sustainable manner. The technological solutions consist of multi-functional low-carbon resilient technologies embedded in modular and prefabricated construction for the next generation of high performance and smart buildings, characterized by enhanced safety, energy efficiency, environmental-sustainability, improved quality of life, circularity, and scalability for a broad range of natural events and end-user. The plug & play technologies will be applied to either new multi-story buildings or existing structures by means of low-invasive external interventions. The digital solutions consist of a suite of multi-disciplinary digital services and tools for performing multi-hazard resilience assessment, design, operation and management across multiple scales (material, component, building, neighborhood/city). The new digital tools will enable stakeholders to make informed decisions in the selection of materials/solutions, including for heritage buildings, and support resilient supply chains. The effectiveness of the MULTICARE solutions will be demonstrated through large-scale pilots (3 buildings, 4 neighborhoods/district) in three different European countries carefully selected for their diverse local environmental, social and economic conditions (Italy, Netherlands, Romania). Banks and institutional investors will be engaged to better understand the financial risk reduction value of resilience and update existing and future "green finance" mechanisms that will help to leverage the project results. A user-center, inclusive and participatory approach will be consistently implemented throughout the project to engage citizens and extend the durability of MULTICARE impact.

To achieve these ambitious goals, MULTICARE brings together a unique interdisciplinary Consortium of 21 partners (**Table 1.** Consortium) from 6 different EU countries with strong R&D and practical expertise, who are either established leaders in their sector or agile SMEs in emerging fields. Altogether the Consortium members span across the whole technical

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and value chain required for developing and implementing solutions in terms of design, digitization, manufacturing, construction and monitoring of resilient and sustainable buildings. The Consortium also includes partners with experience in social sciences, user engagement, and training to ensure the success and widespread application of new technologies in local communities. The Consortium will also support clustering activities with other relevant research projects to share knowledge and raise public awareness of building resilience. An international outreach and cooperation strategy will also be implemented to tackle the project challenges.

Table 1. Consortium

Number	Role	Short Name	Legal Name	Country
1	CO	TU Delft	TECHNISCHE UNIVERSITEIT DELFT	NL
2	BEN	PFE	PRIEDEMANN FASSADENBERATUNG GMBH	DE
3	BEN	IES R&D	IES R&D	IE
4	BEN	INCDFP	INSTITUTUL NATIONAL DE CERCETARE-DEZVOLTARE PENTRU FIZICA PAMANTULUI	RO
5	BEN	UNIROMA1	UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA	IT
6	BEN	XLD	X-LAM DOLOMITI SRL	IT
7	BEN	STRESS	SVILUPPO TECNOLOGIE E RICERCA PER L'EDILIZIA SISMICAMENTE SICURA ED ECOSOSTENIBILE SCARL	IT
7.1	AE	UNINA	UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II	IT
8	BEN	AMS Institute	STICHTING AMSTERDAM INSTITUTE FORADVANCED METROPOLITAN SOLUTIONS(AMS)	NL
9	BEN	PMB	MUNICIPIUL BUCURESTI	RO
10	BEN	ASM	ASM - CENTRUM BADAN I ANALIZ RYNKUSPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA	PL
11	BEN	RoGBC	ASOCIATIA ROMANIA GREEN BUILDING COUNCIL	RO
12	BEN	RINA-C	RINA CONSULTING SPA	IT
13	BEN	UTBV	UNIVERSITATEA TRANSILVANIA DIN BRASOV	RO
14	BEN	ACER	AGENZIA CAMPANA PER L EDILIZIA RESIDENZIALE	IT
15	BEN	Boom	BOOM BUILDS B.V.	NL
16	BEN	OMRT	OMRT BV	NL
17	BEN	ROTHO BLAAS SRL	ROTHO BLAAS SRL	IT
18	BEN	ARUP	ARUP BV	NL
19	BEN	Tecuci	MUNICIPIUL TECUCI	RO
20	BEN	Hölscher	DIPL.-ING. HPLSCHER GMBH & CO.KG	DE

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1.2. Framework and rating system for resilient buildings

This deliverable presents quantitative metrics aimed at measuring and comparing the resilience of buildings (as-built vs. retrofitted options; alternative designs). The document discusses resilience measures from multiple perspectives, encompassing both multi-hazard (heat, seismic, wind, flood) and multi-domain (physical, economic, social, environmental) considerations. The resilience metrics are grounded in the analysis of current literature and practices, focusing on resilience principles for buildings (Robustness, Redundancy, Resourcefulness and Rapidity). Human resilience factors are also integrated into the measurement framework to ensure a comprehensive assessment approach.

The proposed indicators will be used to establish resilience-based design objectives for the MULTICARE's technological solutions, tailored to the specific building use and its exposure to hazards. This includes defining resilience goals related to building functionality during hazards and recovery post-events, thereby guiding decision-making in the resilience design and retrofitting of buildings. Moreover, the proposed approach is intended for prioritizing intervention planning on a large scale, offering a rapid assessment method suitable for initial screening assessments or more detailed investigations.

1.2.1 Objectives and method

The document provides multiple indicators for assessing the resilience of buildings exposed to multiple hazards. To facilitate comparative analysis of data, normalization rules are established for each indicator based on specific threshold values. These indicators are integral to formulating Resilience Readiness levels either single or multi-hazard scenarios, aimed at categorizing building systems according to their capacity to respond and recover from extreme events.

Hazard	Resilience Readiness Level (RR)
Heat	RR_H
Earthquake	RR_S
Flood	RR_F
Wind	RR_W

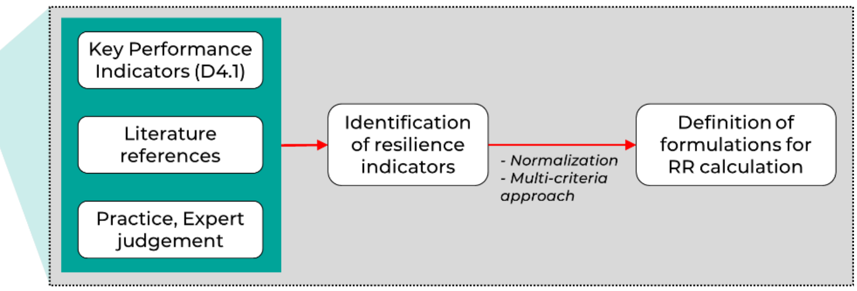

Figure 1. Definition of Resilience Readiness Levels

The resilience indicators are derived from literature or extrapolated from a comprehensive list of performance parameters defined in deliverable D4.1. These encompass structural safety, energy efficiency, carbon emissions, occupant well-being and cost effectiveness. The normalization schemes for the various parameters are determined through a combination of literature references, existing standards and expert judgment. Multi-attribute decision

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making is adopted for deriving single hazard Resilience Readiness Levels and finally derive multi-hazard resilience scores and related labelling systems.

1.2.2 Relation to other activities

Table 2. Relation to other WPs illustrates the principal connections of this deliverable to other activities developed within the MULTICARE project, which should be taken into account alongside this document to gain a deeper understanding of its contents.

Table 2. Relation to other WPs

Work Package	Contribution
WP4 - Performance requirements, criteria and user's needs, and MULTICARE overall approach	This deliverable contributes to the establishment of the overall project concept by defining a method for evaluating multi-hazard resilience.
WP6 - Multi-risk framework and support tools for improving the whole-life resilience of buildings	This deliverable serves as the foundation for the definition of resilience indicators and related scores to be integrated into decision-support tools.
WP7 - Spatial decision-support framework and system for multi hazard resilience analysis at urban level	This deliverable defines resilience scores that will be extended at urban analysis and integrated into the Spatial Decision Support Framework.
WP9 - Health monitoring of buildings for data-driven prediction and warning systems	This deliverable is linked to WP9 through the seismic and flood resilience indicators, to be integrated into the early warning system workflow.
WP12 - Plug and play low-carbon resilient structural systems	This deliverable provides support for establishing design criteria and objectives for the MULTICARE technological solutions.
WP14 - Acerra – Preparation and Virtual demonstrator	This deliverable establishes indicators to be used for the multi-criteria assessment of renovation scenarios and/or virtual demonstrators.
WP16 - Amsterdam – Preparation and Virtual demonstrator	
WP18 - Bucharest – Preparation and Virtual demonstrator	
WP21- Tecuci – Monitoring & Assessment	
WP23 - Impact assessment of the MULTICARE solutions	This deliverable provides inputs for quantifying the potential impacts and benefits of the project's solutions.

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2. Resilience indicators

This chapter explores the resilience indicators, each described with references to existing labeling systems and accompanied by a proposed normalization rule. For each hazard, these resilience indicators are integrated into a single resilience score, facilitating a unified parameter that can be further combined with other indicators in multi-hazard scenarios.

2.1 Heat resilience

Indicators description

Diverse factors, including building construction, cooling measures (passive or active), and building occupants should be encapsulated in the assessment of the individual building's thermal response to a heatwave (HW). Although the physical domain is less relevant for this resilience category, since the structural integrity of the components is not significantly compromised by the heat hazard, the impact on the social, environmental and economic domains is notable. Particularly:

- **Social** domain refers to how humans respond to extreme heat events, particularly heatwaves. An indicator of this is the Standard Effective Temperature (SET), a model that assesses human reaction to the thermal environment. SET is defined as the dry-bulb temperature in a hypothetical environment with 50% relative humidity, assuming suitable clothing is worn for the activity [1]. Relevant resilience indicators (Cumulative Degree Hours between SET_minimal and SET_critical, Cumulative Degree Hours after SET_critical, and Cumulative Time from SET_critical to SET_minimal) not only express the severity of the thermal conditions but also the duration of exposure to these conditions. The impact of extreme temperatures on loss of life, represented by the Mortality Rate, is estimated using the Gasparrini method [2].
- **Economic** domain refers to the monetary losses from operating the cooling system during the heatwave in order to maintain acceptable thermal conditions in the interior.
- **Environmental** domain is also fundamental for building resilience, given the need to curb carbon emissions from the built environment and achieve the climate goals for energy neutrality. Economic and environmental aspects are jointly considered in the efficiency factor, which is related to the total energy consumed for the cooling of the building.

Normalization rules

Thermal resilience is divided into three stages: resistance, robustness and recovery. As defined by Attia et al. [3], resistance refers to the depth and ability to react to shock, robustness signifies the response to failure, and recovery represents the ability to return to a balanced state. Several key performance indicators (KPIs) are incorporated when evaluating thermal resilience. These indicators vary with resilience stages and assessment periods. **Table 3** provides a summary of the various KPIs and definitions used in the thermal resilience assessment.

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The resistance stage is evaluated by calculating the cumulative SET degree hours between the minimal and critical SET thresholds throughout the year. Robustness is assessed by the cumulative SET degree hours above the critical SET threshold during the identified heatwave. Both indicators are normalized based on reference SET degree * total hours in a year. The recovery stage is evaluated by the cumulative hours from the critical SET threshold to the minimal SET threshold after the heatwave and normalized with respect to the total hours per year. An illustrative figure **(Figure 1**) explains the building's response during the heatwave and the implications of each KPI.

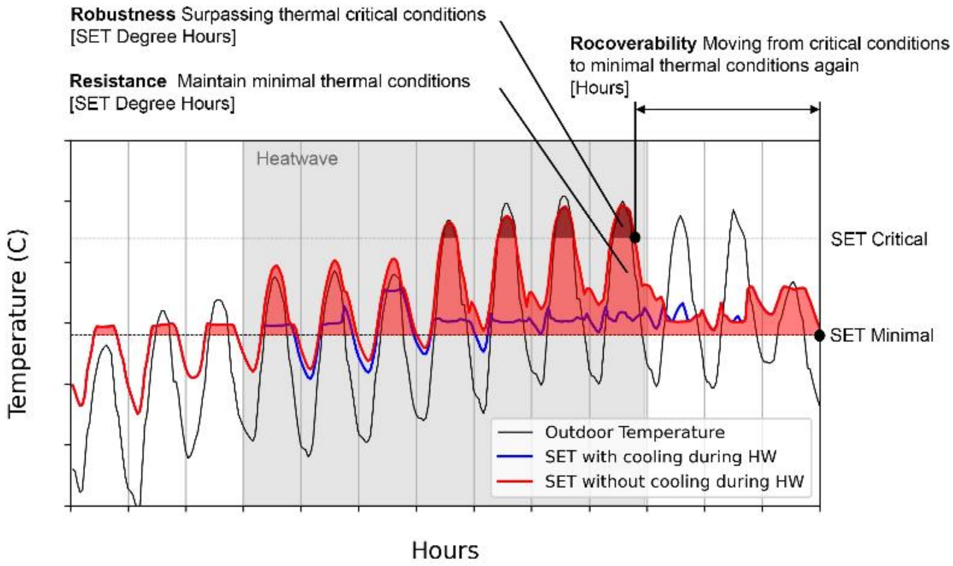

Figure 2. Thermal resilience stages and assessment KPIs

Finally, an **efficiency factor** is implemented to deduce the final resilience score. The multiplier refers to both buildings with and without active cooling systems and, particularly, penalizes the score if thermal resilience is achieved with the help of an active system that does not consume energy produced by renewables in the plot. Thus, it provides information on the trade-off between thermal resilience and environmental/economic impact aiming ultimately to achieve the necessary comfort level with minimum compromises in the total building energy efficiency. In this case, the normalization is performed according to a reference acceptable cooling level extracted from the energy consumption levels provided by energy labelling schemes.

The indicators are evaluated annually covering the possibility of multiple heatwave occurrences over a year period. The assessment is based on synthetic data produced by energy simulators using weather files that include both historical and projected future heatwaves.

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Table 3. Summary of heat resilience indicators

Resilience phase	Index	Domain	Indicator name	Normalization
Resistance (Response)	I_{Res1}	Social	Cumulative degree hours between SET_minimal and SET_critical	Indicator / reference SET degree * total hours in a year
Robustness (Response)	I_{Res2}	Social	Cumulative degree hours after the SET_critical	Indicator / reference SET degree * total hours in a year
Robustness (Response)	I_{Res3}	Social	Mortality rate	Number of deaths in the building / total number of occupants in the building
Recovery	I_{Rec}	Social	Cumulative time from SET_critical to SET_minimal	Indicator / Total hours in a year
All phases	e_f	Environmental, Economic	Efficiency Factor	Cooling energy consumption without energy produced by renewables [kWh/m^2] / Reference acceptable cooling level [kWh/ m^2]

Resilience Readiness calculation method

The total heat Resilience Readiness level (RR_H) is calculated as:

$$RR_H = TR \times e_f$$

Particularly, **Thermal Resilience** (TR) factor is a measure of a building's ability to maintain a comfortable indoor temperature with/without using cooling systems. This value ranges from 0 to 1 and is calculated from the individual thermal resilience indicators as:

$$TR = (1 - I_{Res1} * I_{Res2} * I_{Res3}) * m_1 + (1 - I_{Rec}) * m_2$$

where m1, m2 are weighting factors assigned based on the importance of each resilience phase.

Efficiency Factor (e_f) is a multiplier that increases with the efficiency of cooling energy usage when this is not produced by renewables in the own plot. Buildings without cooling systems have e_f = 1, and buildings with cooling systems have e_f between 0 and 1, depending on their cooling energy consumption.

$$e_f = \max\left(1 - \frac{E}{E_{ref}}, 0\right)$$

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Here, E is the cooling energy consumption and E_{ref} is the reference acceptable cooling energy consumption as extracted from the respective energy label schemes. This function ensures that the efficiency factor does not drop below 0 when energy consumption exceeds E_{ref} the efficiency factor function to cap E at E_{ref}.

- When E=0 (no cooling energy consumption), e_f=1.
- When $E \geq E_{\max}$ (maximum cooling energy consumption), e_f=0.

An indicative diagram of heat resilience scores associated with different scenarios can be seen in **Figure 3**.

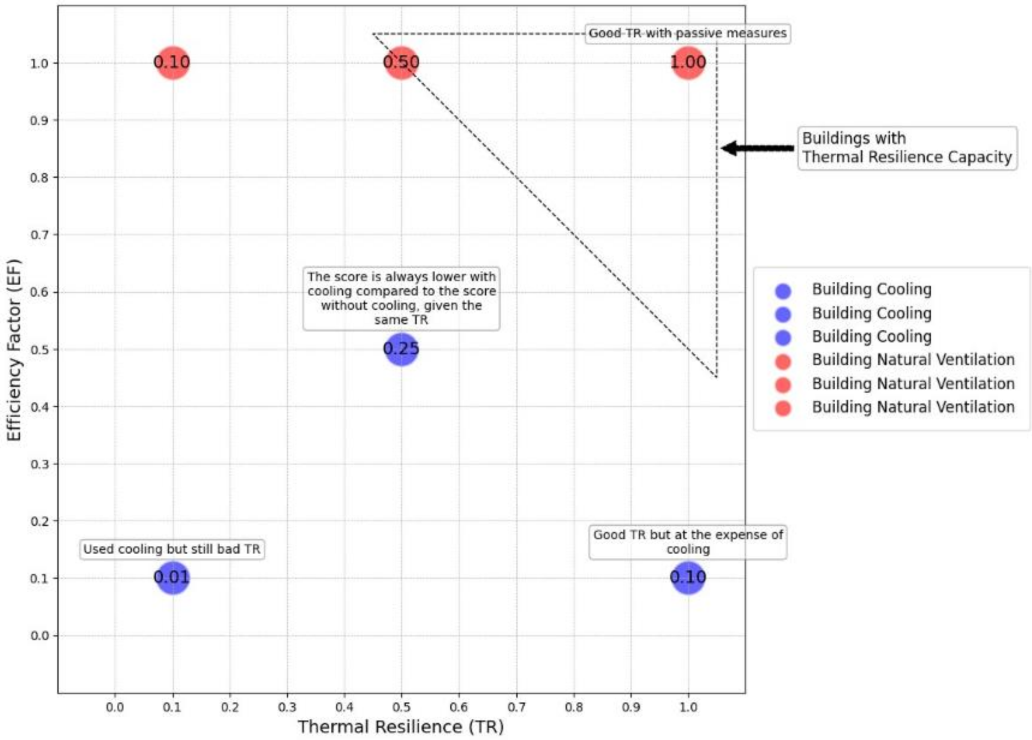

Figure 2. Heat resilience score of buildings with/without cooling systems

2.2 Seismic resilience

Indicators description

To quantify seismic resilience multiple aspects and domains should be taken into account. The main four domains must be taken into account when assessing the resilience of a building:

- **Physical** domain is one of the most relevant, since the earthquake resilience depends on structural behavior and physical response to a seismic event. This domain includes the following indicators, detailed described in deliverable D4.1: Ratio of Mean Annual Frequency of Collapse between damaged and undamaged;

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% New Building Standard; Mean Annual Frequency of Exceedance of a Limit/Damage State (1/years); Residual Drift Ratio.
- **Social** domain is related to the risk for people's safety and well-being. Damaged buildings might lead to partial collapses of structural and non-structural elements leading to a loss of life or dwellings.
- **Economic** domain is associated with the monetary impact related to building damage, both in terms of direct repair costs (Expected Annual Loss or Probable Maximum Loss) and indirect costs (Downtime) induced by daily activities interruption.
- **Environmental** domain is the last domain which is related to the environmental impact (Expected Annual Loss or Probable Maximum Loss). Several elements of a building might get damaged and in need of repair or replacement, leading to carbon emissions produced by the construction of new components, the repair process and the debris disposal.

<u>Normalization rules</u>

% of New Building Standard (%NBS) is a simple yet effective indicator used to assess the relative safety of a building. When it was introduced in NZSEE (2017) [4] and NTC (2018) [5], the index was intended to be used for existing buildings, but it can be used also for new buildings. The %NBS is the ratio between the capacity of a building and the minimum required capacity of a building following the current building codes. This KPI mostly represents the Physical domain and the Response phase of the resilience as it is a safety index. This KPI is already normalized, with multiple labeling systems existing (e.g., Decreto SismaBonus in Italy).

Mean Annual Frequency of Exceedance (MAFE) is the annual probability of exceeding a limit state. Limit states can be multiple and can concern structural safety as well as building serviceability Jalayer et al. (2007) [6]. Thresholds can be chosen ad hoc to represent what the stakeholder deems satisfactory. MAFE itself has to do with the Physical domain and concerns the Response phase of the resilience. MAFE can be normalized by setting thresholds and using them as reference for normalization, higher is better:

$$\frac{MAFE_{threshold}}{MAFE_{building}}$$

By combining the MAFE before and after the earthquake, it is possible to compute the **Ratio of Mean Annual Frequency of Collapse** between damaged and undamaged. This KPI is defined as the ratio between the MAFE of the undamaged structural system and the one damaged by an event. This KPI is related to the Physical domain and the Response phase of the resilience as it is a safety index. This KPI has been included as, after an event, the residual capacity of a damaged structure is an important aspect in the decision-making process of repair, retrofit or demolish. It can be computed as follows:

$$\frac{MAFE_{damaged}}{MAFE_{undamaged}}$$

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This KPI is already normalized. Lower is better. Bazurro et al. (2004) [7] offers a labeling system considering both the KPI itself and the undamaged value of the MAFE. This has been considered because the lack of damage of a poor-performing building is not a sign of safety when compared with a damaged high-performing building.

Residual Drift Ratio is a KPI used to measure the permanent residual deformation affecting a building after an earthquake. It is the ratio of the overall displacement over the height of a floor or the whole building. This KPI belongs to the Physical domain and concerns the Response phase, even if it greatly affects the recovery phase as well. This indicator can be computed from numerical simulations (usually time-history non-linear analyses). It can be normalized using the thresholds proposed by the FEMA P-58 (2018) [8].

Casualties is the number of people that are expected to perish due to the building inability to withstand the earthquake. This KPI belongs to the Social domain and it concerns the Response phase. Multiple models have been developed to estimate casualties. Two notable examples are the methodology developed in FEMA P-58 (2018) [8] or the damage to casualties' model proposed by Dolce et al. (2021) [9] based on data relative to the Italian past earthquakes. It can be normalized by considering the expected number of casualties with respect to the number of building occupants. A similar approach is adopted in the EFEHR technical report [10], providing a labelling system based on the annual loss of life.

Expected Annual Loss or EAL is the expected cost of the repairs a structure is expected to sustain during its life cycle and computed annually. This KPI belongs to the Economic domain, and it concerns the Response phase. Several methodologies exist to compute this KPI by integrating the Performance Based Earthquake Engineering integral for different levels of details and different scales, however the component-based procedure described in FEMA-P58 is arguably the most accurate because it can grasp the effect of damage to structural and non-structural components. The value of the economic losses is normalized with respect to the building replacement cost.

Probable Maximum Loss or PML is like EAL, however it is related to the impact of single events. It can be computed following the approach described by FEMA P-58 (2018) [8]. Similarly to the EAL, this KPI belongs to the Economic domain, and it concerns the Response phase. Differently from EAL, this KPI does not consider the hazard probability of the modeled event, making it more suitable for single event assessment. Like EAL it can be normalized by expressing it as a percentage of the reconstruction cost. A labeling system for this KPI is provided by the REDi guidelines (2013) [11].

Downtime is the expected time that a building remains not operational. Downtime drives indirect economic losses due to lost income, business interruption or relocation costs. The estimation of downtime is computed by applying the framework described by the REDi guidelines (2013) [11]. This KPI is included in the Economic domain even if it has also impacts the social aspect as well. Downtime mainly concerns the Recovery phase. It can be normalized by considering the expected downtime relative to the building service life. A labeling system is provided by the REDi guidelines.

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Displaced people are the number of humans which are not able to access their dwellings because of the sustained damage induced by the earthquake. Displacements might be driven by damage to structural components or the building envelope. The number of displaced people can be computed according to Hazus (2022) guidelines [12]. This KPI is mainly related to the Social domain even if it also drives indirect costs related to temporary housing. The number of displaced concerns the Recovery phase. Like the number of casualties, this indicator can be normalized by considering the people of the building that are expected to be displaced following an event.

Annualized Carbon Output is the amount of CO2 global warming potential equivalent expected to be produced to repair and/or replace building components or the building itself over the building's lifetime. The calculation methodology is like EAL and it is described in the FEMA P-58 (2018) [8]. This KPI belongs to the Environmental domain, and it concerns the Recovery phase. It can be normalized by considering the replacement carbon footprint of the building, thus following a similar approach as per economic losses.

Probable Maximum Carbon Output is like Annualized Carbon Output; however it is related to the impact of single events. It can be computed following the approach described by FEMA P-58 (2018) [8]. Similarly to the Annualized Carbon Output, this KPI belongs to the Environmental domain, and it concerns the Recovery phase. Differently from Annualized Carbon Output, this KPI does not consider the hazard probability of the modeled event, making it more suitable for single event assessment. Like Annualized Carbon Output it can be normalized by considering the replacement carbon footprint of the building.

Table 4. Summary of seismic resilience indicators

Resilience phase	Index	Domain	Indicator name	Normalization
Response	I_{Res1}	Physical	Ratio of Mean Annual Frequency of Collapse between damaged and undamaged	The normalization is carried out considering the building as undamaged as reference.
			% New Building Standard	The capacity of the building is normalized considering the minimum capacity requirements of a new building.
			Mean Annual Frequency of Exceedance of a Limit/Damage State (1/years)	It is normalized by setting a desirable target for the damage state. (Threshold)
Response	I_{Res2}	Physical	Residual Drift Ratio	It is normalized by setting a desirable target for the residual drift ratio. (Threshold)
Response	I_{Res3}	Social	Casualties	The number of casualties can be normalized by the number building occupants.

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Response	I_{Res4}	Economic	Expected Annual Loss (cost/m2/year or % Reconstruction Cost/year)	The building's cost is normalized as a percentage of the total building replacement cost.
			Probable Maximum Loss (cost/m2 or % Reconstruction Cost)	The building's cost is normalized as a percentage of the total building replacement cost.
Recovery	I_{Rec1}	Economic	Downtime (months)	Downtime is normalized in relation to the life cycle of the structure.
Recovery	I_{Rec2}	Social	Displaced	The number of displaced can be normalized by the number of building occupants.
Recovery	I_{Rec3}	Environmental	Annualized Carbon Output (CO2gwp_eq/sqm/y)	The carbon output can be normalized considering the total building carbon footprint
			Probable Maximum Loss (CO2gwp_eq/sqm/y)	The carbon output can be normalized considering the total building carbon footprint

Resilience Readiness calculation method

A formulation integrating the different indicators above is proposed based on the work developed by Bertilsson et al. (2019) [13] . Considering the two resilience phases, each part acts as a sub-index, calculated by subtracting the indicators from unity to ensure that high numbers represent high resilience while numbers near zero indicate low resilience.

$$RRs = \left(1 - I_{Res1}^{n_1} \cdot I_{Res2}^{n_2} \cdot I_{Res3}^{n3} \cdot I_{Res4}^{n4}\right) \cdot m_1 + \left(1 - I_{Rec1}^{n_5} \cdot I_{Rec2}^{n_6} \cdot I_{Rec3}^{n7}\right) \cdot m_2$$

Each part can be weighted (m_i, n_i) according to its importance or relevance to the case under analysis. These weights can be modified to adapt to a particular interpretation and need to be properly defined by decision makers.

2.3 Wind resilience

Indicators description

To quantify wind resilience, multiple aspects and domains should be taken into account:

- **Physical** domain is mostly relevant for high-rise buildings, given that the construction materials of mid- and low-rise buildings in Europe are usually prone to structural failure due to wind loading. In this context, the relevant indicator, as detailed in deliverable D4.1, is the Ratio of Mean Annual Frequency of Collapse between damaged and undamaged structures, and the Mean Annual Frequency of Exceedance of a Limit/Damage State (1/year).

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- **Social** domain relates to the risks impacting people's safety and well-being. Wind can damage the building envelope, causing water ingress and temporary displacement of residents. In high-rise buildings, wind loads can induce building sway, leading to user discomfort and potential downtime.
- **Economic** domain is concerned with the financial impact of building damage. This includes direct repair costs, such as Expected Annual Loss or Probable Maximum Loss, and indirect costs resulting from downtime and the interruption of daily activities.
- **Environmental** domain focuses on the environmental impact of building damage, including Expected Annual Loss or Probable Maximum Loss. Damage to various building elements may necessitate repair or replacement, resulting in carbon emissions from the construction of new components, the repair process and debris disposal.

<u>Normalization rules</u>

Mean Annual Frequency of Exceedance (MAFE) represents the annual probability of exceeding a defined limit state. These limit states can vary and may be considered to address both structural safety, building serviceability and user comfort. Stakeholders can select thresholds that reflect their specific requirements. MAFE is associated with the Physical domain and relates to the Response phase of resilience. MAFE can be normalized by setting appropriate thresholds and using them as references for comparison (Petrini & Francioli 2022 [13], ASCE Prestandard 2019 [14], CNR DT 207/R1 (2018) [15], where a higher value indicates better performance:

$$\frac{MAFE_{threshold}}{MAFE_{building}}$$

Probable Maximum Loss or PML is related to the impact of a single event. It can be computed following the approach described by FEMA P-58 (2018) [8] adapted from earthquake. This KPI belongs to the Economic domain, and it concerns the Response phase. This KPI does not consider the hazard probability of the modeled event, making it more suitable for single event assessment. It can be normalized by expressing it as a percentage of the reconstruction cost. A labeling system for this KPI is provided by the REDi guidelines (2022) [16].

Downtime is the expected period during which a building remains non-operational. It contributes to indirect economic losses due to lost income, business interruptions, and relocation costs. The estimation of downtime follows the framework outlined in the REDi guidelines (2022) [16], as defined for earthquakes. Although downtime is categorized under the Economic domain, it also significantly impacts the social domain. Downtime primarily pertains to the Recovery phase and can be normalized by considering the expected downtime relative to the building's service life. The REDi guidelines provide a labeling system for this purpose.

Casualties are the number of people expected to perish due to extreme winds. This KPI belongs to the Social domain and it concerns the Response phase. Given the type of

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buildings typical of the European Union, most casualties are expected to be related to windborne debris (e.g., windborne trees) rather than structural failure. Hazus (2022) [12] proposes a framework for the evaluation of casualties due to extreme wind events. This metric can be normalized by considering the percentage of casualties relative to building occupancy.

Displaced people are the number of humans which are not able to access their dwellings because of the sustained damage to the envelope. The number of displaced people can be computed according to Hazus (2022) guidelines [12]. This KPI is mainly related to the Social domain even if it also drives indirect costs related to temporary housing. The number of displaced concerns the Recovery phase. As for the number of casualties, this indicator can be normalized by considering the percentage of people that are expected to be displaced following an event.

Probable Maximum Carbon Output is related to the impact of a single event. It can be computed following the approach described by FEMA P-58 (2012) [8] adapted from earthquake. This KPI belongs to the Environmental domain, and it concerns the Recovery phase. This KPI does not consider the hazard probability of the modeled event, making it more suitable for single event assessment. It can be normalized by considering the replacement carbon footprint of the building.

Table 5. Summary of wind resilience indicators

Resilience phase	Index	Domain	Indicator name	Normalization
Response	I_{Res1}	Physical	Mean Annual Frequency of Exceedance of a Limit/Damage State (1/years)	It is normalized by setting a desirable target for the damage state.
Response	I_{Res2}	Economic	Probable Maximum Loss (cost/m2 or % Reconstruction Cost)	The building's cost is normalized as a percentage of the total building replacement cost.
Response	I_{Res3}	Social	Casualties	The number of casualties can be normalized by the number building occupants.
Recovery	I_{Rec1}	Economic	Downtime (days)	The building's cost is normalized as a percentage of the total building life cycle.
Recovery	I_{Rec2}	Social	Displaced	The number of displaced can be normalized by the number of building occupants.
Recovery	I_{Rec3}	Environmental	Carbon Output (related to wind damage, CO2gwp_eq/sqm)	The carbon output can be normalized considering the total building carbon footprint

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Resilience Readiness calculation method

Following the same approach adopted for the seismic Resilience Readiness level:

$$RRs = \left(1 - I_{Res1}^{n_1} \cdot I_{Res2}^{n_2} \cdot I_{Res3}^{n3}\right) \cdot m_1 + (1 - I_{Rec1}^{n_4} \cdot I_{Rec2}^{n_5} \cdot I_{Rec3}^{n6}) \cdot m_2$$

Each part can be weighted (m_i, n_i) according to its importance or relevance to the case under analysis. These weights can be modified to adapt to a particular interpretation and need to be properly defined by decision makers.

2.4 Flood resilience

Indicators description

Measuring flood resilience requires considering multiple aspects and domains. For assessing a building's flood resilience, four main domains were considered:

- **Physical** domain has a high relevance in terms of flood resilience research field. It should be noted that the flood damages depend, on the one hand, on the mechanical impact of moving or stationary water, and on the other hand, on the physical characteristics of the buildings.
- **Social** domain is mainly related to the safety of the people that are living in an affected building and also to their recovery process after the event that generated the disaster.
- **Economic** domain, as for the seismic resilience, is mostly related to the monetary impact related to building damage in terms of direct and indirect costs.
- **Environmental** domain is associated with the hazard-related environmental indicators (flood depth and flow velocity) and the quantity of carbon emission caused by interaction between moving or stationary water and the building.

Normalization rules

Resistance of facades/buildings (RF)to floods is a KPI belonging to the Physical domain of flood resilience. The description of this KPI was included in the Deliverable 4.1. The main reference document is represented by the FEMA [18]. This KPI is included in this case in the Response Resilience phase. The normalization of this indicator can be done as follows:

$$RFn = \frac{RFi}{RFm}$$

Where RFn is the normalized value of resistance of facades/buildings to floods; RFi is the actual value of the resistance of facades/buildings to floods; RFn is the maximum value of the resistance of facades/buildings to floods.

Water depth (WD) is a KPI associated with the Environmental domain. This indicator can be estimated using the hydraulic modeling, as described in the Deliverable 4.1. This KPI is

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included in the Response Resilience phase. The normalization procedure can be implemented as follows:

$$WDn = \frac{WDi}{WD0.1\%}$$

Where WDn is the normalized value of water depth; WDi is the actual value of water depth; $WD0.1\%$ is the water depth corresponding to a return period of 0.1%.

Flow velocity (FV) is another KPI already described in the Deliverable 4.1. As for the water depth, the flow velocity is included in the Environmental domain and, specifically, in the Response Resilience phase. The normalization procedure can be implemented as follows:

$$FVn = \frac{FVi}{FV0.1\%}$$

Where FVn is the normalized value of flow velocity; FVi is the actual value of flow velocity; $FV0.1\%$ is the flow velocity corresponding to a return period of 0.1%.

Building flooded perimeter (BFP) is a KPI related to the Physical domain. This can be a very important indicator for the degree to which a building is affected in the event of a flood. Thus, the longer the flooded perimeter of a building is, the more vulnerable that building becomes and the potential damage increases. The flood perimeter is determined by summing the lengths of the building sides that are touched by the water generated by a flood. Hydraulic modeling combined with the application of GIS techniques are the basis for determining the values of this indicator. This KPI is included in the Response Resilience phase. The normalization procedure can be implemented by using the following formulation:

$$BFPn = \frac{BFPi}{BPt}$$

Where $BFPn$ is the normalized value of building flooded perimeter; $BFPi$ is the actual value of building flooded perimeter; BPt is the total perimeter of the building.

Area of building facades (ABFF) affected by flood is a KPI related to the Physical domain. This indicator complements the previous one because it provides additional information on the degree to which the water from the flood can affect a building facade. Thus, combining the length of the facade with the water depth, the flooded area for each of the building facades can be derived. The total area affected by flooding of the facades of a building will be determined by adding up the areas affected by flooding of all facades. The indicator can be normalized as:

$$ABFFn = \frac{ABFFi}{ABFt}$$

Where $ABFFn$ is the normalized value of KPI represented by the area of building facades affected by flood; $ABFFi$ is the actual value of KPI represented by the area of building facades affected by flood; $ABFt$ is the total area of the building facades.

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Number of affected people (NP) is a KPI that was introduced in the Deliverable 4.1. The main difference between the KPI used in this deliverable and the KPI with the same name used in Deliverable 4.1, is given by the fact that in the present deliverable, the KPI refers to the building scale, meanwhile in Deliverable 4.1 the KPI belongs to the urban scale. In both of the cases, this indicator is associated with the Social domain. The normalization procedure can be implemented as follows:

$$NPn = \frac{NPi}{NPt}$$

Where NPn is the normalized value of affected people from a building; NPi is the actual value of affected people from a building; NPt is the total number of building occupants.

Total economic damage (TED) generated by floods is a KPI included in the Economic Domain and associated with the Recovery Resilience phase. This indicator was included in the Deliverable 4.1, but it is now referring to the building scale.

$$TEDn = \frac{TEDi}{TEB}$$

Where $TEDn$ is the normalized value of economic damage for a building; $TEDi$ is the actual value of economic damage for a building; TEB is the total economic value of the building.

Downtime is the expected time that a building remains not operational. Downtime drives indirect economic losses due to lost income, business interruption or relocation costs. The estimation of downtime is computed by applying the framework described by the REDi guidelines. This KPI is included in the Economic domain even if it has also impacts the social aspect as well. Downtime mainly concerns the Recovery phase. It can be normalized by considering the expected downtime relative to the building service life.

Annualized Carbon Output is the amount of CO2 global warming potential equivalent expected to be produced to repair and/or replace building components or the building itself over the building's lifetime. The calculation methodology is like EAL and it is described in the FEMA P-58 [8]. This KPI belongs to the Environmental domain, and it concerns the Recovery phase. It can be normalized by considering the replacement carbon footprint of the building, thus following a similar approach as per economic losses.

Table 6. Summary of flood resilience indicators

Resilience phase	Index	Domain	Indicator name	Normalization
Response	I_{Res1}	Physical	Resistance of facades/buildings to floods	This indicator is normalized using the following ratio: the value of resistance for a particular case / the maximum value of resistance (according to FEMA documents)
Response	I_{Res2}	Environmental	Water depth	This indicator can be normalized using the

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				following ratio: the value of water depth for a particular case / the value of water depth corresponding to 0.1% return period
Response	I_{Res3}	Environmental	Flow velocity	This indicator can be normalized using the following ratio: the value of flow velocity for a particular case / the value of flow velocity corresponding to 0.1% return period
Response	I_{Res4}	Physical	Building flooded perimeter	This indicator can be normalized using the following ratio: the value of flooded perimeter for a particular case / the total perimeter of building
Response	I_{Res5}	Physical	Areas of building facades affected by flood	This indicator can be normalized using the following ratio: the affected facade area for a building / the total area of building facades
Recovery	I_{Rec1}	Social	Number of affected people	This indicator can be normalized using the following ratio: the value of affected people from a building / the total number of people from that building
Recovery	I_{Rec2}	Economic	Total economic damage	This indicator can be normalized using the following ratio: the total economic damage generated to a building / the economic value of that building
Recovery	I_{Rec3}	Economic	Downtime	This indicator can be normalized using the following ratio: the value for a specific building / the value for a reference building
Recovery	I_{Rec4}	Environmental	Carbon Output (CO2gwp_eq/sqm/y)	This indicator can be normalized using the following ratio: the value for a specific building / the value for a reference building

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Resilience Readiness calculation method

Following a similar approach as for the other hazards:

$$RRs = (1 - I_{Res1}^{n1} \cdot I_{Res2}^{n2} \cdot I_{Res3}^{n3} \cdot I_{Res4}^{n4} \cdot I_{Res5}^{n5}) \cdot m_1 + (1 - I_{Rec1}^{n6} \cdot I_{Rec2}^{n7} \cdot I_{Rec3}^{n8} \cdot I_{Rec4}^{n9}) \cdot m_2)$$

Each part can be weighted (m_i, n_i) according to its importance or relevance to the case under analysis. These weights can be modified to adapt to a particular interpretation and need to be properly defined by decision makers.

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3. Multi-hazard resilience score

3.1. Multi-criteria approach

Multi-attribute decision-making (MADM) is adopted as a technique to integrate the different resilience indicators in a multi-hazard approach. MADM enables the comparison of predefined alternatives such as existing buildings or retrofit / design options based on selected quantitative resilience criteria. In this approach, each criterion is assigned a weight and rating, allowing for a comprehensive evaluation of each building system's overall performance.

Two compensatory methods, the Analytic Hierarchy Process (AHP) (Saaty 1980 [19]) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981 [20]), are used in a hybrid mode for generating a unified resilience score:

- **Use of AHP to determine weights**. This involves creating a hierarchy and performing a pairwise comparisons of the criteria to determine their relative importance (1 to 9). For each level of the hierarchy, a comparison matrix from the pairwise comparisons is created. The comparison matrix is normalized and the eigenvectors are calculated to obtain the weights for the criteria. Consistency is checked by calculating the consistency ratio to ensure that the pairwise comparisons are consistent. Once the decision matrix is created with the normalized single-hazard resilience scores, this is multiplied by the AHP weights.

- **Use of TOPSIS for ranking the alternatives.** The ideal (best) and negative-ideal (worst) solutions are identified. The ideal solution consists of the maximum values for each criterion if it is beneficial, and the minimum values if it is non-beneficial. Conversely, the negative-ideal solution consists of the minimum values for beneficial criteria and the maximum values for non-beneficial criteria. The Euclidean distance of each alternative from the ideal and negative-ideal solutions are computed, along with the relative closeness of each alternative to the ideal solution. The alternatives are finally ranked based on their relative closeness, where the highest is considered the best option.

Therefore, AHP is used to determine the weighted criteria by leveraging pairwise comparisons, ensuring consistent and reliable judgment on criteria importance. TOPSIS complements AHP by ranking decision variants based on their relative performance. TOPSIS is favored for its simplicity, computational efficiency and ability to evaluate alternatives against an ideal solution using a straightforward mathematical function. By combining AHP for criteria weighting and TOPSIS for ranking decision variants, the hybrid approach in MULTICARE integrates the strengths of both methods. This methodology facilitates the identification of optimal solutions through a systematic process of trade-offs or prioritization of the importance of individual criteria.

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3.2. Implementation within the MULTICARE project

The proposed multi-hazard approach serves as a versatile initial assessment method designed to quickly understand the impact of specific retrofit or design choices on demo buildings. This approach uses a total resilience rating scheme based on a classification scale from 0 to 1, with 1 representing the best possible performance. To visually represent the final result for each building, specific labels ranging from A to G will be assigned, where A indicates higher resilience.

This approach can function as an initial screening tool, leveraging performance criteria derived from existing calculations for various building archetypes. It can also facilitate a more detailed resilience assessment through numerical modeling and simulations tailored to the specific building. For a detailed resilience assessment, the process involves defining hazard models for specific extreme events, as well as developing structural and energy models for the buildings. Performance assessments (deterministic or probabilistic) are then conducted to quantify the proposed resilience parameters.

Furthermore, this approach can be employed to compare the resilience levels of existing buildings within a specific area (**Figure 3**). By using either rapid screening or detailed assessments, a prioritization scheme for intervention planning can be created, ensuring that resources are allocated effectively to enhance building resilience. This study will specifically focus on the demo sites, conducting initial assessments of the areas under investigation. The assessments will consider building archetypes as defined in deliverable 4.4 for Italy, Romania, and The Netherlands.

Hazard				
Heat	H1 H2 ..	H1 H2 ..	H1 H2 ..	H1 H2 ..
Seismic	S1 S2 ..	S1 S2 ..	S1 S2 ..	S1 S2 ..
Flood	F1 F2 ...	F1 F2 ...	F1 F2 ...	F1 F2 ...
Wind	W1 W2 ...	W1 W2 ...	W1 W2 ...	W1 W2 ...
Total score	x1	x2	x3	x4

Figure 3. Prioritizing based on resilience scores, where colors such as red, orange, and green indicate specific resilience levels (high, medium, low).

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4. Conclusion

This deliverable presents quantitative metrics designed to measure and compare the resilience of buildings across various scenarios, including as-built vs retrofitted options and alternative designs. Resilience is addressed from multiple perspectives, encompassing multi-hazard considerations (heat, seismic, wind, flood) and multi-domain factors (physical, economic, social, environmental). By establishing multi-hazard Resilience Readiness levels and categorizing building systems based on their capacity to respond and recover, the framework supports informed resilience planning and enhances building sustainability.

Grounded in extensive analysis of current literature and practices, the proposed resilience metrics will guide the establishment of resilience-based design objectives for the MULTICARE's technological solutions, tailored to specific building uses and hazard exposures. This includes defining resilience goals related to building functionality during hazards and recovery post-events, thereby informing decision-making in resilience design and retrofitting efforts. Moreover, the proposed approach aims to streamline intervention planning on a large scale, offering a rapid assessment method suitable for both initial screening assessments and detailed investigations.

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