Cambiamento climatico, incertezza e valutazione del rischio per le strategie di adattamento nel progetto di architettura

SAGGI E PUNTI DI VISTA/ ESSAYS AND VIEWPOINT

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Giancarlo Paganin[1], https://orcid.org/0000-0002-1508-7570 giancarlo.paganin@polimi.it
Cinzia Talamo[2], https://orcid.org/0000-0001-5916-7620 cinzia.talamo@polimi.it
Nazly Atta[2], https://orcid.org/0000-0003-4221-2020 nazly.atta@polimi.it
[1] Dipartimento di Architettura e Studi Urbani, Politecnico di Milano, Italia
[2] Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Italia

Abstract. Il saggio analizza il rapporto tra ambiente costruito e impatti derivanti dai cambiamenti climatici con l'obiettivo di evidenziare la necessità di sviluppare metodi e strumenti per gestire efficacemente in fase di progetto i numerosi fattori di incertezza presenti nel quadro delle azioni climatiche sugli edifici. In questo ambito il paper propone una analisi delle numerose tecniche di valutazione del rischio disponibili in letteratura per individuare strumenti in grado di supportare la progettazione edilizia nella gestione della incertezza delle azioni climatiche, individuando opportune strategie di adattamento. In una prospettiva di trasferimento tecnologico da altri settori produttivi si propone una sperimentazione nel progetto edilizio di una specifica tecnica di valutazione dei rischi – la *Hazard and Operability study* HAZOP – adattandone le caratteristiche al progetto edilizio e sperimentandone la applicazione in un caso di studio nell'ambito del progetto europeo RE-SKIN.

Parole chiave: Gestione del rischio; Tecnica HAZOP; Rischio climatico; Progetto; Strategie di adattamento.

Introduzione

I molteplici fenomeni connessi con il cambiamento climatico stanno ponendo una urgente sfida ai progettisti e agli altri operatori della filiera delle costruzioni quando chiamati a definire strategie di adattamento: si tratta di una sfida culturale per la quale sono necessari il confronto con molteplici discipline e aree di competenza e l'acquisizione di specifici e finalizzati metodi e strumenti di indagine e valutazione al fine di riconoscere bisogni emergenti e vulnerabilità di sistema, definire priorità, prefigurare soluzioni di adattamento e prevedere la loro efficacia.
Le strutture di progettazione sono chiamate ad acquisire nuove conoscenze e chiavi interpretative per comprendere gli effetti multiscalari sull'ambiente costruito di fenomeni climatici complessi per le loro interazioni, difficilmente riconducibili a precisi perimetri spaziali e temporali e incerti nei loro accadimenti. All'interno di questo scenario di complessità e incertezza, oltre che una consapevolezza della dimensione e delle dinamiche del cambiamento climatico, emerge la necessità di competenze analitiche. Tali competenze sono indispensabili, ad esempio, per: l'interpretazione dei dati climatici (dalla micro alla macroscala); l'indagine delle dinamiche prestazionali dei manufatti edilizi sottoposti ai pericoli cronici e acuti del cambiamento climatico, difficilmente modellizzabili nelle evoluzioni dei loro effetti; il riconoscimento delle trasformazioni dei comportamenti dei fruitori dell'ambiente costruito.
In questa prospettiva di allargamento di conoscenze, competenze e relazioni si collocano gli apparati metodologici della valutazione del rischio climatico, che rappresentano oggi una importante potenzialità come supporto ai processi di conoscenza e decisione finalizzati alla definizione di misure di adattamento. Attualmente la maggior parte delle applicazioni di questi apparati, sviluppati da importanti organismi internazionali (IPCC, ecc.), si colloca alla scala regionale e urbana: è urgente sperimentare alla scala dell'edificio l'appropriatezza dei metodi e strumenti per la valutazione del rischio climatico oggi disponibili, eventualmente individuando logiche di trasferimento e finalizzazione rispetto al progetto di architettura.

Climate change, uncertainty and risk assessment for adaptation strategies in architectural design

Abstract. The paper analyses the relationship between the built environment and impacts deriving from climate change with the aim of highlighting the need to develop methods and tools to effectively manage the numerous uncertainty factors present in the framework of climate actions on buildings in the design phase. In this context, the paper proposes an analysis of the many risk assessment techniques available in the literature to identify tools capable of supporting building design in managing the uncertainty of climate actions by defining appropriate adaptation strategies. In a perspective of technology transfer from other production sectors, the paper proposes an application to the building scale of a specific risk assessment technique – the Hazard and Operability study (HAZOP) – adapting its characteristics to the building project and testing its application to a case study within the European *RE-SKIN* project.

Keywords: Risk management; HAZOP technique; Climate risk; Project; Adaptation strategies.

Introduction

The multiple phenomena related to climate change are posing an urgent challenge to designers and other operators in the construction supply chain when called upon to define adaptation strategies. It is a cultural challenge, which requires the convergence of multiple disciplines and areas of expertise. It also needs the acquisition of specific and targeted methods and tools of investigation and evaluation to recognise emerging needs and system vulnerabilities, define priorities, envisage adaptation solutions, and predict their effectiveness.
Design structures are called upon to acquire new knowledge and interpretative keys to understand the multiscalar effects on the built environment of complex climatic phenomena resulting from their interactions. These are difficult to trace back to precise spatial and temporal perimeters and are uncertain concerning occurrence. The need for analytical skills, as well as awareness of the extent and dynamics of climate change, emerges within this complex and uncertain scenario. These skills are essential, for example, to interpret climate data (from micro to macro scale); to investigate the performance dynamics of buildings subjected to the chronic and acute dangers of climate change, which are difficult to model in the evolution of their effects; and to recognise transformations in the behaviour of users of the built environment.
The methodological apparatuses of climate risk assessment are situated in this perspective of extended knowl-

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Tab. 01 | Classificazione dei pericoli (*hazard*) legati al clima. Fonte: Commission Delegated Regulation (EU) 2021/2139 4 June 2021
Classification of climate-related hazards. Source: Commission Delegated Regulation (EU) 2021/2139 4 June 2021

La dimensione del problema climatico e le strategie di adattamento

A quasi trent'anni dal protocollo di Kyoto, che ha aperto a una presa di coscienza collettiva sulla responsabilità per il cambiamento climatico delle emissioni antropogeniche di gas serra, a oggi le misurazioni evidenziano che le concentrazioni di CO_2 hanno raggiunto il massimo degli ultimi 2 milioni di anni, e che per gli altri gas serra CH4 e N2O sono arrivate al massimo degli ultimi 800.000 anni (WMO, 2025). Gli effetti del cambiamento climatico si presentano come pericoli sia cronici – cambiamenti permanenti – che acuti (Tab. 1), anche identificati come eventi estremi, ormai noti nei loro effetti, ma altamente incerti nei loro tempi di accadimento e nella magnitudo (IPCC, 2023).

L'analisi del nesso di causalità tra cambiamento climatico ed evento estremo specifico è stata oggetto di numerosi studi (Zhai *et al*., 2018; Otto, 2023; Perkins-Kirkpatrick *et al*., 2022). Per quanto riguarda la regione Europea, tali studi evidenziano come i più rilevanti eventi siano relativi a ondate di calore e, a seguire, piogge estreme, inondazioni e siccità.
L'impatto degli eventi climatici – sia cronici che acuti – è rilevante sull'ambiente naturale e antropico con gravi ricadute per la salute e l'incolumità delle popolazioni come pure per i danni economici: in Europa si stima che nel periodo 1980-2023 oltre 240.000 persone abbiano perso la vita per eventi climatici e i danni economici abbiano superato abbondantemente i 700 miliardi di euro (Fig. 1).

| Tab .01

	TEMPERATURE-RELATED	BOUND TO THE WIND	WATER-RELATED	CORRELATED SOLID MASS
CHRONIC	Temperature change (air, fresh water, sea water)	Changing the wind regime	Change in precipitation regime and type (rain, hail, snow/ice)	Coastal erosion
	Heat stress		Precipitation or hydrological variability	Soil degradation
	Temperature variability		Ocean acidification	Soil erosion
	Melting permafrost		Saline intrusion	Solifluction
			Sea level rise	
			Water stress	
ACUTE	Heat wave	Cyclone, hurricane, typhoon	Drought	Avalanche
	Cold/frost wave	Storm (including blizzards, dust, and sandstorms)	Heavy precipitation (rain, hail, snow/ice)	Landslide
	Fires	Air Horn	Floods (coastal, fluvial, rainwater, underground)	Subsidence
			Collapse of glacial lakes	

edge, skills and relationships. Today they have remarkable potential as support for knowledge and decision-making processes aimed at defining adaptation measures. Most of the applications of these devices, developed by leading international bodies (IPCC, etc.), are currently located at the regional and urban scale. It is urgent to experiment at the building scale with the appropriate methods and tools for climate risk assessment available today, possibly identifying a rationale of transfer and finalisation with respect to the architectural project.

Extent of the climatic issue and adaptation strategies

Almost thirty years after the Kyoto Protocol, which opened up a collective awareness of the responsibility for climate change of anthropogenic greenhouse gas emissions, to date measurements show that CO2 concentrations have reached the maximum levels of the last 2 million years. The levels of other greenhouse gases, such as CH4 and N2O, have reached the maximum of the last 800,000 years (WMO, 2025). The effects of climate change are both chronic – permanent changes – and acute hazards (Tab. 1), also identified as extreme events, now known in their effects, but highly uncertain in their timing of occurrence and magnitude (IPCC, 2023).
The analysis of the causal link between climate change and specific extreme events has been the subject of numerous studies (Zhai P., *et al*., 2018; Otto, 2023; Perkins-Kirkpatrick *et al*., 2022). As far as the European region is concerned, these studies show that the most relevant events are related to heat waves and are, subsequently, extreme rainfall, floods and drought.

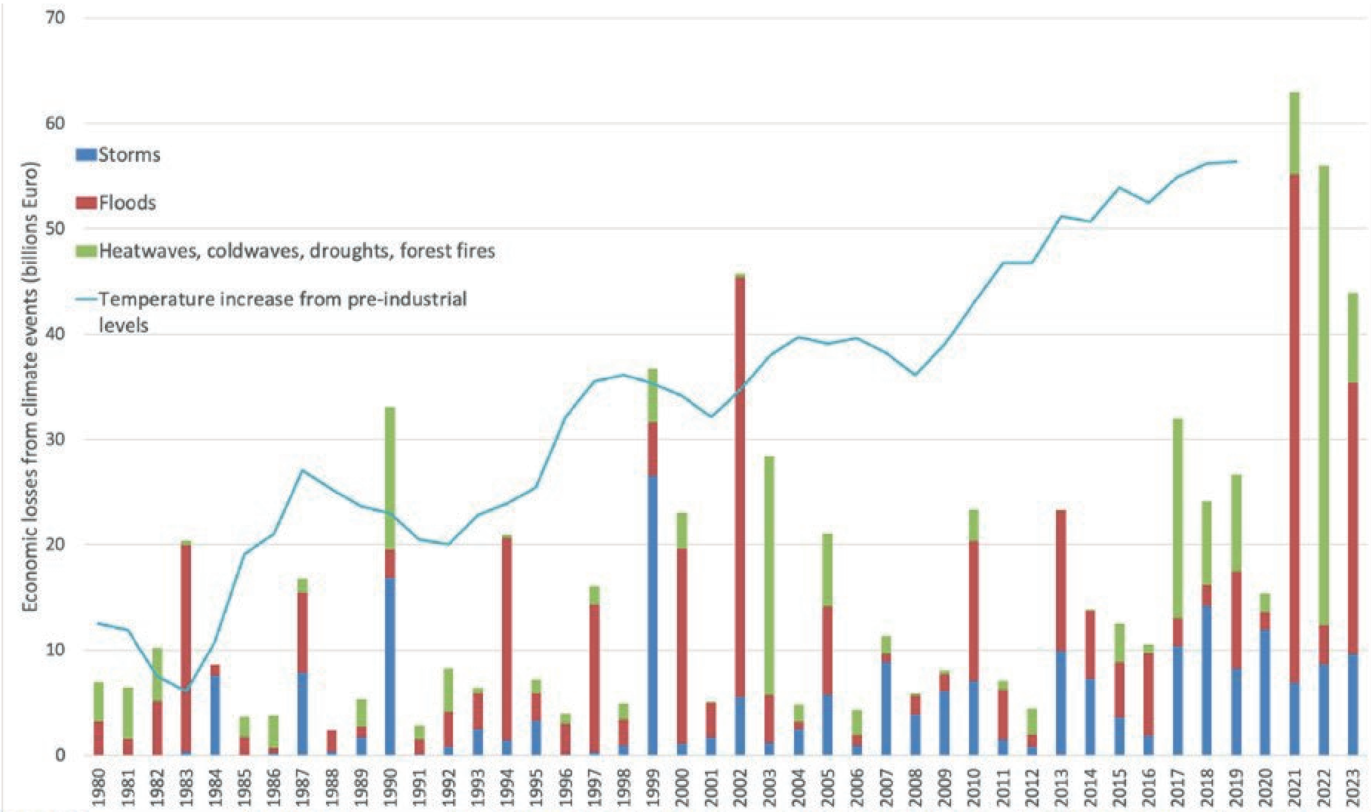
The impact of climate events – both chronic and acute – is significant on the natural and anthropogenic environment, with serious repercussions for the health and safety of populations, as well as for economic damage. It is estimated that more than 240,000 people lost their lives due to climatic events in Europe in the period 1980-2023 with economic damage exceeding 700 billion euros (Fig. 1).
The direct relationship between the average increase in global temperature and the increase in damage caused by extreme events is evident. Indeed, more than half of the total damage recorded over a period of 44 years (1980-2023) has occurred in the last 15 years, highlighting the correlation between the growth of impacts and the acceleration of temperature increase in the European region (Fig. 1).

On the basis of estimates from forecasting models and climate projections, the major international bodies (UNEP, 2024; IPCC, 2014; UNFCCC, 2015) agree that even if greenhouse gas emissions were reduced to zero today, thanks to widespread and effective mitigation actions, the time needed to slow down climate change is in the order of decades. In this scenario, climate adaptation can no longer be seen as a secondary or alternative measure, assuming instead the role of a priority and urgent strategy that must be developed in a multi-scalar dimension, and according to multidisciplinary approaches (Losasso *et al*., 2020; Losasso, 2025), as is the case for mitigation actions.
In the production, management and transformation of the built environment, the definition of adaptation measures at various scales requires

01 | Danni economici e decessi da eventi climatici estremi in Europa. Grafico: andamento dei danni economici causati da eventi climatici estremi in Europa nel periodo 1980-2023 confrontati con l'incremento medio delle temperature annuali rispetto ai livelli pre-industriali. Fonte: European Environment Agency website https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related/annual-economic-losses-caused. Tabella: distribuzione dei danni economici e dei decessi da eventi climatici estremi in Europa dal 1980 al 2023: primi cinque paesi per entità del danno economico. Fonte: https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related

Economic damage and deaths from extreme weather events in Europe. Graph: Trend in economic damage caused by extreme weather events in Europe in the period 1980-2023, considering the average increase in annual temperatures, compared to pre-industrial levels; source: European Environment Agency website https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related/annual-economic-losses-caused. Table: Distribution of economic damage and deaths from extreme weather events in Europe from 1980 to 2023: top five countries in terms of extent of economic damage; source: https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related

01 |



Country	Total losses	Losses per sqkm	Losses per citizen	Insured losses	Insured losses	Fatalities
	Millions EURO	EURO	EURO	Millions EURO	%	N
Germany	180.372	504.438	2.225	54.759	30	104544
Italy	133.934	443.373	2.311	5.916	4	21822
France	129.897	203.449	2.092	46.052	35	50461
Spain	95.966	189.662	2.258	5.243	5	32053
Poland	20.630	66.138	545	1.379	7	2553
Total EU-27	738.280			139.872		245719

the ability to develop, integrate and implement "hard" and "soft" strategies (Sovacool, 2011) by balancing choices based on assessments of risks associated with the effects of climate change, and their impacts in a condition of highly uncertain forecasts of occurrence (Mentges, *et al.* 2023, WEC, 2018).
The Climate-ADAPT adaptation platform (Source: https://climate-adapt.eea.europa.eu) categorises three main categories of adaptation measures, namely grey (infrastructure, technological and engineering solutions), green (nature-based solutions), and soft (political, legal, social, managerial, governance and financial measures). IPCC2 (2014) reinforces the dual "material" and "immaterial" nature of adaptation measures by classifying them as structural and physical, social and institutional. This duality brings out new needs, and the need to develop design approaches oriented towards the flexibility and adaptability of physical systems, besides services capable of strengthening the resilience of systems by leveraging the organisation and management of information (Bernardini, 2024).

Building design, uncertainty and climate risk

The operators in the construction supply chain now have to deal with climate change in their design and production strategies which, as the data show, appears to be characterised by multiple aspects of uncertainty such as speed of evolution and magnitude of the phenomena, ways in which they will affect natural and anthropogenic systems, deriving effects and their interferences, possible impact of current and future policies, funding, regulations and measures.
In this scenario, in which traditional statistical methods and forecasting models no longer appear sufficient to support cognitive and decision-making processes (Taleb, 2009), designing and managing the built environment from the perspective of adaptation, in its hard and soft forms, as a strategy for managing uncertainty implies approaching the culture of risk. Specifically concerning climate risk, this approach found initial criteria, methods and tools in the context of Disaster Risk Reduction (DRR) (Wen *et al.*, 2023; Imamguluyev *et al.*, 2025). The method has steadily evolved, particularly in the last decade (IPCC 2007, IPCC 2014, IPCC 2023, ISO 14901), with the consolidation of some interrelated concepts (Tab. 3). These are essential for assessing climate risk in anthropogenic systems, for developing adaptive design strategies, and for defining intervention priorities. Hazard, vulnerability, sensitivity, exposure, adaptive capacity, and impact are the key concepts common to a series of approaches to climate risk estimation, developed by different international

Il rapporto diretto tra l'aumento medio della temperatura globale e l'incremento dei danni provocati dagli eventi estremi appare evidente: del totale dei danni che sono stati registrati in un periodo di 44 anni (1980-2023) più della metà è stato registrato negli ultimi 15 anni evidenziando la correlazione tra la crescita degli impatti e la accelerazione dell'aumento di temperatura della regione europea (Fig. 1).

Sulla base delle stime derivanti dai modelli previsionali e dalle proiezioni climatiche, i maggiori organismi internazionali (UNEP, 2024; IPCC, 2014; UNFCCC, 2015) concordano sul fatto che anche se le emissioni di gas serra venissero ridotte a zero oggi, grazie ad azioni di mitigazione capillari ed efficaci, il tempo necessario per rallentare i cambiamenti climatici è nell'ordine di grandezza dei decenni. In questo scenario, l'adattamento climatico non può più essere visto di conseguenza come una misura secondaria o alternativa, assumendo viceversa il ruolo di strategia prioritaria e urgente che si deve sviluppare in una dimensione multiscalare e secondo approcci multidisciplinari (Losasso *et al*., 2020; Losasso, 2025), così come avviene per le azioni di mitigazione.

Nella produzione, gestione e trasformazione dell'ambiente costruito la definizione delle misure di adattamento alle varie scale richiede la capacità di sviluppare, integrare e attuare strategie "*hard*" e "*soft*" (Sovacool, 2011) bilanciando le scelte sulla base di valutazioni dei rischi connessi con gli effetti dei cambiamenti climatici e dei loro impatti in una condizione di elevata incertezza delle previsioni di accadimento (Mentges, *et al.* 2023, WEC, 2018).

La piattaforma di adattamento Climate-ADAPT (https://climate-adapt.eea.europa.eu) individua tre principali categorie di misure di adattamento: grigie (soluzioni infrastrutturali, tecnologiche e ingegneristiche), verdi (*nature-based solutions*) e soft (misure politiche, legali, sociali, gestionali, di governance e finanziarie). IPCC[2] (2014) rafforza la duplice natura "materiale" e immateriale" delle misure di adattamento classificandole come strutturali e fisiche, sociali e istituzionali. Questa dualità fa emergere nuove esigenze e la necessità sviluppare da una parte approcci progettuali orientati alla flessibilità e alla adattabilità dei sistemi fisici, dall'altra servizi capaci di rafforzare la resilienza dei sistemi facendo leva sull'organizzazione e sulla gestione delle informazioni (Bernardini, 2024).

Progettazione degli edifici, incertezza e rischio climatico

Appare ormai ineludibile per gli operatori della filiera delle costruzioni il dover confrontarsi nelle loro strategie progettuali e produttive con il cambiamento climatico che, come i dati dimostrano, appare essere caratterizzato da molteplici aspetti di incertezza quali: velocità di evoluzione e magnitudo dei fenomeni, modalità con cui questi interesseranno i sistemi naturali e antropici, effetti derivanti e loro interferenze, possibile incidenza delle politiche, dei finanziamenti, delle normative e delle misure presenti e future.

In questo scenario, nel quale i tradizionali apparati statistici e i modelli previsionali appaiono non più sufficienti a supportare i processi conoscitivi e decisionali (Taleb, 2009), progettare e gestire l'ambiente costruito nella prospettiva dell'adattamento, nelle sue forme hard e soft, come strategia di gestione dell'incertezza implica un avvicinamento alla cultura del rischio, che, nel declinarsi nello specifico del rischio climatico, ha trovato nell'ambito

bodies to systematise and make available various methods and tools of evaluation and decision-making support (Tab. 2) for different types of decision-makers (regions, cities, organisations, etc.) in different fields of action (finance, public administration, etc.).

Developing, right from the meta-design phase (D'Ambrosio, 2017), an architectural organism characterised by adaptive capacity in terms of settlement, typology and technology implies the ability to assess the climate risk with progressive levels of in-depth analysis, by exploring the key concepts described (Tab. 3) regarding the natural and anthropic context, the modes of use, systemic interactions, the possible behaviour of users, as well as technical systems and materials.

If the analysis of climate risks is integrated into the decision-making process and the evaluation of alternative design solutions, articulated skills are required, for example, to select and interpret climate data at different spatial (from macro to micro-local level) and temporal scales; to simulate performance dynamics of buildings (not always known as, for example, the ageing time in relation to the variability and uncertainty of the magnitude of extreme events), in the presence of various chronic and acute climate hazards (Dong *et al.* 2022); and to analyse the needs of users of the built space. With respect to the latter, in order to investigate behavioural reactions and sensitivity to climate change at the level of both communities and individuals (e.g., in relation to age, gender, class), it is necessary to acquire contextual knowledge also with the support of typical methods of the social sciences (e.g., focus groups and interviews).

The several approaches to climate risk assessment (Tab. 2) include those proposed by IPCC in its Assessment Reports (AR4, AR5 and AR6), and by ISO 14091:2021 "Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment" (Monteiro *et al*., 2022; Farinós-Dasí *et al*., 2024; Ye *et al*., 2025).

The IPCC and ISO approaches share some common concepts (Tab. 3) that are used differently. The model proposed by AR 4 (IPCC, 2007) aims to assess the vulnerability of systems, while the subsequent AR5 (IPCC, 2014) aims to assess the risk in relation to the characteristics of the system under consideration. The approach proposed by ISO 14091:2021 appears to be a development of the AR5 approach by highlighting the potential contribution of adaptation actions to the reduction of potential risk.

The ISO approach (Fig. 2) first assesses the potential climate risk, and then introduces the contribution of the system's adaptive capacity to change the level of risk by highlighting its value.

The approaches to risk assessment (Tab. 2) have in common a rationale of identifying the causal links between climate hazards and the extent of the consequences on human systems. In order to systematically assess the links between hazards and consequences – taking into account the multiple stakeholders involved – and to consequently identify priorities for intervention and their possible impact with respect to different value systems, the ISO 14091:2021 standard refers to the Impact Chain approach as an "*analytical approach that enables understanding of how given hazards generate direct and indirect impacts, which propagate through a system at risk*". Impact della *Disaster Risk Reduction* (DRR) (Wen *et al*., 2023; Imamguluyev *et al*., 2025) un iniziale apparato di criteri, metodi e strumenti. Questo apparato ha visto, in particolare nell'ultimo decennio, una costante evoluzione (IPCC 2007, IPCC 2014, IPCC 2023, ISO 14901) e il consolidarsi di alcuni concetti interrelati (Tab. 3), basilari per la valutazione del rischio climatico nei sistemi antropici, per lo sviluppo di strategie progettuali adattive e per la definizione delle priorità di intervento. Pericolo, vulnerabilità, sensibilità, esposizione, capacità adattiva, impatto sono i concetti chiave, comuni ad una serie di approcci alla stima del rischio climatico, sviluppati da diversi organismi internazionali al fine di sistematizzare e mettere a disposizioni vari metodi e strumenti di supporto valutativo e decisionale (Tab. 2) per diversi tipi di decisori (regioni, città, organizzazioni, ecc.) in diversi campi di azione (finanza, amministrazione pubblica, ecc.).

Sviluppare, fin dalla fase metaprogettuale (D'Ambrosio, 2017), un organismo architettonico caratterizzato da capacità adattiva in termini insediativi, tipologici e tecnologici implica la capacità di valutare, con livelli di approfondimento progressivo, il rischio climatico analizzando i concetti chiave descritti (Tab. 3) in relazione al contesto naturale e antropico, ai modi d'uso, alle interazioni sistemiche, ai possibili comportamenti degli utilizzatori e dei sistemi tecnici e dei materiali.

Se l'analisi dei rischi climatici entra nel processo conoscitivo decisionale e nella valutazione delle soluzioni progettuali alternative sono necessarie articolate competenze, per esempio, per: la selezione e interpretazione dei dati climatici a diverse scale spaziali (dal livello macro a quello micro-locale) e temporali; la simulazione in presenza dei vari pericoli climatici cronici e acuti (Dong *et al.* 2022) delle dinamiche prestazionali degli edifici (non sempre note come, per esempio, il tempo di invecchiamento in relazione alla variabilità e alla incertezza della magnitudo degli eventi estremi); l'analisi dei bisogni dei fruitori dello spazio costruito. Rispetto a questi ultimi, per indagare reazioni comportamentali e sensibilità al cambiamento climatico a livello sia di collettività che di individui (per esempio in relazione all'età, al genere, al ceto) è necessario acquisire conoscenze contestuali anche con il supporto di metodi tipici delle scienze sociali (per esempio *focus group* e interviste).

Tra i numerosi approcci alla valutazione del rischio climatico (Tab. 2) appaiono essere maggiormente applicati quelli proposti da IPCC nei suoi *Assessment Report* (AR4, AR5 e AR6) e dalla norma ISO 14091:2021 *"Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment"* (Monteiro *et al*., 2022; Farinós-Dasí *et al*., 2024; Ye *et al*., 2025).

Gli approcci IPCC e ISO sono accomunati da alcuni concetti comuni (Tab. 3) che vengono utilizzati in modo diverso; il modello proposto dall'AR 4 (IPCC, 2007) ha l'obiettivo di valutare la vulnerabilità dei sistemi mentre il successivo AR5 (IPCC, 2014) ha l'obiettivo di valutare il rischio in relazione alle caratteristiche del sistema in esame. L'approccio proposto dalla norma ISO 14091:2021 appare uno sviluppo dell'approccio AR5 mettendo in evidenza il potenziale contributo delle azioni di adattamento alla riduzione del rischio potenziale.

L'approccio ISO (Fig. 2) valuta, in primo luogo, il potenziale rischio climatico e successivamente introduce il contributo della capacità di adattamento del sistema per modificare il livello di rischio evidenziandone il valore.

Gli approcci alla valutazione del rischio (Tab. 2) sono accomunati da una logica di individuazione dei nessi di causalità tra i

Chains are usually developed with the support of workshops, focus groups, round tables and other participatory activities, involving stakeholders and experts. The involvement of different skills in risk assessment, at the basis of the Impact Chain approach, can be developed by integrating different techniques such as, for example, Delphi technique, Brainstorming, Nominal Group Technique, and HAZOP (IEC 31010:2019). These techniques have some characteristics in common, as they:

- involve all project operators in their application in a rationale of participatory planning of adaptation measures;
- allow for a gradual application of the systems under consideration at different levels of complexity;
- are not an additional tool applied by specialists external to the project team but are meant to be a shared tool;
- allow risks to be assessed by interpreting them against the framework of objectives expected for the project.

The impact chain approach is now widely used at the regional or urban scale (Estoque *et al*., 2022; Menk *et al*., 2022) but its rationale can also be used for buildings by activating participatory design processes to acquire knowledge about the system's sensitivity and vulnerability (Dodman *et al*., 2022). There are many recent studies developed with the active involvement of supply chain stakeholders and scholars (André *et al*., 2023; Englund *et al*., 2022; Daniels *et al*., 2020) highlighting the benefits of assessing climate risks, on different scales, by adopting knowledge co-production and sharing case studies.

The potential of the HAZOP technique in climate risk management

Among the techniques mentioned, it seems interesting, with respect to the issues of climate risk management, to evaluate the possibility of applying the HAZOP "Hazard and Operability study" methodology in architectural projects, using it in a broader Impact Chain process or in a timely manner for a preliminary assessment of climate risks and possible adaptive actions. HAZOP derives from risk analysis techniques developed in the 1970s by the chemical industry that led, in 2001, to the publication of the international standard IEC 61882, which formally described HAZOP (Dunjò *et al*., 2010). Although HAZOP was developed for processes involving a significant use of hazardous substances, its application has subsequently spread to other areas such as medical devices, road traffic safety, and operation of photovoltaic systems (Marhavilas *et al*., 2019).

The main features of HAZOP are:

- to be a "collegial" process developed by a team of experts from the different design disciplines under the guidance of a coordinator;
- to be a process directed by the use of "guiding words", which are useful for the shared identification of potential changes in the design parameters;
- to set the goal of identifying potential deviations from the project objectives in order to adopt appropriate risk control measures.

As far as the methodological steps are concerned, the main phases of the HAZOP proposed by the EN 61882:2016 standard are:

- division of the system into sections or subsystems;

Tab. 02 | Esempi di approcci per la valutazione e gestione del rischio da cambiamenti climatici per i sistemi antropici
Examples of approaches for the assessment and management of climate change risk for anthropogenic systems

| Tab. 02

INSTITUTION AND **APPROACH/ METHOD**	**DESCRIPTION**	**KEYWORDS** AND **KEY CONCEPTS**	**REFERENCE/S**
Assessment reports - Intergovernmental Panel on Climate Change (IPCC)	*«The Sixth Assessment Report (AR6) by IPCC proposes an approach to assess the risk related to climate change based on the evaluation of the complex interactions between climate-related hazards, like floods and droughts, and the vulnerability of human and ecological systems to these hazards. The report introduces key concepts that contribute to an understanding of risk, including: the risk components, namely **hazards**, **exposure**, and **vulnerability**; the recognition that risks may be complex and cascading; and the reasons for concern framework used to summarise the most policy-relevant risks.* ***Risk** in the Sixth Assessment Report is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system. In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs or negative side effects».*	– Climate-related hazards – Exposure and vulnerability – Complex interactions	https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-1/
ISO 14091:2021 - International Organization for Standardization (ISO)	*«The ISO 14091:2021 standard "Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment" support the assessment of the risks related to the potential impacts of climate change. It describes how to understand vulnerability and how to develop and implement a sound risk assessment in the context of climate change. It can be used for assessing both present and future climate change risks.* *The ISO 14091 standard poposes the following steps:* ***– Preparing a climate change risk assessment** – including: **i**dentifying objectives and expected outcomes; establishing a project team; setting the time horizon; preparing an implementation plan; etc.* ***– Implementing a climate change risk assessment** – including: screening impacts and developing impact chains; identifying indicators; Assessing adaptive capacity; etc.* ***– Reporting and communicating climate change risk assessment results** – including: communicating climate change risk assessment results; reporting findings as a basis for appropriate adaptation planning; etc.»*	– Adaptation planning – Vulnerability – Participatory approach	https://www.iso.org/standard/68508.html
CLIMADA (CLIMate ADAptation) – ETH Zurich	***«CLIMADA (CLIMate ADAptation)** is a free and open-source software framework for climate risk assessment and adaptation option appraisal. Designed by a large scientific community, it helps reasearchers, policymakers, and businesses analyse the **impacts of natural hazards** and explore **adaptation strategies**.* *CLIMADA integrates **hazard, exposure, and vulnerability data** to provide detailed insights into potential socioeconomic, human, and ecological impacts of climate-related events. The framework supports a wide range of input data and includes tailored solutions for **integrating data from various sources** such as OpenStreetMap, the International Best Track Archive for Climate Stewardship, the Copernicus Climate Data Store, and many more».*	– Framework for climate risk assessment – Natural hazards – Adaptation strategies – Multiple-sources data	https://climada.ethz.ch/
TCFD disclosure recommendations - Task Force on Climate-Related Financial Disclosures (TCFD)	*«The TCFD disclosure recommendations are structured around four thematic areas that represent core elements of how companies operate: governance, strategy, risk management, and metrics and targets. In particular:* ***– Governance** – Disclose the organization's governance around climate-related risks and opportunities.* ***– Strategy** – Disclose the actual and potential impacts of climate-related risks and opportunities on the organization's businesses, strategy, and financial planning where such information is material.* ***– Risk Management** – Disclose how the organization identifies, assesses, and manages climate-related risks.* ***– Metrics and Targets** – Disclose the metrics and targets used to assess and manage relevant climate-related risks and opportunities where such information is material».*	– Financial Markets and Transparency – Financial Implications of Climate Change – Pricing of risks and allocation of capital in the global economy	https://www.fsb-tcfd.org/ https://www.fsb-tcfd.org/recommendations/ https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf
Climate and Disaster Risk Screening - World Bank	*«Climate and Disaster Risk Screening is a process for identifying short and long term climate and disaster risks to build resilience in development projects, policies, and programs.* *The Screening aims to identify risks and proactively incorporate resilience measures at an early stage of project design objectives.* *The Four Main Phases:* ***– Exposure** – evaluate the extent to which the project location will be exposed to risks from climate change and geophysical disasters.* ***– Impact** – assess how these hazards may impact the project's physical investments and beneficiaries. Start to consider risk mitigation measures.* ***– Adaptive Capacity** – examine how a project's non-physical components and the broader sector and development context may influence the level of risk posed to the project. Also consider impacts on vulnerable groups.* ***– Overall Risk Rating** – rate the overall risk from climate and geophysical hazards to the project outcome based on the previous considerations».*	– Adaptive Capacity – Impacts on vulnerable groups – Resilience measures intregrated at an early project design stage	https://climatescreeningtools.worldbank.org/ https://climatescreeningtools.worldbank.org/what-does-the-screening-process-look https://climatescreeningtools.worldbank.org/in-depth-assessment-tool

(Continued)

Tab. 02 | Esempi di approcci per la valutazione e gestione del rischio da cambiamenti climatici per i sistemi antropici
Examples of approaches for the assessment and management of climate change risk for anthropogenic systems

INSTITUTION AND **APPROACH/ METHOD**	**DESCRIPTION**	**KEYWORDS** AND **KEY CONCEPTS**	**REFERENCE/S**
Regional Adaptation Support Tool (RAST) - Climate-ADAPT	*«The Regional Adaptation Support Tool (RAST) is designed to help local and regional authorities with climate change adaptation strategies and plans – from development and implementation to monitoring, evaluating and updating them. RAST provides practical guidance in 6 steps aligned with the key features of climate adaptation policy processes.* *The tool consists of the following subsequential steps:* – ***Preparing the ground for adaptation*** *– including: setting up governance structures to support adaptation; communicating adaptation and raising awareness.* – ***Assessing climate risks and vulnerabilities*** *– including: defining the core elements of your climate risk assessment; identifying and assessing climate risks; defining key adaptation objectives, etc.* – ***Identifying adaptation options*** – ***Assessing and selecting adaptation options*** – ***Implementing adaptation policies and actions*** *– including: developing adaptation strategies and plans; integrating adaptation into existing plans; Funding and supporting governance for implementation, etc.* – ***Monitoring, evaluation and learning»***	– Local or regional authority's policy-making – Development of climate change adaptation plans – Planning and implementing adaptation actions at the regional level	https://climate-adapt.eea.europa.eu/en https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data/regional-adaptation-support-tool https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data
Physical Climate Risk Assessment and Management - Adaptation and Resilience Investors Collaborative (ARIC) and UNEP	*«The Adaptation and Resilience Investors Collaborative (ARIC) have developed the Physical Climate Risk Investor Playbook. The latter provides investors with a simplified step-by-step approach to integrate the identification, assessment and management of physical climate risks in the investment process. It focuses on how to assess* ***physical climate risks*** *and identify* ***adaptation and resilience (A&R) opportunities*** *in the context of corporate finance and is product agnostic, applying to the provision of capital across both equity and debt instruments».*	– Corporate Finance – Physical Climare Risks – Adaptation and resilience opportunities	https://www.unepfi.org/wordpress/wp-content/uploads/2024/10/ARIC-PCR-Playbook-2.pdf

pericoli climatici e l'entità delle conseguenze sui sistemi umani. Al fine di valutare in modo sistematico i nessi tra pericoli e conseguenze – tenendo in considerazione i molteplici portatori di interessi coinvolti – e di individuare di conseguenza priorità di intervento e la loro possibile incidenza rispetto a sistemi di valore diversi, la norma ISO 14091:2021 fa riferimento all'approccio *Impact Chain* che definisce come «*analytical approach that enables understanding of how given hazards generate direct and indirect impacts which propagate through a system at risk*». Le *Impact Chain* sono solitamente sviluppate con il supporto di *workshop*, *focus group*, tavole rotonde ed altre attività partecipative, coinvolgendo *stakeholder* ed esperti. Il coinvolgimento di diverse competenze nella valutazione del rischio, alla base dell'approccio *Impact Chain*, può essere sviluppato integrando diverse tecniche come, ad esempio: *Delphi technique, Brainstorming, Nominal Group Technique*, HAZOP (IEC 31010:2019). Si tratta di tecniche accomunate da alcune caratteristiche:

– coinvolgere nella loro applicazione tutti gli operatori del progetto in una logica di progettazione partecipata delle misure di adattamento;
– consentire un'applicazione graduale a diversi livelli di complessità dei sistemi in esame;
– non essere uno strumento aggiuntivo applicato da specialisti esterni al *team* di progetto ma essere uno strumento condiviso;

– identification of an element of the system under study (e.g., cold production, etc.);
– description of the design objectives attributed to the element (e.g., maintenance of previously established environmental conditions);
– choice of an operating parameter that influences the design objectives (e.g., outdoor temperature, etc.);
– application of guide words describing possible deviations in operating parameters;
– definition of the causes that can lead to deviations and evaluation of the effects;
– selection of appropriate risk management measures.

In the HAZOP technique the use of "guiding words" (Tab. 4) helps to define uncertainty scenarios on the design parameters. The guiding words describe a possible deviation from an expected condition and are, therefore, critical in determining the potential levels of uncertainty and the resulting risks, allowing designers to take counteracting or containment measures.

Applying the HAZOP technique to a case study

For validation purposes, the HAZOP method was applied as part of the European Horizon project "RE-SKIN – Renewable and Environmental-Sustainable Kit for building Integration". The RE-SKIN project aims to develop a scalable and multifunctional system (kit) based on advanced façade and roof solutions and "smart" technological systems. It should be integrated into existing buildings to offer a joint response to the demand for energy efficiency and environmental quality expressed by the recent European regulatory framework (Green Deal, Circular Economy Action Plan, Fit for 55 Package, Energy Performance of Buildings Directive, etc.).

In particular, the HAZOP method has been applied in experimental form to two subsystems of the RE-SKIN project, namely:

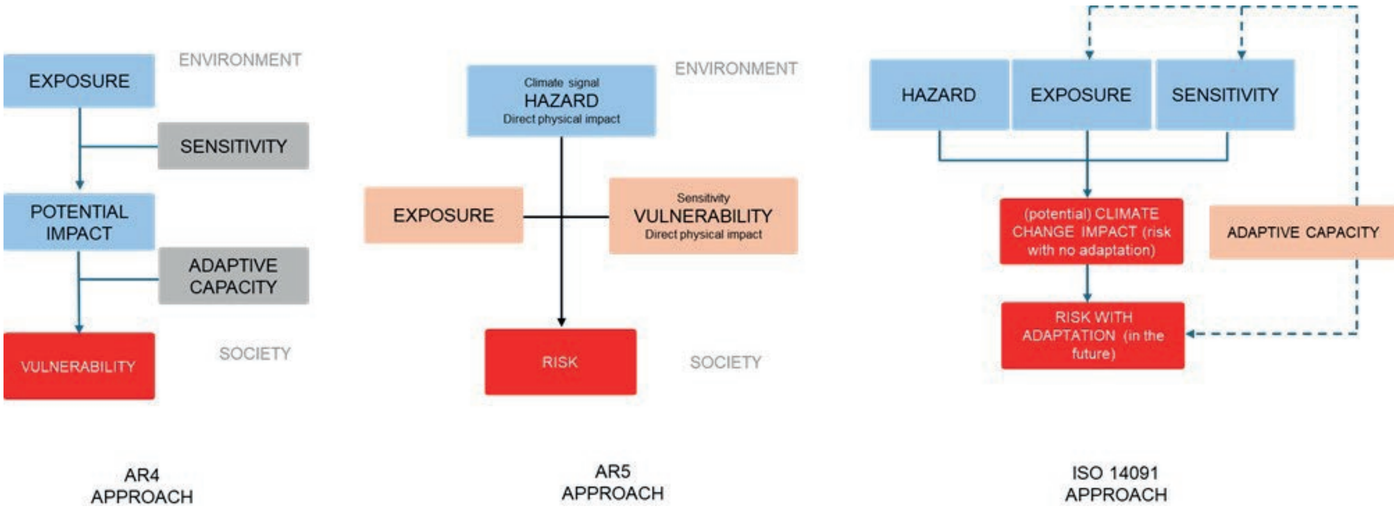
– roofing solution with integrated photovoltaic-thermal system (BI-PVT) (Fig. 3). The solution consists of profiles for curtain walls in recycled aluminium, where box sheet panels containing bio-polyurethane foam and photovoltaic modules are housed;
– air-to-water heat pump (Fig. 4).

Application of the HAZOP technique within the project allowed to assess—by involving various project stakeholders to share knowledge and experiences—the potential risks from climate events for some components of the RE-SKIN system, and to also determine possible technical adaptation measures to be adopted during the design and management phases with a view to reduce the impacts of such events. Experimentation with the transfer of the technique from the traditional industrial context to that of the construction project did not reveal any particular need for modification or adaptation. Indeed, the qualitative approach activated by the guiding words is well suited to the objective of identifying possible climate risk scenarios to be subjected to specific in-depth analyses to identify climate adaptation design or management measures. The application of the HAZOP technique to the architectural project can be implemented without significantly modifying current design practices. It essentially takes place through collegial design review meetings, which, however, require two basic conditions: firstly,

02 | Evoluzione degli approcci alla valutazione del rischio climatico IPCC e ISO 14091
Evolution of IPCC and ISO 14091 climate risk assessment approaches

Tab. 03 | Concetti chiave legati alla gestione del rischio climatico. Fonte: adattato da ISO 14091:2021
Key concepts related to climate risk management. Source: adapted from ISO14091:2021

| 02



– permettere di valutare i rischi interpretandoli rispetto al quadro di obiettivi attesi per il progetto.

L'approccio della *impact chain* è oggi largamente impiegato alla scala regionale o urbana (Estoque *et al.*, 2022; Menk *et al.*, 2022) ma in virtù della sua logica si presta ad impieghi anche alla scala dell'edificio, con l'attivazione di processi di progettazione partecipata per acquisire conoscenza rispetto alla sensitività e alla vulnerabilità (Dodman *et al.*, 2022) del sistema. Sono molteplici gli studi recenti (André *et al.*, 2023; Englund *et al.*, 2022; Daniels *et al.*, 2020) che evidenziano i benefici alle diverse scale sulla capacità di valutare i rischi climatici ottenibili da processi di co-produzione della conoscenza e condivisione di casi di studio, sviluppati con il coinvolgimento attivo di *stakeholder* di filiera e studiosi.

Il potenziale della tecnica HAZOP nella gestione dei rischi climatici

Tra le tecniche citate, appare interessante, rispetto ai temi della gestione del rischio climatico, valutare la possibilità di applicare nei progetti di architettura la metodologia HAZOP "*Hazard and Operability study*", utilizzandola in un processo più ampio di *Impact Chain* o in modo puntuale per una preliminare valutazione dei rischi climatici e delle possibili azioni adattive. La HAZOP deriva da tecniche di analisi del rischio sviluppate

| Tab. 03

	Definition – Source: ISO 14091:2021
HAZARD	***«Potential source of harm.*** *Note 1 to entry: The potential for harm can be in terms of loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.* *Note 2 to entry: In this document, the term usually refers to climate-related physical events or trends or their physical impacts.* *Note 3 to entry: Hazard comprises slow-onset developments (e.g. rising temperatures over the long term) as well as rapidly developing climatic extremes (e.g. a heatwave) or increased variability».*
EXPOSURE	***«Presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected.*** *Note 1 to entry: Exposure can change over time, for example as a result of land use change».*
SENSITIVITY	***«Degree to which a system or species is affected, either adversely or beneficially, by climate variability or change.*** *Note 1 to entry: The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise) ».*
ADAPTIVE CAPACITY	***«Ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences»***
VULNERABILITY	***«Propensity or predisposition to be adversely affected*** *Note 1 to entry: Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt».*
IMPACT	***«Effect on natural and human systems*** *Note 1 to entry: In the context of climate change, the term "impact" is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate change or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts and sea level rise, are a subset of impacts called "physical impacts"».*

Tab. 04 | Esempi di parole guida nella applicazione della metodologia HAZOP. Fonte: EN 61882:2016

Examples of guiding words in the application of the HAZOP methodology. Source: EN 61882:2016

| Tab. 04

GUIDING WORD	MEANING IN THE CONTEXT OF ANALYSIS
NO	Complete denial of design intent
MORE	Quantitative increase
LESS	Quantitative decrease
BEYOND	Qualitative change/increase
PART OF	Qualitative change/decrease
REVERSAL	Logical opposite of design intent
OTHER	Complete replacement
BEFORE	With respect to an order or sequence
AFTER	With respect to an order or sequence
BEFOREHAND	Compared to time
LATE	Compared to time

negli anni '70 dall'industria chimica, le quali hanno portato nel 2001, alla pubblicazione della norma internazionale IEC 61882 che ha descritto formalmente la HAZOP (Dunjò *et al.*, 2010). Anche se la HAZOP è stata sviluppata per processi che prevedono un impiego significativo di sostanze pericolose la sua applicazione si è successivamente diffusa anche ad altri ambiti come dispositivi medicali, sicurezza del traffico stradale, esercizio di impianti fotovoltaici (Marhavilas *et al.*, 2019).

Le caratteristiche principali della HAZOP sono:

- essere un processo "collegiale" sviluppato da un gruppo di esperti delle diverse discipline di progetto con la guida di un coordinatore;
- essere un processo indirizzato dall'uso di "parole guida" utili per la individuazione condivisa dei potenziali cambiamenti dei parametri di progetto;
- porsi l'obiettivo di individuare potenziali deviazioni rispetto agli obiettivi di progetto per adottare appropriate misure di controllo del rischio.

Per quanto riguarda i passaggi metodologici, le principali fasi della HAZOP proposte dalla norma EN 61882:2016 sono:

- divisione del sistema in sezioni o sottosistemi;
- individuazione di un elemento del sistema oggetto di studio (ad esempio: produzione del freddo, ecc.);
- descrizione degli obiettivi progettuali attribuiti all'elemento (ad es. mantenimento di condizioni ambientali prefissate);
- scelta di un parametro di funzionamento che influenza gli obiettivi progettuali (ad esempio: temperatura esterna, ecc.);
- applicazione di parole guida che descrivano le possibili deviazioni dei parametri di funzionamento;
- definizione delle cause che possono portare alle deviazioni e valutazione degli effetti;
- selezione di appropriate misure di gestione del rischio.

Nella HAZOP l'uso di "parole guida" (Tab. 4) aiuta a definire scenari di incertezza sui parametri di progetto. Le parole guida descrivono una possibile deviazione rispetto a una condizione attesa e sono quindi fondamentali per determinare i potenziali livelli di incertezza e i rischi che ne conseguono consentendo ai progettisti di assumere misure di contrasto o contenimento.

Applicazione della tecnica HAZOP a un caso di studio

Per sperimentare la validità dell'ipotesi di trasferimento, la metodologia HAZOP è stata applicata nell'ambito del progetto europeo Horizon "RE-SKIN – Renewable and Environmental-Sustainable Kit for building Integration". Il progetto RE-SKIN mira a sviluppare un sistema (*kit*) scalabile e multifunzionale basato su soluzioni avanzate di facciata, copertura e su sistemi tecnologici "smart" da integrare negli edifici esistenti per offrire una risposta congiunta alla domanda di efficienza energetica e

the identification of a qualified person capable of coordinating the working group; secondly, for effective application of the technique, widespread knowledge of climate risks and their effects on the built environment must be created within the design team.

Conclusions

The chronic and acute hazards of climate change open up scenarios of epistemic uncertainty on how the built environment and its inhabitants react to the many phenomena, which are hard to predict and linked by synergistic and multi-scalar effects. In this scenario, as they are being developed globally, climate risk assessment methods are configured as an important support in the cognitive and decision-making activities of the project. They offer a systematic apparatus for the definition of adaptation strategies, which are declined within different contexts, including design of new interventions characterised by "design for adaptability" approaches; management of the built environment considering which improvement actions can be implemented on buildings (hard), and development of targeted services (soft); transformation of architectural organisms with one objective being an increase in resilience.

The conceptual and methodological apparatus for climate risk assessment is evolving. Today it provides an important support in defining new project requirements, in reading systemic links between territory and buildings at different scales, in evaluating the vulnerabilities of buildings and their inhabitants in the light of hazards deriving from climate change and the potential of adaptation measures for their management. It seems increasingly urgent to adopt methodologies and tools of this framework at the project scale. They are currently applied mostly at the territorial scale.

With respect to these considerations, the paper proposes running a test by transferring the HAZOP technique to the building scale with a view to identify and assess climate risks. This method, applied at the building and subsystem scales, enables effective interaction between the various skills involved in the project, adopting a participatory and shared identification and assessment approach for risks associated with extreme climate events for building systems, and for the effective identification of related adaptation measures.

Based on the findings from the application phase, the tool replicability and scalability appear to be guaranteed, although depending on the availability of information regarding the characteristics of the building systems identified in the project, especially during the preliminary design phase, and of the level of knowledge of the reference climate context and the extreme climate events likely to occur in the project area.

Concluding, transferring and applying the HAZOP technique for climate risk assessment at the building level is an innovation that should be part of a broader effort to develop a suite of tools to support climate adaptation design decisions. This effort must include building new climate adaptation design skills; expanding participatory design and knowledge co-creation practices to include climate change issues; and experimenting with assessment methods at various levels of project development. Among contextual conditions that could both accelerate

qualità ambientale espressa dal recente quadro normativo europeo (*Green Deal*, *Circular Economy Action Plan*, *Fit for 55 Package*, *Energy Performance of Buildings Directive*, ecc.).
In particolare, la metodologia HAZOP è stata applicata in forma sperimentale a due sottosistemi del progetto RE-SKIN, ovvero:
– soluzione di copertura con sistema fotovoltaico-termico integrato (BIPVT) (Fig. 3). La soluzione è costituita da profili per facciate continue in alluminio riciclato, dove sono alloggiati pannelli in lamiera scatolare contenenti schiuma bio-poliuretanica e moduli fotovoltaici;
– pompa di calore aria-acqua (Fig. 4).

L'applicazione della tecnica HAZOP nell'ambito del progetto ha consentito di valutare – coinvolgendo diversi *stakeholder* di progetto per condividere conoscenze ed esperienze – i potenziali rischi da eventi climatici per alcune componenti del sistema RE-SKIN e, nello stesso tempo, di determinare in maniera condivisa possibili misure tecniche di adattamento da adottare in fase di progettazione e in fase di gestione per ridurre gli impatti di tali eventi. La sperimentazione del trasferimento della tecnica dall'ambito tradizionalmente industriale a quello del progetto edilizio non ha evidenziato una particolare necessità di modifiche o adattamento: l'approccio qualitativo attivato dalle parole guida ben si presta all'obiettivo di individuare possibili scenari di rischio climatico da sottoporre poi a specifiche analisi di approfondimento per l'individuazione delle misure progettuali o gestionali di adattamento climatico. L'applicazione della tecnica HAZOP al progetto di architettura può essere attuata senza necessità di modificare significativamente le attuali prassi progettuali sviluppandosi essenzialmente in riunioni collegiali di riesame della progettazione che richiedono però due condizioni di base: da un lato si deve predisporre la qualifica di un soggetto che possa attuare un ruolo di coordinamento del gruppo di lavoro; dall'altro per una efficace applicazione della tecnica si deve creare una conoscenza diffusa all'interno del gruppo di progettazione dei rischi climatici e dei loro effetti sull'ambiente costruito.

Conclusioni

I pericoli, sia cronici che acuti, legati al cambiamento climatico aprono a scenari di incertezza epistemica sulle modalità di reazione dell'ambiente costruito e dei suoi abitanti rispetto alla molteplicità dei fenomeni, difficili da prevedere e legati da effetti sinergici e multiscalari. In questo scenario, le metodiche di valutazione dei rischi climatici si configurano come un importante supporto nelle attività conoscitive e decisionali del progetto, offrendo un apparato sistematico per la definizione di strategie di adattamento, che si declinano all'interno di diversi contesti: progettazione di nuovi interventi connotati da approcci "*design for adaptability*"; gestione dell'ambiente costruito rispetto al quale integrare azioni migliorative sui manufatti (*hard*) e sviluppo di servizi mirati (*soft*); trasformazioni degli organismi architettonici, dove uno degli obiettivi diviene l'innalzamento della loro resilienza.
L'apparato concettuale e metodologico per la valutazione del rischio climatico è in evoluzione e rappresenta oggi un supporto importante per la definizione di nuovi quadri esigenziali per il progetto, per la lettura alle diverse scale dei nessi sistemici tra territorio e manufatti edilizi, per la pesatura delle vulnerabilità degli organismi edilizi e delle potenzialità delle misure di adattamento per la loro gestione. Appropriarsi alla scala del progetto delle me-

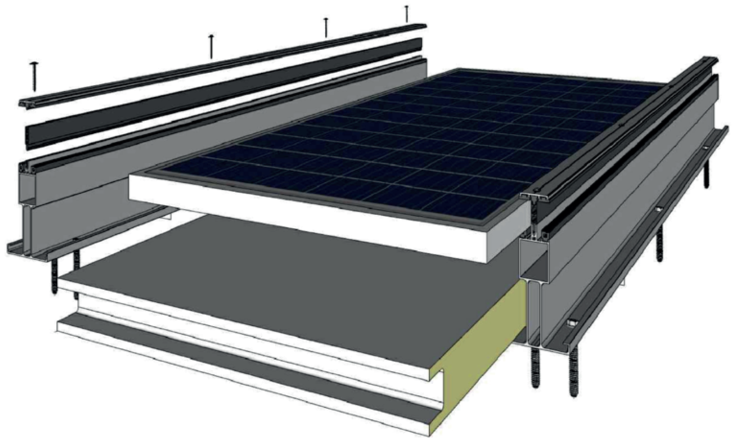
and facilitate widespread application of this experiment, the interaction among the key stakeholders who have to address the impacts of climate change is crucial. Indeed, local governments must manage emergencies caused by climate events, insurance companies can effectively share climate risks, and clients are increasingly requesting buildings that can mitigate the negative impacts of climate events.

ACKNOWLEDGEMENTS
The work presented was carried out as part of the European Horizon project "RE-SKIN – Renewable and Environmental-Sustainable Kit for building Integration". *Grant Agreement* ID: 101079957.

NOTES
[1] The IPCC Sixth Assessment Report (IPCC, 2022) defines human systems as «any system in which human organisations and institutions play an important role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report» (IPCC, 2022).
[2] Created in 1988 by both the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP), the IPCC aims to provide governments at all levels with scientific information that is useful for developing climate policies. The IPCC reports are also a key contribution to international negotiations on climate change. The IPCC is an organisation made up of member governments of the United Nations or WMO. It currently counts 195 members.

03 | Esempio di applicazione dell'analisi HAZOP alla soluzione di copertura "RE-SKIN". Fonte dell'immagine: progetto RE-SKIN
Example of application of the HAZOP analysis to the "RE-SKIN" roof solution. Source of the drawing: RE-SKIN project

03 | **RE-SKIN project's Roof solution: Hybrid building-integrated photovoltaic-thermal (BIPVT) system**



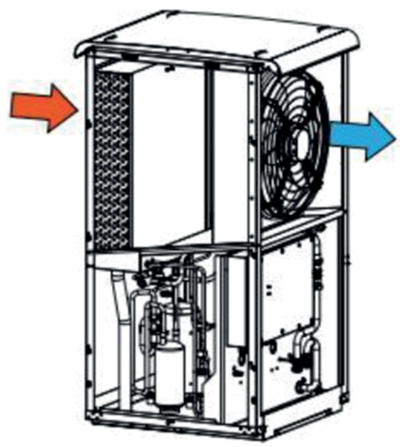
GUIDING WORD	ELEMENT	DEVIATION	CAUSE	CONSEQUENCE ON THE WORK PART	ADAPTATION ACTIONS
MORE	Outdoor temperature	Higher than average outside temperatures	Heat waves	Decrease in efficiency of photovoltaic panels in relation to their temperature coefficient	Sufficient natural ventilation spaces, mechanical ventilation for heat dissipation, dampening systems for temperature reduction
MORE	Outdoor temperature	Higher than average outside temperatures	Heat waves	Overheating of the ventilation chamber between PV panels and insulation panels with potential excessive thermal expansion or deformation	mechanical ventilation for excess heat dissipation
LESS	Outdoor temperature	Very low and below average temperatures	Harsh or late winters	Risk of frost, increase in loads due to permanence of ice or snow, decrease in production efficiency due to ice or snow	Supplemental resistance, cleaning and maintenance
OTHER	Outdoor air quality	Presence of dust/fumes not foreseen during installation	Fires following heat waves	Soiling of the capturing surface of the panels and reduction of energy production efficiency	Periodic cleaning, automatic washing systems
OTHER	Outdoor air quality	Presence of dust/fumes not foreseen during installation	Fires following heat waves	Reduction of radiant energy that reaches the surface of the panels with less energy production	Storage Battery System
MORE	Hail	Hail size well above average	Gales	Damage to glass surface panels, damage to sealing gaskets	Movable panel protection, use of glass with increased impact resistance, risk transfer or sharing (insurance coverage)
MORE	Rainfall	Rain with intensity well above average	Gales	Insufficient drainage of the roof with possible infiltration	Additional watertight layer placed under the insulation panels, sizing of the gutter sections.
MORE	Wind	Wind speed well above average	Gales	Panel lifting actions, possible impacts from wind-blown debris	Panel Fixture Sizing, Impact Risk Transfer and Sharing (Insurance Coverage)

04 | Esempio di applicazione della analisi HAZOP all'elemento pompa di calore aria-acqua DC. Fonte dell'immagine: progetto RE-SKIN
Example of application of the HAZOP analysis to the "RE-SKIN" DC air-to-water heat pump. Source of the drawing: RE-SKIN project

todiche e degli strumenti di questo apparato, oggi maggiormente applicato alla scala territoriale, appare sempre più urgente.
Rispetto a queste considerazioni, l'articolo propone e sperimenta il trasferimento alla scala dell'edificio della tecnica HAZOP per l'identificazione e la valutazione dei rischi climatici. Tale metodo, applicato alla scala dell'edificio e dei sub-sistemi, consente di attivare un'efficace interazione tra le diverse competenze coinvolte nel progetto adottando un approccio di identificazione e valutazione partecipata e condivisa dei rischi legati ad eventi climatici estremi per i sistemi edilizi e per una efficace individuazione delle relative misure di adattamento.
Sulla base di quanto riscontrato nella fase di applicazione, la replicabilità e la scalabilità dello strumento sembrano essere garantite, pur dipendendo dalla disponibilità informativa rispetto alle caratteristiche dei sistemi edilizi individuati nel progetto soprattutto in fase di progettazione preliminare, alla conoscenza del contesto climatico di riferimento e degli eventi climatici estremi ipotizzabili nell'area di progetto.

DC air-to-water heat pump of RE-SKIN project

| 04



GUIDING WORD	ELEMENT	DEVIATION	CAUSE	CONSEQUENCE ON THE WORK PART	ADAPTATION ACTIONS
MORE	Outdoor temperature	Higher than average outside temperatures	Heat waves	Decrease in efficiency of the heat pump due to difficulties in the exchange on the condensing side, excessive thermal loads that increase the demand for cooling power	Auxiliary or booster systems, night ventilation, possible cooling of the exchange surface, for example, with water to increase efficiency
LESS	Outdoor temperature	Very low and below average temperatures	Harsh or late winters	Frequent defrosting, risk of frost, blockages	Supplementary heating element, hybrid heat pump
OTHER	Outdoor air quality	Presence of dust/fumes not foreseen during installation	Fires following heat waves	Dirtying of the exchange surface on the condenser side and reduction of the efficiency of the heat pump	Filters, periodic condenser cleaning, automatic washing systems
OTHER	hail	Hail size well above average	Gales	Damage to capacitor-side exchange surfaces	Mechanical Impact Resistant Protections

Concludendo, il trasferimento e l'applicazione a livello di edificio della tecnica HAZOP per la valutazione dei rischi climatici rappresenta una innovazione da collocare all'interno di una più vasta azione volta a costruire un apparato di strumenti a supporto delle scelte di progetto per l'adattamento climatico che non può prescindere: dalla costruzione di nuove competenze progettuali in materia di adattamento climatico; dall'ampliamento con i temi del cambiamento climatico delle pratiche di progettazione partecipata e di co-creazione di conoscenza; dalla sperimentazione di metodi valutativi ai diversi livelli di sviluppo del progetto. Tra le condizioni di contesto che potrebbero accelerare e agevolare la diffusione di questa sperimentazione si ritiene possa essere decisiva l'interazione tra i principali *stakeholder* che sono chiamati a intervenire sugli impatti del cambiamento climatico: le amministrazioni di governo del territorio che devono gestire le situazioni emergenziali causate dagli eventi climatici, le compagnie di assicurazione che possono condividere efficacemente i rischi climatici e i committenti che, sempre di più, stanno esprimendo richieste di edifici in grado di limitare gli impatti negativi degli eventi climatici.

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NOTE

[1] Il sesto *Assessment Report* dell'IPCC (IPCC, 2022) definisce i sistemi umani come «Qualsiasi sistema in cui le organizzazioni e le istituzioni umane svolgono un ruolo importante. Spesso, ma non sempre, il termine è sinonimo di società o sistema sociale. Sistemi come i sistemi agricoli, i sistemi urbani, i sistemi politici, i sistemi tecnologici e i sistemi economici sono tutti sistemi umani nel senso applicato in questo rapporto».

[2] Creato nel 1988 dall'Organizzazione Meteorologica Mondiale (OMM) e dal Programma delle Nazioni Unite per l'Ambiente (UNEP), l'IPCC ha come obiettivo quello di fornire ai governi di tutti i livelli informazioni scientifiche utili per elaborare politiche climatiche. I rapporti dell'IPCC costituiscono inoltre un contributo fondamentale ai negoziati internazionali sui cambiamenti climatici. L'IPCC è un'organizzazione composta da governi membri delle Nazioni Unite o OMM. Attualmente conta 195 membri.

REFERENCES

Alizadeh, O. (2022), "Advances and challenges in climate modeling", *Climatic Change*, Vol. 170, n. 1, p. 18. Available at: https://doi.org/10.1007/s10584-021-03298-4.

Bernardini, C. (2022), "Approccio soft all'adattamento ai cambiamenti climatici. Il ruolo attivo dei servizi urbani", *TECHNE: Journal of Technology for Architecture & Environment*, Vol. *23*, pp. 78-84. Available at: https://doi.org/10.36253/techne-12153.

D'Ambrosio V., (2017), "Processi di adattamento in ambito urbano. La Piattaforma Metropolis come strumento di supporto alle decisioni" in D'Ambrosio V., Leone M.F. (a cura di), *Progettazione ambientale per l'adattamento al Climate Change*, CLEAN, Napoli.

Dodman, D., Hayward, B., Pelling, M., Broto, V.C., Chow, W., Chu, E., ... Munoz, T.A. (2022), *Cities, Settlements and Key Infrastructure. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Available at: https://doi.org/10.1017/9781009325844.008.

Döll, P. and Romero-Lankao, P. (2017), "How to embrace uncertainty in participatory climate change risk management. A roadmap", *Earth's Future*, Vol. 5, n. 1, pp. 18-36. Available at: https://doi.org/10.1002/2016EF000411.

Dong, B., Liu, Y., Mu, W. *et al.* A (2022), "A Global Building Occupant Behavior Database", *Sci Data*, Vol. 9, pp. 369. Available at: https://doi.org/10.1038/s41597-022-01475-3.

EN 61882:2016 Hazard and operability studies (HAZOP studies). Application guide. Available at: https://knowledge.bsigroup.com/products/hazard-and-operability-studies-hazop-studies-application-guide

Estoque, R.C., Ooba, M., Togawa, T. *et al.* (2022), "Climate impact chains for envisaging climate risks, vulnerabilities, and adaptation issues", *Reg Environ Change*, Vol. 22, pp. 133. Available at: https://doi.org/10.1007/s10113-022-01982-4.

Farinós-Dasí, J., Pinazo-Dallenbach, P., Peiró Sánchez-Manjavacas, E. and Rodríguez-Bernal, D. C. (2024), "Disaster risk management, climate change adaptation and the role of spatial and urban planning: evidence from European case studies", *Natural Hazards*, pp. 1-34. Available at: https://doi.org/10.1007/s11069-024-06448-w.

Flood, S., Paterson, S., O'Connor, E., O'Dwyer, B., Whyte, H., Le Tissier, M. and Gault, J. (2020), *National risk assessment of impacts of climate change: bridging the gap to adaptation action.* Environmental Protection Agency. Available at: https://www.epa.ie/publications/research/climate-change/Research_Report_346.pdf.

Gerber, D.J. and Lin, S.H.E. (2014), "Designing in complexity: Simulation, integration, and multidisciplinary design optimization for architecture", *Simulation*, Vol. 90, p. 8, pp. 936-959. Available at: https://doi.org/10.1177/0037549713482027.

Hallegatte, S. (2009), "Strategies to adapt to an uncertain climate change", *Global environmental change*, Vol. 19, n. 2, pp. 240-247. Available at: https://doi.org/10.1016/j.gloenvcha.2008.12.003.

IEC 31010:2019 Risk management. Risk assessment techniques. Available at: https://www.iso.org/standard/72140.html.

Imamguluyev, R., Hajizada, S., Badalova, S., Mammadova, A., Abdullayeva, S., Karimova, S. (2025), "Fuzzy Logic for Modeling Climate Changes: Overcoming Uncertainty in Environmental Forecasts" in International Conference on Intelligent and Fuzzy Systems, pp. 278-285. Cham: Springer Nature Switzerland. Available at: https://doi.org/10.1007/978-3-031-98304-7_32.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Geneva, Switzerland: IPCC. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf.

Intergovernmental Panel on Climate Change (IPCC) (2014), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Geneva*, Switzerland: IPCC. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_Front_matters.pdf.

Intergovernmental Panel on Climate Change (IPCC) (2022), *Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Available at: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

Intergovernmental Panel on Climate Change (IPCC), *2022: Annex II: Glossary In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2897-2930. Available at: https://doi.org/10.1017/9781009325844.029.

ISO 14091:2021 Adaptation to climate change. Guidelines on vulnerability, impacts and risk assessment. Available at: https://www.iso.org/standard/68508.html.

Jones, R. N. (2000), "Managing uncertainty in climate change projections–issues for impact assessment", *Climatic change*, Vol. 45, n. 3, pp. 403-419. Available at: https://doi.org/10.1023/A:1005551626280.

Losasso, M. (2025), "Ambiti Urbani Climate Neutral", TECHNE: Journal of Technology for Architecture & Environment, Vol. 29, n. 1, pp. 7-8. Available at: https://doi.org/10.36253/techne-17666.

Losasso, M., Lucarelli M.T., Rigillo, M., Valente, R. (2020), Adattarsi al clima che cambia. Innovare la conoscenza per il progetto ambientale. Maggioli Editore. Available at: https://www.maggiolieditore.it/adattarsi-al-clima-che-cambia.html.

Menk, L., Terzi, S., Zebisch, M., Rome, E., Lückerath, D., Milde, K., Kienberger, S. (2022), "Climate change impact chains: a review of applications, challenges, and opportunities for climate risk and vulnerability assessments", *Weather, Climate, and Society*, Vol. 14, n. 2, pp. 619-636. Available at: https://doi.org/10.1175/WCAS-D-21-0014.1.

Monteiro, A., Ankrah, J., Madureira, H., Pacheco, M.O. (2022), "Climate risk mitigation and adaptation concerns in urban areas: a systematic review of the impact of IPCC assessment reports", *Climate*, Vol. 10, n. 8, p. 115. Available at: https://doi.org/10.3390/cli10080115.

Muthumanickam, N.K., Brown, N., Duarte, J.P., Simpson, T.W. (2023), "Multidisciplinary design optimization in Architecture, Engineering, and Construction: a detailed review and call for collaboration", *Structural and Multidisciplinary Optimization*, Vol. 66, n. 11, p. 239. Available at: https://doi.org/10.1007/s00158-023-03673-y.

Otto, F. E. (2023), "Attribution of extreme events to climate change", *Annual Review of Environment and Resources*, Vol. 48, n. 1, pp. 813-828. Available at: https://doi.org/10.1146/annurev-environ-112621-083538

Perkins-Kirkpatrick, S.E., Stone, D.A., Mitchell, D.M., Rosier, S., King, A.D., Lo, Y.T.E., … Wehner, M. (2022), "On the attribution of the impacts of extreme weather events to anthropogenic climate change", *Environmental Research Letters*, Vol. 17, n. 2, p. 024009. Available at: https://doi.org/10.1088/1748-9326/ac44c8.

Rathnayaka, B., Siriwardana, C., Amaratunga, D., Haigh, R., Robert, D. (2022), "Climate change impacts on built environment: a systematic review" in 12th International conference on structural engineering and construction management: Proceedings of the ICSECM 2021 (pp. 443-459). Singapore: Springer Nature Singapore. Available at: https://doi.org/10.1007/978-981-19-2886-4_31.

Risser, M.D., Tebaldi, C. (2025), "Uncertainty and Extremes". In: Mearns, L.O., Forest, C.E., Fowler, H.J., Lempert, R., Wilby, R.L. (Eds) *Uncertainty in Climate Change Research*. Springer, Cham. Available at: https://doi.org/10.1007/978-3-031-85542-9_21

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., … Zwiers, F.W. (2012), *Changes in climate extremes and their impacts on the natural physical environment*. Available at: https://academiccommons.columbia.edu/doi/10.7916/d8-6nbt-s431

Smith, P., Francombe, J., Lempert, R.J., Gehrt, D. (2022), "Consistency of UK climate risk approaches with new ISO guidelines", *Climate Risk Management*, Vol. 37, p. 100422. Available at https://doi.org/10.1016/j.crm.2022.100422.

Snyder, C. W., Mastrandrea, M. D., Schneider, S. H. (2011), "The complex dyanmics of the climate system: Constraints on our knowledge, policy implications and the necessity of systems thinking" in *Philosophy of complex systems*, pp. 467-505, North-Holland. Available at: https://doi.org/10.1016/B978-0-444-52076-0.50017-1.

Taleb, N. N. (2009), *Il cigno nero. Come l'improbabile governa la nostra vita* (Vol. 77). Il saggiatore.

Voordijk, H. (2009), "Construction management and economics: the epistemology of a multidisciplinary design science. Construction management and economics", Vol. 27, n. 8, pp. 713-720. Available at: https://doi.org/10.1080/01446190903117777.

Wilby, R. L. (2007), "A review of climate change impacts on the built environment", *Built environment*, Vol. 33, n. 1, pp. 31-45. Available at: https://doi.org/10.2148/benv.33.1.31.

World Meteorological Organization (WMO) (2025), State of the Global Climate 2024, WMO, Geneva. Available at: https://library.wmo.int/records/item/69455-state-of-the-global-climate-2024.

Ye, X., Yigitcanlar, T., Xu, Y., Head, M., Hang, Y., Sanchez, T., … Niyogi, D. (2025), "Urban planning and IPCC-like city assessments integration for climate-resilient cities". *Environment and Planning B: Urban Analytics and City Science*, Vol. 52, n. 7. Available at: https://doi.org/10.1177/23998083251330940.

Ylhäisi, J. S., Garre, L., Daron, J., Räisänen, J. (2015), "Quantifying sources of climate uncertainty to inform risk analysis for climate change decision-making", *Local Environment*, Vol. 20, n. 7, pp. 811-835. Available at: https://doi.org/10.1080/13549839.2013.874987.

Zhai P., Zhou B., Chen Y. A., (2018), "A Review of Climate Change Attribution Studies", *Journal of meteorological research,* Vol. 32, n. 5, pp. 671–692. Available at: https://doi.org/10.1007/s13351-018-8041-6.

Zhang, Y., Wu, S., Dai, E., Liu, D., Yin, Y. (2008), "Identification and categorization of climate change risks", *Chinese Geographical Science*, Vol. 18, n. 3, pp. 268-275. Available at: https://doi.org/10.1007/s11769-008-0268-1.

Zięba, Z., Dąbrowska, J., Marschalko, M., Pinto, J., Mrówczyńska, M., Leśniak, A., … Kazak, J. K. (2020), "Built environment challenges due to climate change" in *IOP Conference Series: Earth and Environmental Science*, Vol. 609, n. 1, p. 012061. IOP Publishing. Available at: 10.1088/1755-1315/609/1/012061.