The role of co-design in assessing climate risk: case of Bologna Airport

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Introduction

Climate change is an urgent global challenge characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. These changes pose significant risks to critical infrastructure, particularly in the aviation sector[1,2]. As essential hubs in the global transportation network, airports are highly vulnerable to climate-related disruptions such as flooding, heatwaves and severe storms. These events can impair operations, damage infrastructure, and compromise safety, resulting in significant economic losses and widespread societal impacts. Addressing these challenges requires innovative and reliable climate risk assessment methods that foster active stakeholder engagement. Indeed, traditional risk assessments often fail to capture the full scope of system vulnerabilities, which can only be better understood through collaborative approaches. A co-design methodology ensures, instead, the development of resilient and context-specific adaptation strategies by integrating expert knowledge and localized insights, leading to solutions that are not only scientifically rigorous but also socially and economically sustainable[3]. Considering these aspects, a co-design matrix approach was developed for **Guglielmo Marconi Airport of Bologna** (hereinafter Bologna Airport) as a case study in order to quantify the climate risk. Bologna Airport, located 6 km northwest of the city center, is the seventh busiest in Italy, with more than 10 million passengers in 2024[4]. It is a key hub for national and international flights and an important economic driver for the region, supporting tourism, manufacturing, and logistics. The risk analysis involved identifying climate hazards and their evolution under different concentration scenarios using high-resolution climate data. Exposed elements were then defined, and their vulnerability was assessed through targeted questionnaires distributed to key airport stakeholders. By integrating hazard (H), exposure (E), and vulnerability (V) data, a risk matrix was created for each identified hazard (*Figure 1*). This matrix enabled a comprehensive assessment of climate risks affecting the airport system and predicting their evolution over time.

Key aspects of methodology

The first step of the risk analysis involved assessing the current and future **climate hazard** using several climate indicators based on return period (50 and 100 years return periods), identified through consultations with stakeholders. These return periods are commonly used for designing,

1 De Vivo, C.; Barbato, G.; Ellena, M.; Capozzi, V.; Budillon, G.; Mercogliano, (2023) P. Climate-Risk Assessment Framework for Airports under Extreme Precipitation Events: Application to Selected Italian Case Studies. Sustainability 2023, 15, 7300. https://doi.org/10.3390/su15097300

2 De Vivo, C., Ellena, M., Capozzi, V. et al. Risk assessment framework for Mediterranean airports: a focus on extreme temperatures and precipitations and sea level rise. Nat Hazards (2021). https://doi.org/10.1007/s11069-021-05066-0

3 Fleming, A., Bohensky, E., Dutra, L.X.C., Lin, B.B., Melbourne-Thomas, J., Moore, T., Vertigan, C., 2023. Perceptions of co-design, co-development and co-delivery (Co- 3D) as part of the co-production process–Insights for climate services. Clim. Serv. 30, 100364.

4 https://www.bologna-airport.it/benvenuto-all-aeroporto-di-bologna/?idC=62175

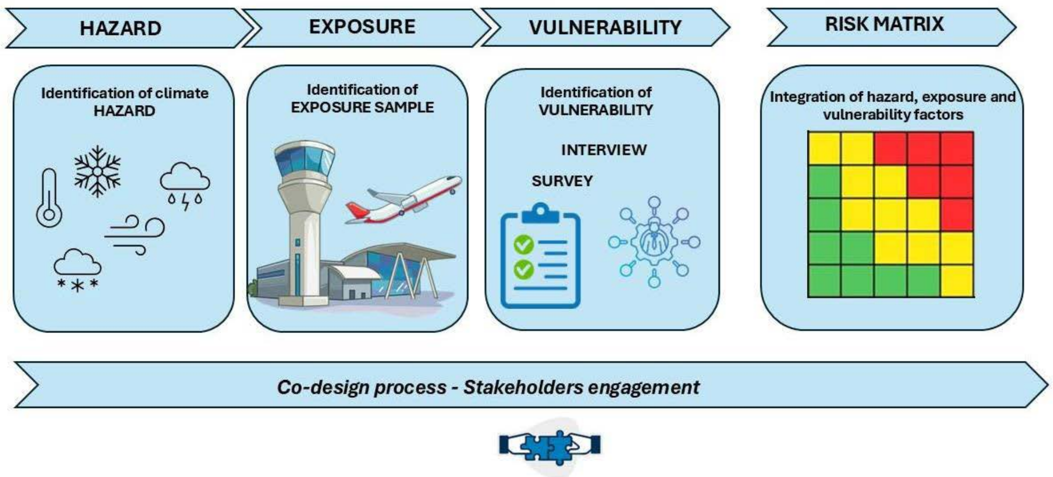

FIGURE 1: Matrix based co-design approach (adjusted from De Vivo et al. 2024).

maintaining, and adapting infrastructure to anticipated climate change impacts[5]. These climate indicators are considered representative of climate hazards that have contributed to, and may potentially cause, future losses and damages at the airport — such as an increase in extreme heat and cold events, heavy precipitation, and strong wind occurrences. The climate indicators were assessed for the reference climate period 1981-2010 using the E-OBS dataset[6], while the climate variations were evaluated by comparing the values of these indicators in the future period 2036-2065 with those of the reference period 1981-2010 using the ensemble of high-resolution climate models provided by the EURO-CORDEX[7] initiative under the three Intergovernmental Panel on Climate Change (IPCC) scenarios[8] – RCP8.5, RCP4.5 and RCP2.6. The use of indicators based on return time periods allowed to define the probability of occurrence for selected climate events and categorize them into specific classes: "Very Low" (≥100 years), "Low" (100 > TR ≥50 years), "Medium" (50 > TR ≥20 years), "High" (20 > TR ≥10 years), and "Very High" (10 > TR ≥2 years).

The second step of the risk analysis involved the **exposure assessment** through the active involvement of airport managers. This collaborative method helped to identify the most climate-vulnerable elements of the airport system, drawing on the direct experience of managers. Based on a thorough review of recent scientific literature[9] and extensive discussions with key stakeholders, the exposed elements were categorized into three main groups:

- **Airside:** includes the elements used for aircraft movement, such as runways, taxiways, control towers and aprons;
- **Landside:** refers to public access areas such as offices, terminals, airport access systems and parking areas;
- **Airport information systems** (Airport IT infrastructures): include all information systems responsible for the correct management and operation of airport services (both those relating to the airside and landside components).

5 Rianna, G., Reder, A., Sousa, M.L., Dimova, S., 2023. Harmonised procedure to update thermal loads in the Eurocodes. Case study for Italy. Climate Services 30, 100391. https://doi.org/10.1016/j.cliser.2023.100391)

6 Cornes, R., van der Schrier, G., van den Besselaar, Jones, P.D., 2018. An Ensemble Version of E-OBS Temperature and Precipitation Datasets. J. Geophys. Res. Atmos. 123. https://doi.org/10.1029/2017JD028200;

7 Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Beldaet, M., et al., 2020. Regional climate downscaling over Europe: perspectives from the EURO- CORDEX community. Regional Environmental Change 20 (51), 1–20. https://doi. org/10.1007/s10113-020-01606-9.

8 Representative Concentration Pathways (RCPs) are climate scenarios consistent with a wide range of possible changes in future anthropogenic greenhouse gas emissions, and aim to represent their atmospheric concentrations. They are subdivided into RCP2.6 (Aggressive Mitigation Scenario), RCP4.5 (Strong Mitigation Scenario), RCP6.0, and RCP8.5 (High Emission Scenario).

9 De Vivo, C., Ellena, M., Barbato, G., Pugliese, A., Marinucci, F., Barilli, T., & Mercogliano, P. (2025). A co-design matrix-based approach to evaluate the climate risks for airports: A case study of Bologna airport. *Climate Services*, *37*, 100536.

The third step was the **vulnerability assessment**, as the predisposition of the system to suffer the negative effects of climate change. Also in this phase, the main stakeholders of the two airports were actively involved, promoting an inclusive and participatory approach. Two specific questionnaires were distributed to identify the vulnerability characteristics of the exposed elements. The first questionnaire allowed to evaluate the severity of the impact of each element in relation to the climate hazards considered (e.g., assessing the potential impact of heat waves on runway performance). The second questionnaire collected information on the intrinsic characteristics of the exposed elements that influence their susceptibility to impacts of climate change (e.g. the level of maintenance of the exposed elements, the presence of materials resistant to extreme temperatures, preventive measures for addressing climate change impacts as well as the drainage capacity of the systems etc.). Once the answers to the two questionnaires had been processed, an integrated vulnerability matrix was built, which allowed to classify the exposed elements into four vulnerability categories for each climate hazard (low, medium, high, very high).

The **climate risk matrix** was developed by integrating hazard, exposure and vulnerability data. Specifically, the matrix results from the multiplication of the probability of occurrence values (hazard) and the vulnerability characteristics evaluations of the exposure samples. The resulting risk value were categorized into four risk levels: low, medium, high and very high (Table 1).

Principle results

For confidentiality reasons, only the extreme heat events results are presented, using the runway as an exposed sample. The results show that the final risk is strongly influenced by the variations of the hazards in different scenarios (RCP 2.6, RCP 4.5 and RCP8.5) and by the vulnerability characteristics identified by the questionnaires. Specifically, the "Runway" shows a "Low" risk for the RCP2.6 scenario and "High" risk level in the RCP4.5 and RCP8.5 scenarios, considering events with a return period of 50 years. Analyses highlighted that the adoption of a mitigation scenario (RCP 2.6) can lead to a substantial decrease in climate risk in the area compared to stabilization scenarios with higher concentrations (such as RCP 4.5), and compared to the scenario with high emissions and no mitigation strategy (RCP 8.5). These results helps airport stakeholders identify the areas of high climate risk that could compromise airport infrastructure. Therefore, their involvement in the planning and design of protective measures is crucial. Future adaptation strategies should prioritize the most vulnerable assets while also addressing lower-risk areas to ensure overall resilience. Specifically, to mitigate the risks due to extreme temperature events, integrating heat-resistant materials and updating design standards is essential. Innovative solutions, such as hybrid mineral fillers (HMF)[10] in asphalt and perimeter irrigation[11], can reduce surface temperatures and improve structural durability. Specifically, HMF increases emissivity, enhances rutting resistance, and improves thermal conductivity, reducing surface temperatures by up to 5.4 °C.

TABLE 1: Risk matrix to evaluate the Climate Risk levels for Airport Assets.

RISK MATRIX				
HAZARD Probability of occurrence	**VULNERABILITY OF EXPOSURE SAMPLES**			
	Low (1)	**Medium (2)**	**High (3)**	**Very high (4)**
Very low (1)	**Low (1)**	**Low (2)**	**Low (3)**	**Low (4)**
Low (2)	**Low (2)**	**Low (4)**	**Medium (6)**	**Medium (8)**
Medium (3)	**Low (3)**	**Medium (6)**	**Medium (9)**	**High (12)**
High (4)	**Low (4)**	**Medium (8)**	**High (12)**	**Very high (16)**
Very high (5)	**Medium (5)**	**High (10)**	**Very high (15)**	**Very high (20)**

10 Kong, L., Xu, L., Du, Y., Jin, J., Loprencipe, G., Moretti, L., 2022. Use of Hybrid Mineral Filler with High Emissivity in Asphalt Mixture for Cooling Road Pavements. Materials 16 (1), 175.

11 Qian, J., Miao, S., Tapper, N., Xie, J., Ingleton, G., 2020. Investigation on airport landscape cooling associated with irrigation: A case study of Adelaide airport, Australia. Sustainability 12 (19), 8123. https://doi.org/10.3390/su12198123.

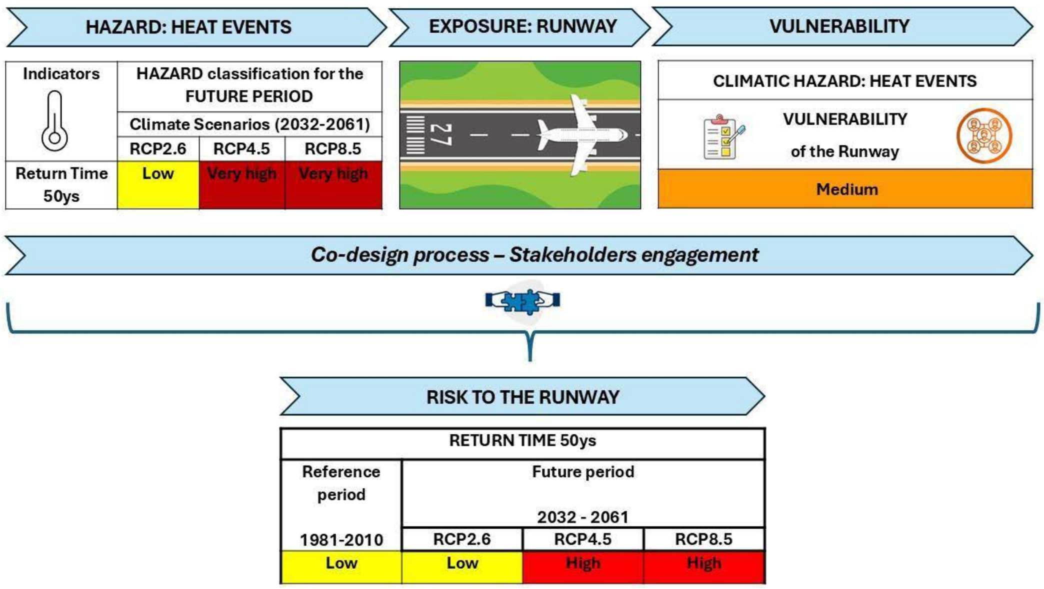

FIGURE 2: Interaction of hazard, exposure and vulnerability results to define climate risks for runways (adjusted from De Vivo et al. 2024).

Integrating climate resilience into airport infrastructure and operations will be key to addressing future challenges and ensuring the safety and efficiency of the airport system.

Conclusion

The matrix based co-design approach has emerged as a robust, scalable and highly adaptable method for evaluating climate risks to airport infrastructure. The active involvement of stakeholders during all the phases of the activity has provided critical, context-specific valuable insights. This has ensured that the risk matrices are not only scientifically sound, but also deeply rooted in the real-world conditions considering the vulnerabilities of the infrastructure. This participatory and interacting approach enhances the credibility, relevance, and practical usability of the results, supporting their seamless integration into existing decision-making and planning processes. By offering a structured yet flexible framework, this approach effectively addresses the inherent complexity of climate risk, accommodating various greenhouse gas concentration pathways and return time periods of climate events. Its versatility is particularly evaluable in responding to the variation of the climate hazards, and infrastructure vulnerabilities. A key strength of the approach lies in its capacity for dynamic updating: the matrices can be refined over time as new data becomes available, or when local factors (e.g. social/economical) change risk analysis. This enables a continuous dynamical process and fosters long-term strategic planning for adaptation. Moreover, its innovative and adaptable nature promises to enhance resilience planning for airport infrastructure, offering valuable insights for similar applications in other critical sectors facing climate challenges. Currently, the risk assessment framework is being generalized to support its application in a broader range of contexts. To this end, dedicated digital interfaces (e.g., www.dataclime.com) are being developed to streamline data collection, integration, and sharing, thus facilitating a more agile transfer of knowledge to end-users. These developments pave the way for a new generation of decision-support tools that bridge the gap between climate science and action.

This work opens up promising avenues for further research and collaboration, particularly in exploring the co-evolution of infrastructure adaptation and climate services. It invites the scientific and operational communities to co-develop next-generation frameworks that are not only technically rigorous, but also deeply embedded in stakeholder realities and decision contexts.