From risk storylines to a risk-driven ontology of urban systems

From Risk Storylines to a Risk-Driven Ontology of Urban Systems

Cristine Griffo[1][a], Liz Jessica Olaya Calderon[1][b], Massimiliano Pittore[1][c]
and Theodore G. Shepherd[2,3][d]
[1] *Eurac Research, Bolzano, Italy*
[2] *Department of Meteorology, University of Reading, Reading, U.K.*
[3] *Jülich Supercomputing Centre, Forschungszentrum Jülich, Jülich, Germany*

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Abstract: Ontological models empower stakeholders to establish shared ontological commitments for achieving objectives, including (1) fostering domain-specific understanding; (2) formalizing communication between stakeholders and modelers; and (3) enabling knowledge inference through formal rule-based systems. A significant challenge arises as conceptual modeling transitions from single-organizational contexts to heterogeneous, multi-perspective environments, raising questions about how *quasi-universal conceptualizations* can ensure data interoperability. To address this, we propose storylines to integrate diverse perspectives across past and future scenario narratives. This study applies risk-oriented storylines and ontologies through a middle-out approach, synthesizing top-down and bottom-up strategies, in the ontology engineering of urban systems at risk. The results demonstrate that storylines effectively surface domain-specific terminology among stakeholders but exhibit limitations in capturing abstract, generic concepts and relationships. Conversely, the top-down approach (guided by competency questions, literature, and interviews) revealed imperceptible abstract concepts that storylines overlooked, while missing specialized terms identified through narrative methods. These results highlight the complementary value of hybrid methodological frameworks: the middle-out approach mitigates blind spots inherent to purely top-down or bottom-up strategies, enabling more robust ontology development in complex, multi-stakeholder environments. This work advances pragmatic methodologies for interoperable ontology design in urban systems, with implications for risk management and urban resilience planning.

1 INTRODUCTION

We are the sum of all the stories that we live and that we tell ourselves. It could be said that our identities are often influenced by the collective narratives we internalize and perpetuate (Golden, 1997). These stories, in turn, are shaped by the experiences and perspectives of those who tell them. From an early age, humans are drawn to fascinating stories and captivating storytellers who help us understand the world through their unique lenses. It is no surprise that *storylines* have been used as an effective tool for gathering information and expressing the nuances of a domain. They offer stakeholders a way to identify concepts, properties, and relationships in an engaging and enlightening way using natural language.

[a] https://orcid.org/0000-0002-4033-8220
[b] https://orcid.org/0009-0006-2169-9019
[c] https://orcid.org/0000-0003-4940-3444
[d] https://orcid.org/0000-0002-6631-9968

In parallel, ontologies provide formal, unambiguous representations of domain semantics using symbolic logic. They enable *ontological commitment*, a shared agreement among stakeholders, facilitating domain understanding, cross-perspective communication, knowledge inference, and semantic interoperability. However, achieving this commitment faces significant challenges in heterogeneous, multi-stakeholder contexts like urban risk management. Diverse disciplines (e.g., infrastructure engineering, social science, law, policy) employ diverse terminologies and mental models, creating *semantic gaps* that hinder interoperability. The question of how a 'quasi-universal conceptualization, an ontology, can be adopted to guarantee the interoperability of the data produced by historians' has been raised by some scholars (Beretta, 2021). Indeed, the ontological commitment negotiated and accepted by a group of stakeholders in a specific context will not necessarily align with the ontological commitment accepted by

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other groups of stakeholders. The harmonization of these commitments represents a significant and challenging issue that requires careful consideration.

This paper addresses the issue of semantic interoperability in the context of multi-stakeholder ontology engineering for urban risk, with a focus on the potential of storylines as translational bridges. The present study proposes that storylines serve to mitigate semantic disconnects by employing the following mechanism:

1. Providing narrative scaffolds that contextualize abstract ontology concepts within concrete, temporal scenarios;
2. Surfacing implicit assumptions and terminological conflicts through collaborative co-development workshops;
3. Enabling explicit mapping between narrative elements (agents, events, consequences) and ontological primitives (classes, relations, axioms), ensuring formal rigor.

This narratively mediated approach transcends conventional terminology harmonization by preserving critical causal dependencies essential for urban risk modeling while maintaining bidirectional traceability between storylines and the formal ontology.

To evaluate this approach, we conducted research within the Return project[1], employing a hybrid top-down (existing theories, taxonomies) and bottom-up (specialist-designed storylines) methodology (Marciano et al., 2024). The resulting risk-driven ontology of urban systems supports the analysis of diverse scenarios, including upward (best-case) and downward (worst-case) counterfactuals, crucial for predictive modeling of risk drivers in urban areas.

The remainder of this paper is structured as follows: Section 2 reviews ontologies for urban systems and the application of storylines, particularly in climate change. Section 3 details the methodology and materials for ontology design. Section 4 presents the results, followed by discussion and related work in Section 5. Final considerations and future work are provided in Section 6.

2 LITERATURE REVIEW

2.1 Smart City–Related Ontologies

Ontologies have emerged as a tool for the conceptual modeling of urban systems, offering structured frameworks to represent their complexity, integrate heterogeneous data sources, and promote interoperability across systems. For instance, the city infrastructure ontology (Du et al., 2023) exemplifies such applications, facilitating unified representations of urban components. Similarly, CityGML (Kutzner et al., 2020), an open, XML-based data model for storing and exchanging virtual 3D city models, serves as a cornerstone for semantic interoperability in urban datasets. Microsoft's Smart Cities ontology, developed using the Digital Twins Definition Language (DTDL), further underscores the role of ontologies in enhancing interoperability for digital twin systems.

The biological dimensions of urban systems are addressed through ontologies aligned with principles from biological sciences. A notable example is the Population and Community Ontology (PCO)[2], which formalizes interactions among organismal groups (e.g., populations, communities). Grounded in the Basic Formal Ontology (BFO)(Arp et al., 2015), PCO ensures compatibility with established biological ontologies such as the Gene Ontology (GO)[3] and the Phenotype and Trait Ontology (PATO)[4].

Infrastructure modeling in urban contexts adopts dual perspectives: physical (e.g., roads, buried assets) and service-oriented (e.g., energy, water systems). The Assessing the Underworld Ontology (ATU) (Du et al., 2023), a top-level ontology inheriting concepts from Semantic Web for Earth and Environmental Terminology (SWEET) (DiGiuseppe et al., 2014), exemplifies this approach. ATU integrates five sub-models—Environment, Ground, Road, Buried Asset, and Human Activity—and incorporates a dedicated Methods sub-ontology to classify tools and techniques used in human activities.

Service-driven infrastructure ontologies are increasingly prevalent. The SEMANCO project[5] developed an OWL 2-based urban energy ontology to guide CO2 reduction strategies, integrating actors, data, and scenarios through use-case methodologies. This ontology aligns with ISO standards (e.g., ISO/IEC CD 13273 for energy efficiency, ISO 15927-1 for hygrothermal performance) to enhance reusability. Similarly, the Flood Disaster Support Ontology (FDSO)[6], designed in OWL, supports flood response by formalizing terms like NaturalDisaster and RiskManagement. Additional risk-driven ontologies address water distribution failures (Lin et al., 2012) and river quality

[1] Return - Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate - https://www.fondazionereturn.it/en/

[2] Available at https://bioportal.bioontology.org/ontologies/PCO

[3] https://geneontology.org/docs/download-ontology/

[4] https://bioregistry.io/registry/pato

[5] Available at: http://semanco-project.eu/ontology.htm

[6] Available at https://www.isibang.ac.in/ns/fdso/index.html

monitoring (Wang et al., 2020).

A comprehensive review by (Pruski et al., 2022) highlights advancements in urban ontologies. However, it reveals an absence of ontologies that unify biological and artificial urban components based on foundational ontological structures. This gap limits holistic risk assessment and interoperability in complex urban systems, thus motivating the development of the ontology presented in this work.

2.2 Storylines

A storyline is defined as a physically self-consistent unfolding of past events, or of plausible future events or pathways (Shepherd et al., 2018). The utilization of past events in analyzing climate and disaster risk is particularly advantageous because they serve as individual examples of the realization of processes and their consequences, thereby illuminating the dependencies and vulnerabilities of the affected systems. However, this approach may also obscure potential alternative realizations, which are particularly useful in understanding and modeling the impact of infrequent events with potentially severe consequences. Therefore, it is essential to consider plausible scenarios that are realistic enough to provide a coherent narrative or to integrate or enhance an existing one. One such approach involves the incorporation of near misses, which has been identified as a potential avenue for extending a storyline towards a plausible alternative future (Woo and Johnson, 2023).

Storylines enable exploring, in the case of a past event, what could have occurred under specific circumstances without requiring definitive attribution of every causal factor (Sillmann et al., 2020). This flexibility of the method allows the examination of different alternatives based on their plausibility rather than their probability of occurrence, which is particularly valuable in contexts of deep uncertainty (Sillmann et al., 2020). By moving beyond a narrow focus on fixed historical events, storylines help mitigate retrospective bias and instead promote the consideration of alternative plausible scenarios. This approach highlights the dynamic interaction of contributing factors, enhancing our understanding of how complex systems may react under various conditions.

Counterfactual analysis effectively explores alternative pathways by examining how changes in contributing factors of a past event could lead to different outcomes. When these outcomes are negative, they are referred to as downward counterfactuals. Nevertheless, ensuring the plausibility of working with downward counterfactuals remains the main challenge in developing frameworks guiding integration of counterfactual analysis using storylines and climate and disaster risk (Ciullo et al., 2021), (Roese, 1999). In (Ciullo et al., 2021), the authors propose a framework with an exploratory and retrospective approach: analyzing a fixed past event and then systematically changing its historical parameters to simulate how outcomes could have been more severe- this is particularly beneficial for limited data environments. On the other hand, (Lin et al., 2020) advocates for a participatory and iterative framework that involves stakeholder input at multiple stages. This approach applies counterfactuals across a range of model simulations to build climate storylines, which are then used to assess the vulnerabilities of a given system. While both frameworks deploy downward counterfactual reasoning to analyze risk, they differ in key aspects such as the degree of stakeholder involvement, the scope of their analysis (whether focusing on a single event or multiple simulations), and exploring past events versus future-oriented strategies.

Storylines facilitate the integration of diverse data sources, serving as a tool for crossing disciplinary boundaries (Shepherd and Lloyd, 2021), which fosters interdisciplinary research—a key requirement of climate and disaster risk science. Interdisciplinarity, understood as the collective effort to tackle a single issue from multiple perspectives, bridges the natural sciences, social sciences, and humanities (Schipper et al., 2021). By adopting multiple sources of knowledge—from quantitative data to qualitative insights—storylines can ensure that climate and disaster science is robust and actionable, including physical and socioeconomic elements, and moves from theory to usable knowledge for decision-making.

Additionally, storylines can be used to represent impact chains. Impact chains are conceptual models that describe risk-related impacts, focusing on identifying and describing the linkages between the different components of risk (such as hazards, impacts, vulnerabilities, and exposure) (Zebisch et al., 2023). The impact chains in this paper delineate risk-transmission pathways along different urban environments, pinpointing the cascading effect that hazardous events can trigger in such scenarios, as well as providing relevant information about physical and socioeconomic vulnerabilities. Furthermore, this conceptualization outlines three different types of connection among the risk factors: the 'leads to' connection details the sequence from hazards to impacts; the 'affects' connection indicates how vulnerabilities influence impacts; and the 'impacts' connection specifies the exposed elements that ultimately bear the consequences, attributing specific interactions among the coupled risk factors.

3 METHOD AND MATERIALS

The methodology employed a collaborative approach integrating top-down and bottom-up strategies (*aka* middle-out approach). Table 1 shows the ontology design process, containing the following steps: 1) Literature Review and Requirement Elicitation; 2) Taxonomy Design; 3) Ontology Design; 4) Vocabulary Release; 5) Validation; 6) Iterative Publication.

During the first step, key elements were identified through information elicitation techniques such as document and form analysis and interviews. The output was a set of competency questions (e.g., *What constitutes an urban system at risk? What are the main subsystems of the urban system? What does it need to represent? What is contingent? Which components/subsystems include non-artificial components?*) and a list of functional and non-functional requirements (e.g., *The built taxonomies should be displayed using graphic software (e.g., Miro) and standards (e.g., SKOS)*). This output was used in the top-down approach combined with the literature review (briefly summarized in sections 2.1 and 2.2) [7].

Also, a list of existing taxonomies and ontologies related to urban infrastructure (e.g., taxonomy of buildings) and population was provided by the experts and compiled in a deliverable document to be analyzed and reused in the *taxonomy design* and *ontology design* steps.

Concomitantly, workshops were held with stakeholders to design storylines using the *multi-risk storylines path* proposed in (Marciano et al., 2024). Stakeholders and domain experts - including civil authorities, engineers, sociologists, geologists, physicists, mathematicians, and statisticians - contributed to iterative refinements of functional and non-functional requirements based on individualized scenarios.

The second step was based on reuse taxonomies, e.g., the GED4ALL taxonomy, which is designed for multi-hazard risk analysis (Silva et al., 2018), was applied to design the taxonomy of urban infrastructure. Also, the taxonomy of agents and the taxonomy of population were designed reusing some definitions from the ontology of people and households (CPV_AP-IT)[8].

The third step entailed the adoption of the taxonomies developed in the second step into the ontologies of population and urban systems. The top-down approach was employed in the design of these ontologies. On the other hand, the risk ontology was designed using both top-down and bottom-up approaches, and the results were compared. All ontological models were verified using debugging in the OntoUML plugin for Visual Paradigm. The results are detailed in Section 4. With the *turtle file* generated from the ontological models, the fourth step was to implement and release a vocabulary on the Skosmos platform[9].

In step 5, storylines - different from the storylines used for designing the ontologies - were used to validate the ontologies. Also, the case study conducted by experts to analyze heatwave scenarios was used to validate the ontologies[10].

The publication of the designed ontologies was completed in step 6 using GitLab[11] and Eurac site[12].

Given the focus of this paper on the application of storylines within ontology engineering processes, particular emphasis will be placed on *step 3.a* due to its role in aligning narrative structures with formal ontological representations. Consequently, this component of the methodological framework will be prioritized in subsequent analysis, while other procedural elements will receive comparatively less attention.

4 RESULTS

The research question was addressed by designing two ontological models. The first ontological model (Fig. 1, 2, and 3) was developed based on the literature review and with a top-down approach. The possibility of reusing existing ontologies and taxonomies was evaluated for each sub-ontology shown in Fig.1.

Fig.1 shows a macro view of the Ontology of Risk-Driven Urban Systems (ORdUS). Based on the UFO foundation ontology, it consists of 4 sub-ontologies: 1) the population sub-ontology; 2) the agent sub-ontology; 3) the infrastructure sub-ontology; and 4) the geosphere sub-ontology. The ORdUS ontology is represented as a system ontology, as shown in Fig. 2. In this figure, an *urban system* is defined as a kind of human-made system (e.g., villages, cities) that interacts with natural systems (e.g., natural water system). Every urban system

[7] Due to space limitations, the twenty-three competency questions and the functional and non-functional requirements are described in Chapter 9 of the Deliverable Document, which is available at https://gitlab.inf.unibz.it/earth_observation_public/CCT/pnrr-return/ts1

[8] Available at https://www.istat.it/en/ontology/

[9] Available at https://skos.cct.eurac.edu/vocab/en/

[10] See https://www.eurac.edu/it/institutes-centers/center-for-climate-change-and-transformation/news-events/a-case-study-in-bolzano-heat-waves-and-participation

[11] See https://gitlab.inf.unibz.it/earth_observation_public/CCT/pnrr-return/ts1

[12] See https://return-ontology-doc-816f2b.pages.scientificnet.org/

Table 1: Ontology Design Process.

Steps	Description
1. Literature Review and Requirement Elicitation	Identification of requirements and competency questions. Design of storylines. Literature review.
2. Taxonomy Design	Taxonomies were built or reused considering the output of step 1.
3. Ontology Design	Domain ontologies were developed based on a foundational ontology (UFO/OntoUML). This step included three substeps: a) **Conceptual Modeling**: Ontology-driven models created using Visual Paradigm software with OntoUML plugin b) **Syntactic Verification**: Models debugged to eliminate errors c) **Operational Ontology Generation**: OWL-based Turtle file generated to populate an open-source RDF database
4. Vocabulary Release	Core concepts were identified, semantic meanings were negotiated, and foundational theories for domain ontologies and taxonomies were established.
5. Validation	A bottom-up approach validated the models using case studies and storylines.
6. Iterative Publication	Artifacts were refined through iterative design-validation cycles and subsequently published.

comprises three main elements: population (human and non-human populations), geosphere, and infrastructure. Populations live in a space (*aka* geosphere) that comprises soil, subsoil, and atmosphere. Also, an infrastructure is built in the geosphere, and it is used by the human population. An urban system exposed to hazardous events is called *urban system at risk*.

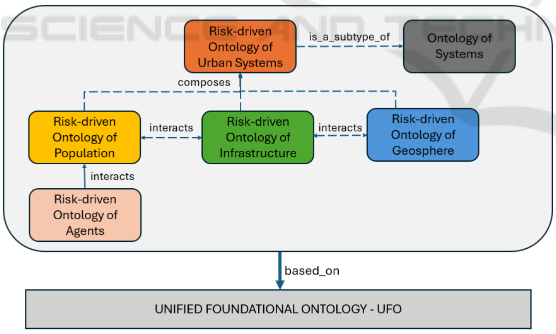

Figure 1: Risk-driven Ontology of Urban Systems - top down approach.

An urban system is susceptible to risk in specific circumstances, which are herein categorized as a composite of roles undertaken by urban systems at risk (*rolemixin*). The integrity of an urban system is contingent upon the stability of its constituent elements, namely the population, agents, infrastructure, and geosphere. Figure 3 presents a refinement of the term *urban system at risk* as depicted in Figure 2. The focal point of this figure is the relation between *Risk Driver* and *Urban System at Risk*. This relation is reified and designated *Urban Risk*, composed of one or more vulnerabilities inherent in the urban systems at risk. These vulnerabilities are externally dependent on the risk driver. The concept of "externally dependent on" in the context of urban systems indicates that the vulnerability of a system is manifested when a risk driver exists. This, in turn, is related to the existence of one or more vulnerabilities inherent in an object at risk.

In the literature, risk has been defined with different ontological natures. For some, risk is an *event*, for others, a *condition*, and for others, risk is a *probability*. In this work, considering the top-down approach, risk was defined as a *relation* between *Risk Driver* and *Urban System at Risk* in which vulnerabilities of an urban system exposed to hazardous events are manifested in these hazardous situations.

In contrast, a second ontological model was built taking into account the storyline diagrams designed by the experts in the workshops held. A preliminary ontological model was extracted from the storylines to build this second ontology, configuring a bottom-up approach (Figure 4). In this figure, *risk* is the result of *the possibility of occurrence of hazards, a set of impacts, urban system vulnerabilities, and exposure of an urban system at risk*. In other words, from the stakeholders' perspective, *risk* is the *likelihood* of a hazardous event with *impacts* (damages and losses) occurring, considering the existence of vulnerabilities and exposures to risks. Thus, a *Driver* leads to a *Hazard*, which can lead to a chain of hazards. Hazards are affected by *vulnerabilities*. A hazard leads to one or more impacts (damages and losses), which are related

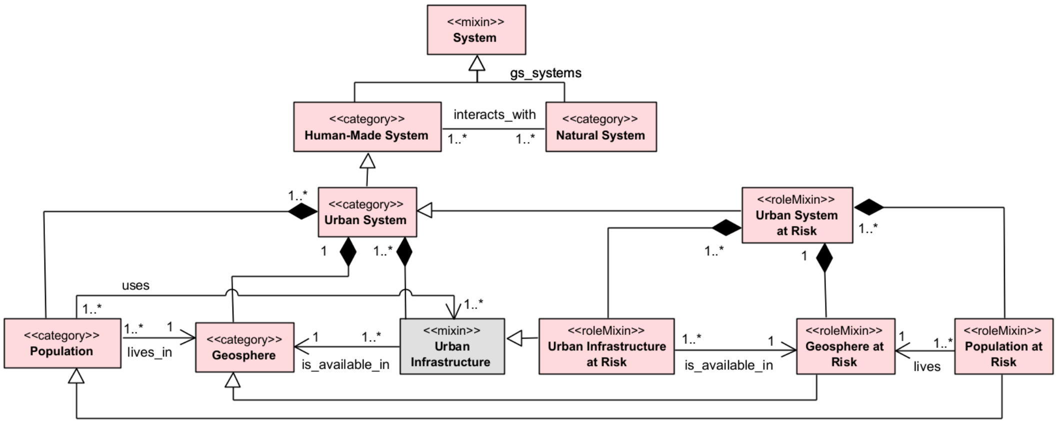

Figure 2: Ontology of Urban Systems - fragment.

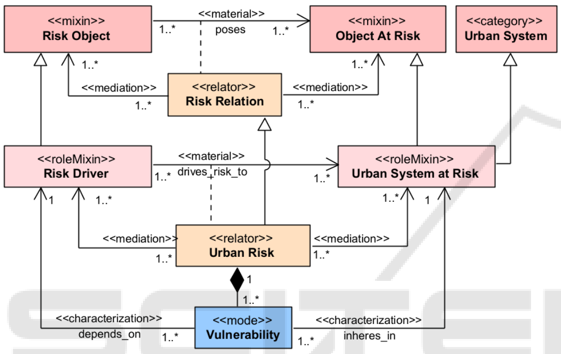

Figure 3: Risk-driven Ontology of Urban Systems - frag.

to the *exposure* of objects at risk. Finally, a *Risk* can lead to a set of risks or be the origin of other sets of hazards.

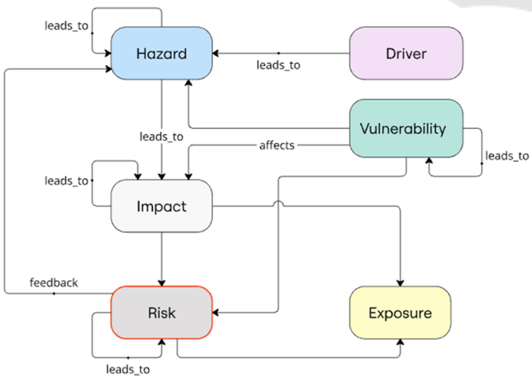

Figure 4: First ontological model based on storylines.

From the storylines (see figures in Appendix), a taxonomy of hazardous events was designed, considering the terms used by stakeholders in the meetings (Figure 5). The taxonomy also classified the types of hazardous events as *disjoint*, considering that the nature of each hazard event is distinct and that an instance of an event *A* cannot be an instance of an event *B*, although such events can occur in cascade or as a result of other events; and *incomplete*, since not all hazardous events have been identified and represented.

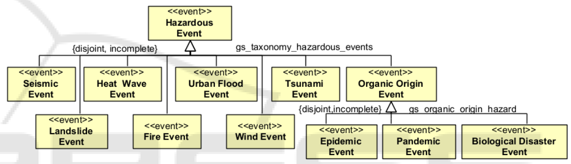

Figure 5: A taxonomy of hazardous events.

Finally, the resulting models from the two approaches were merged into one (Figure 6). Initially, it was found that combining both approaches in the ontology-building process resulted in more complete models that were more consistent with the perception of reality of the domain represented. Both models and their respective glossaries are available at https://www.eurac.edu/en/institutes-centers/center-for-climate-change-and-transformation/tools-services/risk-oriented-models.

To combine the two models, it was necessary to apply ontological patterns from the underlying ontology (e.g., UFO-B pattern (Almeida et al., 2019)) and harmonize the semantics of *risk* and *risk driver*. The application of the UFO-B pattern resulted in the categorization of the key concepts found in both models. In the resulting model, the experts' perspective was taken into account, with risk defined as the probability of a risk situation occurring and the necessary adjustments made. As far as possible, the nomenclature used by the experts for the concepts and relationships was maintained to ensure proximity to the experts' practices.

A particular emphasis was placed on the semantics of risk. It was considered that risk is a *probability*, a quality that a risk situation possesses, considering the factors of exposure of urban systems to hazardous events and their potential impacts, thus following the definition of risk in (IPCC, 2022).

The figure 6 presents the resulting ontology, detailing the interplay between risk drivers, hazardous events, risk situations, and impact events. A *Risk Driver* (e.g., heavy rainfall) can trigger hazardous events (e.g., flooding), exposing urban systems to risks. These urban systems (*Exposed Urban System*), characterized by inherent vulnerabilities, become participants in risk situations when hazardous events occur. The vulnerabilities are manifest during such events, amplifying the system's exposure and susceptibility to impacts (damages and losses).

In addition, hazardous events can occur as chained hazardous events, where one event *A* can lead to event *B*, creating a historical dependence, i.e., event B cannot occur unless event *A* happens first. This cascading effect underscores the complexity of urban risk dynamics. Additionally, the ontology represents qualitative dimensions such as *Risk Likelihood*, *Impact Value*, and *Hazard Magnitude*, which are assigned by an *Assigner* (e.g., seismologist, meteorologist). The *Assigner* evaluates each *Hazardous Event* by estimating its *probability* and *magnitude*, while also assessing *risk situations* and *impacts* based on their likelihood and severity. For impacts, specific *values* are assigned depending on the affected properties, whether tangible (e.g., infrastructure), intangible (e.g., social cohesion), or cultural heritage.

The results of both approaches were compared, revealing the existence of concepts at more specialized levels in the bottom-up approach results (see Table 2 and Figures 7, 8, 9, 10, 11). On the other hand, the model built using a top-down approach presented abstract concepts derived from risk theories that were not perceived in the storylines, e.g., *Assigner*, *Urban System*, and *Urban System at Risk*.

A further observation is that the storyline-based approach, despite its limited scope in terms of relation types (i.e., *leads_to* and *affects*), emphasizes cascading aspects of events and scale dependencies, which may be overlooked in a top-down approach. Conversely, the top-down approach encompasses a more extensive array of relation types, thereby facilitating enhanced categorization of existing relation types and contributing to the disambiguation of terms utilized by stakeholders.

5 DISCUSSION AND RELATED WORK

The integration of storylines and ontological modeling in this study underscores the role of hybrid methods in capturing the complexity of urban risk systems. By synthesizing top-down and bottom-up approaches, the middle-out approach demonstrated its capacity to mitigate the inherent limitations of each method when applied in isolation. This aligns with prior research emphasizing the value of interdisciplinary frameworks in addressing multi-faceted challenges in urban resilience and risk management (Shepherd et al., 2018), (Du et al., 2023).

The top-down approach, guided by competency questions and foundational ontologies, successfully identified abstract concepts such as *Urban System at Risk* and *Assigner*, *Urban Risk Situation*, *Impact Value* (Fig. 6). These constructs, rooted in formal ontological commitments, provided a theoretical framework for interoperability. Conversely, the bottom-up approach, driven by stakeholder narratives, surfaced domain-specific terminology (e.g., the taxonomy of hazardous events) and contextual relationships (hazard magnitude in Table 3). For instance, storylines explicitly modeled cascading risks in Fig. 7, Table 2), which enriched the ontology with granular, scenario-specific dynamics. However, as noted in prior work (Sillmann et al., 2020), narrative methods often struggle to formalize higher-order abstractions, a gap addressed here through top-down integration.

The merged ontology (Fig. 6) enables a representation of urban systems, bridging physical infrastructure (e.g., roads, buried assets) and socioeconomic vulnerabilities (e.g., energy poverty). This aligns with the IPCC's (2022) risk framework (IPCC, 2022), emphasizing the interplay of hazards, exposure, and vulnerability. For practitioners, the ontology's structure supports predictive scenario analysis[13].

Regarding the ontologies mentioned in (Section 2), they do not use foundational ontologies, which introduces inconsistencies for the built domain ontology. However, it is possible to integrate or reuse them with some harmonization. One relevant work is the HIP ontology (Stephen et al., 2024), which proposes a standardized classification of types of hazards. In this case, the framework of hazards proposed can be reused to classify other hazardous event types (Fig.5).

Despite the positive results of this study, two primary limitations emerged. First, the communicative accessibility of ontological models remains challeng-

[13] The codes in OWL, JSON are available at link https://gitlab.inf.unibz.it/earth_observation_public/CCT/pnrr-return/ts1

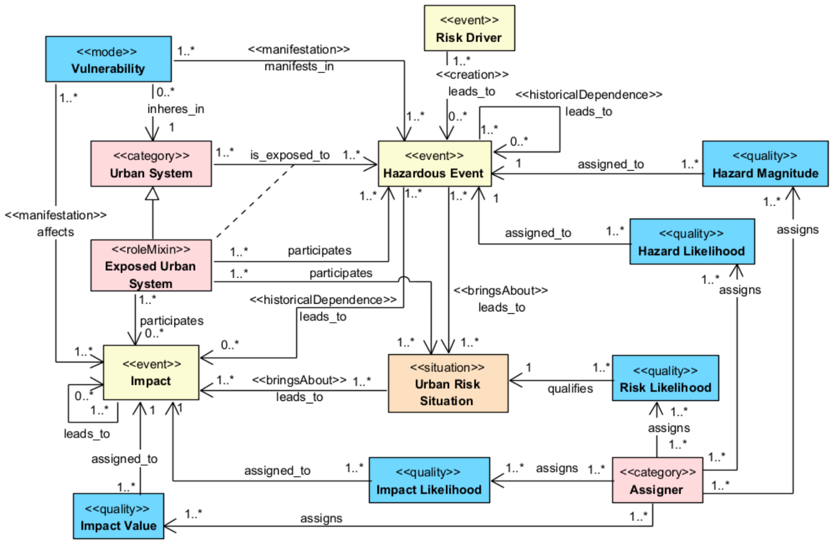

Figure 6: Risk-driven ontology of urban systems - merged ontologies (fragment).

ing. While ontologists adept in knowledge representation navigated the multi-relational structures (e.g., participates_in, manifests_in, inheres_in relations), non-ontologist stakeholders required simplified visualizations (Fig.s 7, 8, 9, 10, 11).

Second, the epistemic bias stemming from a limited storyline corpus was partially mitigated through iterative workshops and literature reviews. However, broader validation—via cross-disciplinary scenarios or computational narrative generation—is necessary to guarantee the validity and reliability of the research. For example, Storyline 1.2 (heatwaves and flooding) focused on social housing vulnerabilities but omitted institutional governance dynamics, highlighting gaps in stakeholder perspectives.

6 FINAL CONSIDERATIONS

This paper introduced the use of storylines in ontology engineering as a means of identifying more specialized classes and attributes. It was observed that while the top-down approach facilitated the identification of more theoretical concepts, it resulted in the oversight of more specialized concepts and attributes. Conversely, the bottom-up approach yielded the opposite effect, with experts not identifying some abstract concepts and relationships, while more specialized concepts and attributes were more readily apparent. Notably, our findings demonstrate that no single elicitation method suffices for comprehensive ontology development in complex socio-technical domains. The observed complementarity between narrative-driven (bottom-up) and theory-driven (top-down) approaches suggests that the middle-out approach - strategically combining both paradigms - offers the most robust foundation for urban risk ontology engineering.

Concerning results, it is important to note that the quality of ontologies is often contingent upon their development through an engineering-based approach, drawing upon foundational ontologies. This methodological foundation results in the creation of well-formed models that exhibit high levels of expressivity and shared comprehension within the domain of risk-driven urban systems. The project's scale and complexity, involving over twenty-six institutions and stakeholders from diverse academic disciplines, underscores the necessity for such a comprehensive and collaborative approach. A further outcome of the project line is the establishment of a controlled vocabulary published on the Skosmos platform that can be shared between different ontologies or other computational structures[14].

These results, while effective for experts in knowledge representation, present at least two limitations that warrant discussion. First, the **communicative accessibility of ontological models** emerges as a persistent challenge. The inherent complexity of multi-relational conceptual structures necessitates adaptive visualization strategies to accommodate diverse audiences. Future work should prioritize the development of tiered representation frameworks capable of dynamically adjusting granularity levels, ranging from high-abstraction overviews to detailed axiomatic specifications, based on stakeholder expertise and use-case requirements.

[14] See https://skos.cct.eurac.edu/vocab/en/

Second, the limited sample of storylines introduces potential epistemic biases during ontology design. Although the hybrid approach partially mitigated this limitation, broader validation remains essential. To address these limitations, future work will focus on expanding the storyline corpus through: 1) cross-disciplinary scenario workshops; 2) computational narrative generation techniques; and 3) multi-decadal temporal sampling.

Future work includes population of the ontology and an empirical study with stakeholders to evaluate the middle-out approach's *ease of use*, *comprehensibility*, and *completeness*.

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Table 2: Summary of Storylines with Notes and Legend.

Storyline	SC	Dim.	Pop.	Reference Hazards	Exposure	Vulnerabilities	Key Risks	Stakeholders	Relevant Data
1.1	SC_03 (Coastal metropolitan)	80 km^2	200k	Earthquake → Tsunami → Pollutant release	Residents, infrastructure	Coastal industries; road redundancy	Loss of life, systemic risks	Civil Protection, industry	None
1.2	None defined	1 km^2	5k	Heatwaves & flooding	Social housing	Energy poverty, drainage issues	Health, socioeconomic damage	Residents, municipality	None
2	SC_XX (Tectonic plain)	50 km^2	50k	Earthquake → Flooding	Residents, agriculture	Aged buildings, urbanization	Seismic damage, flooding	Civil Protection, farmers	Historical data
3	SC_04 (Hilly area)	80 km^2	200k	Pipeline leaks + Landslide	Urban infrastructure	Soil impermeability, road redundancy	Infrastructure damage, fatalities	Road managers	Soil, rainfall data
4	SC_04 (Hilly area)	1 km^2	8k	Rain → Landslide + Chemical leak	Refinery, railway	Aged buildings, logging	Industrial risks, railway disruption	Railway/industry	Convective data

Legend:
SC: Settlement Context.
→: Cascading/compound hazards.
Exposure: Elements at risk.
Vulnerabilities: Amplifying factors.
Notes:
1. Storylines 3 & 4 share SC_04 but differ in hazards.
2. Systemic risks (e.g., road blockage) common in non-redundant infrastructure.
3. Climate/historical data for Storylines 2–4.

Table 3: List of Core Concepts.

Name	**Stereotype (UFO)**	**Description**	**Approach**
Urban Risk Situation	«situation»	Context where urban systems face risks from hazards and vulnerabilities	middle-out
Impact	«event»	An event resulting from hazardous events, causing measurable consequences (damages and losses)	top-down and bottom-up
Vulnerability	«mode»	A state of susceptibility to harm within a system or population	top-down and bottom-up
Urban System	«category»	A structured entity comprising human-made and natural urban components	top-down and bottom-up
Hazardous Event (taxonomy)	«event»	A specific incident posing danger to urban systems (e.g., floods, earthquakes)	bottom-up
Exposed Urban System	«roleMixin»	An urban system in a role where it is susceptible to hazards.	top-down
Risk Likelihood	«quality»	Probability of a risk materializing in a given context	top-down
Assigner	«category»	An entity responsible for assigning values or roles (e.g., risk assigner)	top-down
Impact Value (scale)	«quality»	Quantitative or qualitative measure of adverse consequences	bottom-up
Hazard Magnitude	«quality»	Severity or intensity of a hazardous event.	top-down
Hazard Likelihood	«quality»	Probability of a hazardous event occurring	top-down
Impact Likelihood	«quality»	Probability of specific consequences arising from a hazard	bottom-up
Risk Driver	«event»	A factor or event that amplifies or triggers risks (e.g., climate change)	top-down and bottom-up

Table 4: List of Relations.

Type (UFO/UFO-B)	Relation Name	Description
Creation	assigns	Establishes a responsibility or role (e.g., Assigner assigns Impact Value to a Risk).
Creation	leads_to	an event creates or becomes a hazardous event (e.g., Risk Driver leads_to a Hazardous Event).
BringsAbout	leads_to	a situation results in a situation (e.g., Impact Event leads_to an Urban Risk Situation).
Characterization	assigned_to	Indicates assignment of a property or role (e.g., Risk Likelihood is assigned_to an Urban System).
Characterization	qualifies	Specifies a characteristic or constraint (e.g., Hazard Magnitude qualifies a Hazardous Event).
Characterization	inheres_in	A quality inherently belongs to an entity (e.g., Vulnerability inheres_in an Urban System).
Historical Dependence	leads_to	A causal or temporal sequence between events (e.g., an Impact Situation leads to another Impact Situation).
Participation	participates	An entity is involved in an event or situation (eg., an Exposed Urban System participates in an Impact Situation).
Manifestation	manifests_in	A property becomes evident in a specific context (e.g., Vulnerability is manifested in an Exposed Urban System).
Manifestation	affects	One entity influences or modifies another (e.g., a Vulnerability affects an Impact Situation).
Material	is_exposed_to	Indicates susceptibility to a hazard (e.g., Urban System is_exposed_to Hazardous Events).

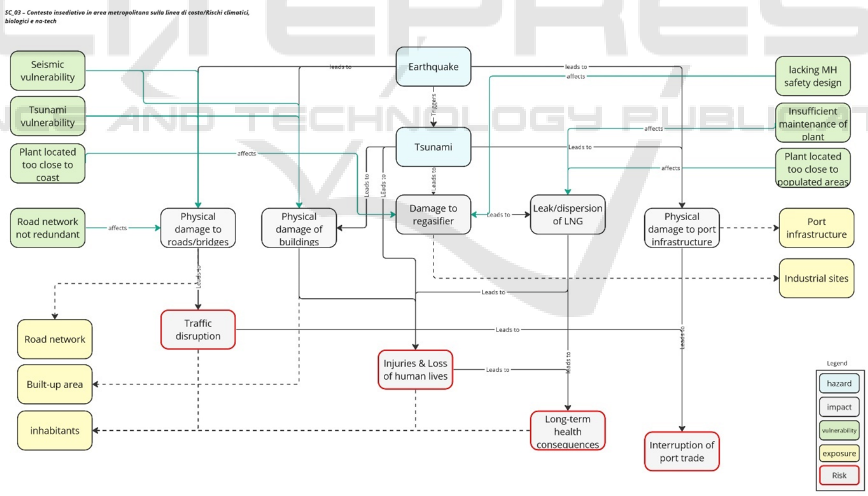

Figure 7: Storyline 1.1.

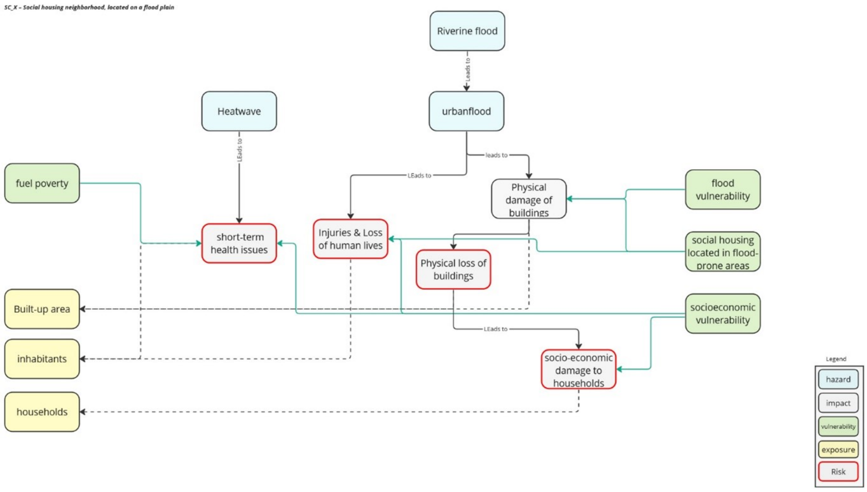

Figure 8: Storyline 1.2.

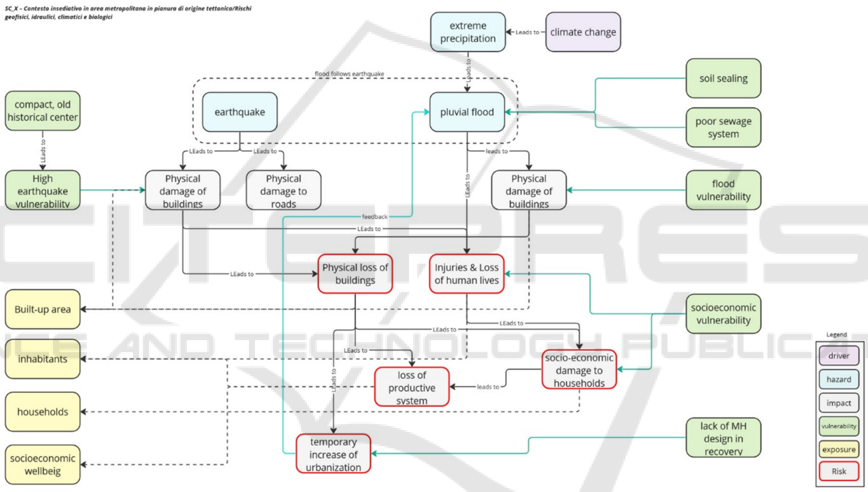

Figure 9: Storyline 2.

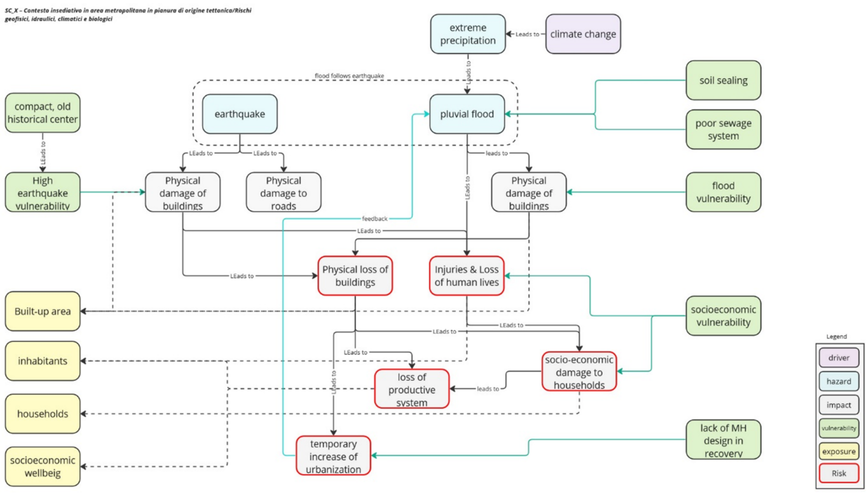

Figure 10: Storyline 3.

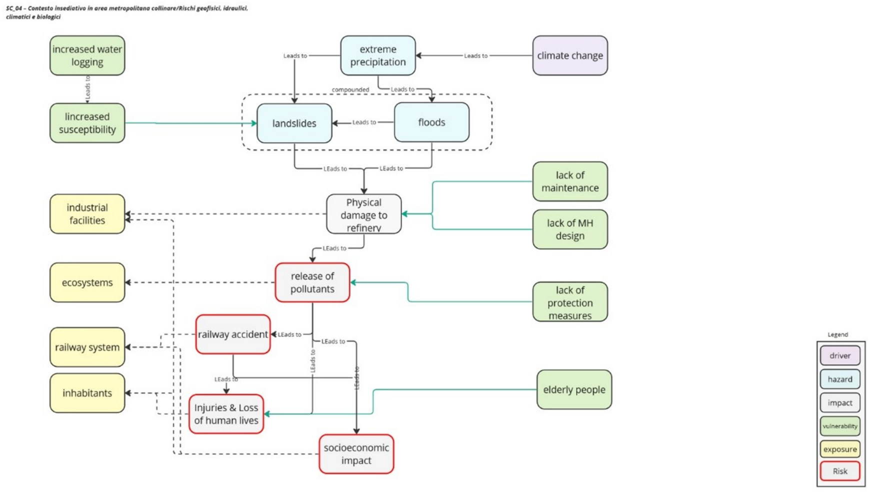

Figure 11: Storyline 4.