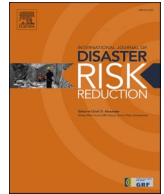






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Layered or simple: Making impact chains more accessible and useful to stakeholders

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ABSTRACT

Multi-hazard disasters underline the need to shift from siloed Disaster Risk Reduction and Management (DRR/M) policies and practice to coordinated, multi-hazard strategies and increased stakeholder engagement. The challenge lies in designing models and tools that accurately convey the intricacies of multi-hazards, compounded impacts, vulnerabilities, and mitigation actions without overwhelming users, thus preserving the clarity needed for effective decision-making. Addressing this critical implementation gap, this study introduces Layered Impact Chains and Simplified Impact Chains as frameworks designed to streamline stakeholders' understanding of Impact Chains. Layered Impact Chains break down the complete model into layers comprising elements and connections relevant for various stakeholder categories, while Simplified Impact Chains distil these layers to their essential components using a customised statistical metric. The proposed frameworks are applied in a case study featuring a multi-hazard event relevant for Bucharest, Romania, wherein a major earthquake would set off a cascade of secondary hazards, including a dam-break flood, fires, and liquefaction. The foundational complete multi-hazard Impact Chain was built collaboratively, integrating insights from a wide group of DRR/M stakeholders via one-on-one interviews, focus groups, and hybrid workshops. The proposed Layered and Simplified models were subsequently validated in terms of understandability, navigability, and usability through dedicated workshops and focus groups with the target stakeholders. By translating complex disaster analysis models into accessible formats, the proposed frameworks empower stakeholders to understand multi-hazard disasters and craft integrated and more effective DRR/M solutions.

1. Introduction

The need to understand what factors converge to transform hazard events into disasters has been drawing the attention and efforts of disaster risk researchers and international agencies for decades [1–5]. This pursuit has grown more urgent against the increasing frequency and impactfulness of multi-hazard events with a high potential to evolve into disasters, propelled by climate change and rapid, unsustainable socio-economic development. This increased complexity is addressed through the development of different frameworks capable of analysing the interplay of disasters' components: Impact Chains [6], causal loop diagrams [7], influence

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diagrams [8], fuzzy cognitive maps [9,10], Impact Webs [11], etc. Nevertheless, many of these frameworks remain confined to the scientific community and are yet to be integrated into Disaster Risk Reduction (DRR) or Management (DRM) practice. A key reason for this implementation gap is that the tools are often designed without considering end-user usability [12] and skills, or without integrating their perspectives and needs [13].

Among the aforementioned frameworks for disaster analysis, Impact Chains have been gaining significant traction as valuable conceptual and communicative tools in both DRR and DRM research. These are state-of-the-art conceptual models developed by UNDRR [6] to analyse climate-related risks [14–19]. Despite their recent introduction, the scope of Impact Chains expanded to describe cause-and-effect relationships in systemic multi-sectoral and multi-hazard risk assessments [20,21]. Integrated into DRM research, Impact Chains have also been combined with forensic analysis to inform the emergence of a new intertwined DRM model for long-lasting, wave pattern-based disasters [22] or used as a basis for developing metrics-focused methodologies that help elicit best practices and areas of improvement in flood risk management [23]. Moreover, Impact Chains have also been repurposed into new models able to track vulnerability dynamics across space and time in multi-hazard settings (Enhanced Impact Chains, [24]).

Impact Chains can be used to organise, visualise, analyse, and share a large volume of data and information related to hazard events or disasters. Their temporal and geographic scope has to be set from the start of their design, as they are highly versatile and can focus on both past or future hazard events or disasters (disaster scenarios, if their scope is oriented towards the future). Impact Chain's capacity to analyse the unfolding of hazards (independently, simultaneously, or in cascade) and their (compounded) impacts, also accounting for the influence of vulnerability and mitigation efforts, alongside their ability to express this interplay in a visual way, make them the modern “backbone for a risk assessment” [6]. On the other hand, this high analytical capacity is double-edged, as medium- to large-size Impact Chains can become hard to follow [17] by both scientists and stakeholders. Moreover, convoluted models are hard to scale for proper visualisation, and they can divert attention from the essence of the analysis. These shortcomings translate into difficulties in communicating, operationalising, and validating the models [17].

Despite their merits and promises, and motivated by their limitations, Impact Chain models often remain theoretical and fail to be translated into reliable, effective tools for stakeholders. This implementation gap is partially explained by the recent development of

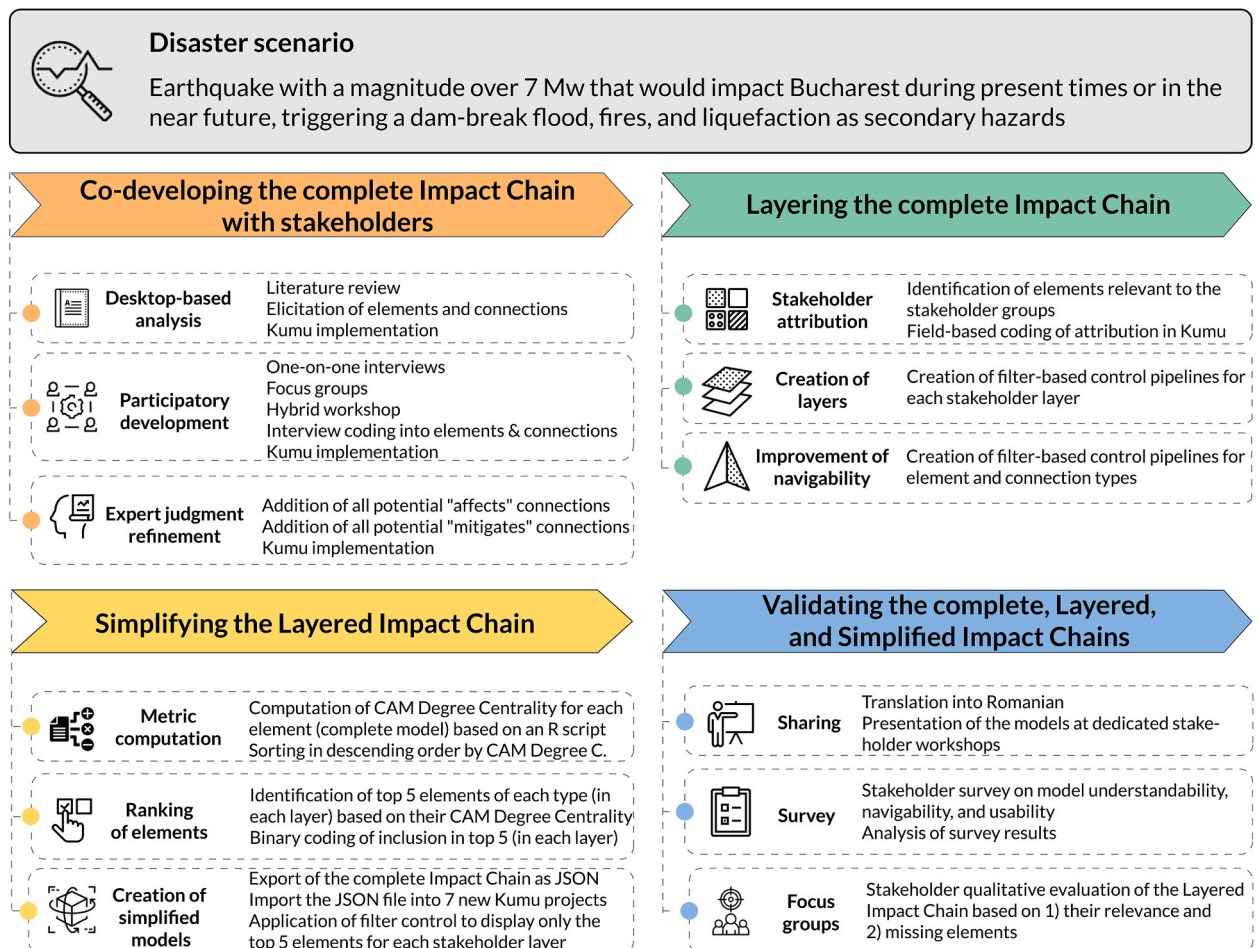


Fig. 1. Methodological workflow.

Impact Chains that can inform policies and actionable emergency intervention plans [22–24]. More importantly, the notable complexity and size (e.g., almost 200 elements and thousands of connections) reached by these models prevent them from being easily understood and accepted by stakeholders. To make them effective, a balance must be achieved between capturing the nuances about the hazards, impacts, vulnerabilities, exposed elements, and mitigation measures that interact to compose a disaster and presenting them in an accessible way that enables increased model use and decision-making across the DRM phases (i.e., preparedness, response, and recovery).

This study aims to introduce Layered Impact Chains and Simplified Impact Chains as frameworks designed to streamline stakeholders' understanding of Impact Chain models, in order to make them more accessible and useful. Layered Impact Chains address the compromise between keeping complexity in place but making it understandable and accessible by dividing the original complete Impact Chain model into layers that comprise only the elements that are relevant for particular stakeholder categories. In this way, comprehensive models are made more practical without the cost of scaling down their content. Simplified Impact Chains take this further, using statistics to extract only the essential elements and connections in each layer. In this sense, Simplified Impact Chains represent the core of the layers in the Layered Impact Chain. By making stakeholders more open to exploring Impact Chains and using them as guiding tools, Layered and Simplified Impact Chains remove the barriers that stand between the translation of these models into DRR/M policy and practice.

2. Methodology

The methodological workflow (Fig. 1) starts by developing the complex multi-hazard Impact Chain focusing on a major earthquake (over 7 M_w , originating in the Vrancea Seismogenic Zone) that would strike Bucharest during present times or in the proximal future. This primary hazard would trigger secondary hazards such as an earthquake-induced dam-break flood, fires, and liquefaction. An initial shorter version of this model was developed as part of our work within Bucharest Case Study in the PARATUS Project. The larger model used in this study was built under a participatory approach that reunites insights from a wide range of relevant stakeholders and it represents one of the most extensive Impact Chain models, comprising 196 elements and 2795 connections.

Next, we introduce the Layered Impact Chain, a model we created with distinct layers (from the complete multi-hazard chain) tailored to the interests and responsibilities specific to different stakeholder categories. Subsequently, we build Simplified Impact Chains as streamlined versions of the layers in the Layered Impact Chain, retaining only the top 5 elements of each type and the connections established among them, for each layer based on a customised metric. All these types of Impact Chains (i.e., complete, Layered, and Simplified) were evaluated in terms of understandability, navigability, and usability, using feedback from the various stakeholders participating in the Third Stakeholder Workshop organised in Bucharest as part of the PARATUS Project and additional focus groups.

2.1. Overview of the Impact cChain methodology

Impact Chains can focus on past or future hazard events or disaster events unfolding at different spatial scales. For this reason, their temporal and spatial scope should be clearly specified at the outset of the analysis. These models are built of elements specific to disaster events (Table 1) and the connections established among them (Fig. 2). Besides the conventional elements listed in Table 1, the Impact Chains in this study also include susceptibility elements that act as a special type of vulnerability of human-made systems that results from environmental (natural) factors and processes. In our models, local site conditions and tectonic settings were included as susceptibilities.

Most of the connections in Impact Chains are directional (i.e., starting from one element and targeting another element) and causal, but their types convey different nuances of causality. Drawing on the initial guidelines proposed by Pittore et al. [27] for Impact Chain development in the PARATUS Project – subsequently refined and detailed by Albulescu and Armaş [24], Armaş et al. [28], and Albulescu et al. [22], these connections are defined as:

Table 1
Definitions of elements included in Impact Chains.

Element	Definition	Source
Hazard	“A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.”	UNDRR [25]
Impact	A negative effect of a hazard, which can be directly or indirectly caused by the hazard or by another impact.	Adapted from the disaster impact definition by UNDRR [25]
Exposed element	“A person, infrastructure element, housing element, production capacity or other tangible human asset located in hazard-prone areas.”	UNDRR [25]
Vulnerability	“The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.”	
Adaptation option	Mitigation measures aiming to attenuate/minimise negative impacts and/or vulnerabilities	Adapted from IPCC [26] as indicated in Pittore et al. [27]; Adapted from the UNDRR [25] also to include vulnerability

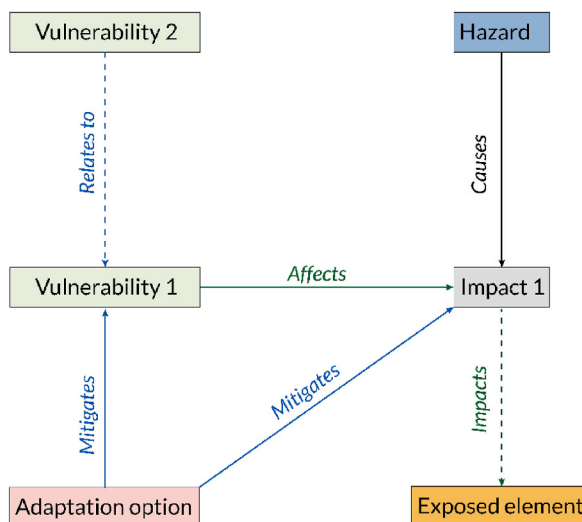


Fig. 2. General structure of an Impact Chain [28].

- “Causes” connections: set between 1) a hazard that triggers another hazard, 2) a hazard that causes an impact, 3) an impact that causes another impact, or 4) an impact that causes a hazard (e.g., earthquake-induced building/lifeline damage causes fires);
- “Affects” connections: set between a vulnerability that contributes to the manifestation of an impact;
- “Mitigates” connections: set between an adaptation option and an impact/a vulnerability that is mitigated by that adaptation option;
- “Impacts” connections: set between an impact and the exposed element that is subject to that impact;
- “Relates to” connections: usually (but not necessarily) set between elements of the same type to convey a low-importance association that cannot be expressed by other connection types.

This intuitive structure (Fig. 2) equips scientists and practitioners with a practical instrument for the exploration, visualisation, organisation, and analysis of the elements associated with hazard or disaster events from the past or future. Impact Chains can be developed following different operational frameworks: desktop analysis, expert workshop, or machine-generated approaches. These methodologies require different resources and are subject to specific limitations. For instance, desktop-based analysis is more readily available, as it relies on integrating empirical evidence collected from multiple data and information sources (e.g., scientific literature, grey literature, statistical or spatial datasets, legal documents, etc.). Conversely, expert workshop approaches for building Impact Chains synthesise insights not only from stakeholder workshops but also from stakeholder interviews, focus groups, or surveys. This participatory approach is essential when disaster-related data are scarce [29] and it can also capture finer details, potentially not included in the literature or available datasets [16]. The resulting robust models based on expert workshops also hold the merits of promoting stakeholder and community involvement and bridging science and practice.

Drawing on these sources, Impact Chains are primarily visual models that have to be implemented in visual collaboration platforms with mind mapping capabilities (e.g., Kumu, Miro, XMind, Lucidchart, etc.). Kumu is the most frequently used open source platform for Impact Chain implementation, as it enables interactive exploration and free download of these models in different data formats. Elements (Table 1) are depicted as boxes colour-coded by type, while connections are shown as lines with directional arrows which are colour-coded by connection type. Illustrative examples of Impact Chains that allow for visual manipulation and download are available in Paratus Deliverable 1.1. [30], Albulescu and Armaş [24], Albulescu et al. [22,23], and Armaş et al. [28].

2.2. Co-developing the complete Impact Chain with stakeholders

The multi-hazard Impact Chain (also referred to as the complete or conventional Impact Chain) revolved around a disaster scenario wherein an earthquake with a magnitude over 7 M_W would hit Bucharest during present times or in the near future. This model was developed under a multi-method approach that combined desktop-based analysis with the expert workshop approach and refinement based on expert judgement (Fig. 1).

First, we elicited information on the impacts, vulnerabilities, and adaptation options of past major earthquakes that severely affected Bucharest in 1940 (7.6 M_W , 150 km in depth) and 1977 (7.4 M_W , 109 km in depth) [31–34]. The desktop-based analysis was supplemented with results from earthquake impact simulations [35–37] and seismic vulnerability analyses [36,38–41] focused on Romania’s capital. These research works have provided an important foundation for the model, as all elements and connections elicited from the literature review were integrated into the Impact Chain using the Kumu platform. The model was designed as a Kumu map [42], representing a visual diagram of shapes (elements as boxes colour-coded by type) connected by directed lines (connections as lines with arrows colour-coded by type),

In the participatory development phase, we conducted one-on-one interviews, focus groups, and one hybrid workshop with stakeholders with expertise and responsibility in managing the envisioned multi-hazard disaster. Contributing stakeholders included: first responders (across hierarchical levels) from the General Inspectorate for Emergency Situations and the Department for Emergency Situations; military workforce in reserve with past employment in special military services; medical professionals (including a doctor specialised in Disaster Medicine); policy and decision-makers from the City Hall of Bucharest (the Executive Director of the Municipal Administration coordinating the retrofitting of buildings with seismic risk, General Council of Bucharest); architects; civil and structural engineers (the Director of the Professional Association of Civil and Structural Engineers in Romania); urban planners; construction experts from the Technical University of Civil Engineering of Bucharest; law experts with extensive knowledge on the legal framework governing seismic risk reduction (SRR) in Romania; and representatives of insurance companies (the Director of the National Insurance Pool against Natural Disasters). These stakeholders were grouped into specific categories relevant to the multi-hazard disaster scenario, as detailed in Fig. 3. Their diverse backgrounds ensured the resulting Impact Chain was comprehensive, directly overcoming the limitation noted by Fekete et al. [43] that “this methodology can only give an impression of the situation”, and guaranteeing a multifaceted perspective on the disaster scenario.

The interviews and focus groups were conducted in January-May 2024 based on a preset agenda. Prior to all data collection, participants provided signed consent and received the discussion agenda, which was approved by the Ethics Committee of the Center for Risk Studies, University of Bucharest. The interview agendas were tailored to the professional expertise and responsibilities of stakeholders. Each agenda included a description of the proposed disaster scenario, a question regarding the area of expertise of the stakeholder, and questions on the hazard impacts, vulnerabilities, and adaptation options that were tailored to their training and tasks. Data collection employed three modalities: i) in-person sessions for first responders, second responders, and law experts (via interviews, with additional focus groups for emergency intervention workers), ii) a hybrid workshop for decision-makers, urban planners, architects, and engineers, and iii) online interviews for the other stakeholders.

The interview, focus group, and hybrid workshop sessions were recorded, and their content was subsequently analysed and coded into elements and connections to be included in the complete Impact Chain. These insights were then integrated into the Kumu platform, together with the source of the information and a description of the elements.

Building upon the stakeholder-provided and literature-driven connections, the model was expanded through expert judgement. We added all the potential “causes”, “affects”, and “mitigates” connections under an expert judgement approach, but did not apply this step to “impacts” or “relates to” connections due to their secondary importance. This expansion of key connection types within the model was critical due to the Impact Chain’s focus on a future multi-hazard event, which requires a deep understanding of potential causal relationships among hazards and impacts (expressed via “causes” connections), contributions of vulnerabilities to the manifestation of impacts (expressed via “affects” connections), and mitigation efforts targeting impacts and/or vulnerabilities (expressed via “mitigates” connections). A key guiding principle in establishing these primary-importance connections related to the prominence of the effect conveyed by that connection in the context of the disaster. In other words, we considered both direct and indirect effects,








STAKEHOLDER CATEGORY	ROLE	CO-DEVELOPMENT OF THE COMPLETE IMPACT CHAIN	FEEDBACK ON THE COMPLETE, LAYERED, AND SIMPLIFIED IMPACT CHAINS
First responders 	Emergency intervention workers with specialised training in DRM (including search and rescue, evacuation operations), who are the first to arrive at hazard impacted sites and provide assistance or incident resolution	First responders (across hierarchical levels) from the General Inspectorate for Emergency Situations and the Department for Emergency Situations	
Military workforce 	Second responders with military training, who support first responders in emergency resolution during response (including search and rescue and evacuation operations), also helping during recovery periods (by setting up temporary shelters, cleaning up sites, supplying essential goods, etc.)	Retired military personnel having operational experience in combat theaters abroad	
Medical professionals 	Second responders with medical training, who can provide medical assistance at hazard impacted sites or in medical facilities. This category includes medical doctors and nurses	Medical doctor with (military) training in Disaster Medicine	Medical doctors representing the Public Health Department of the Municipality of Bucharest
Polymakers and decision-makers 	High-level authorities with the power to influence national, regional, or local scale policies and/or who are in charge of their implementation	Executive Director of the Municipal Administration coordinating the retrofitting of buildings with seismic risk (AMCCRS, General Council of Bucharest) and an urban planner from the City Hall of Bucharest Municipality	Representatives of the Ministry of National Defence, Ministry of Regional Development and Public Administration, Ministry of Transportation, National Administration for State Reserves and Special Problems, and the City Hall of Bucharest Municipality (AMCCRS)
Construction experts 	Experts with training in Construction Science, who are responsible for elaborating and checking for the application of seismic design and construction design codes. This category includes structural engineers, architects, construction project managers, technical and safety experts	Architects, civil and structural engineers (the Director of the Professional Association of Civil and Structural Engineers in Romania), academics from the Technical University of Civil Engineering of Bucharest	Construction experts from the State Inspectorate for Constructions, Academics from the Technical University of Civil Engineering of Bucharest
Law experts 	Consultants with training in all the areas of law, including competences of interpretation and application of the national legal framework	Lawyers and notaries with exetensive knowledge on the legal framework regulating seismic risk reduction at the level of the building stock in Romania	
Insurance companies 	Consultants authorised to act on behalf of an insurance company to sell, service, or manage insurance products and policies. They serve as the critical link between the insurance provider and the policyholders (clients), performing duties that range from sales and customer service to claims processing and risk assessment	Director of the National Insurance Pool against Natural Disasters (PAID)	

Fig. 3. Details on the stakeholder categories involved in the co-development and evaluation of the complete, Layered, and Simplified Impact Chain.

selecting them for inclusion as connections in the chain based on their relevance in the multi-hazard disaster scenario focused on Bucharest. To balance large envisioning vulnerability-impact-adaptation option interactions with practical relevance, we adopted a dual approach: vulnerabilities were allowed to exert a broader, indirect influence on impacts via “affects” connections (as it is difficult to measure the exact contribution of a vulnerability to the manifestation of an impact, [23]), while “causes” and “mitigates” connections were limited to those demonstrating a direct influence. This ensured the model remained both comprehensive and grounded in the realities of the case study.

2.3. Layering the complete Impact Chain

The transformation of the complete multi-hazard Impact Chain described in the last section into a Layered Impact Chain (Fig. 4) comprising different layers tailored to the interests of stakeholders was a three-phase process. During the stakeholder attribution phase, we identified elements relevant to specific stakeholder categories (Fig. 3) based on 1) the insights provided by the stakeholders in question during the co-development of the complete multi-hazard Impact Chain and 2) expert judgement. Therefore, each element was attributed to at least one stakeholder category, with most elements included in two or more such categories. This multiple stakeholder attribution is justified by the shared interests in certain elements (and the connections established among them) and their direct and indirect implications for stakeholders’ DRR/M duties. For instance, first responders, decision-makers, and construction experts found retrofitting works relevant from different perspectives: as a guarantee for safer buildings and lower necessity for emergency intervention (for first responders), as key seismic risk reduction projects to coordinate (for decision-makers), and as one of their main responsibilities (for construction experts).

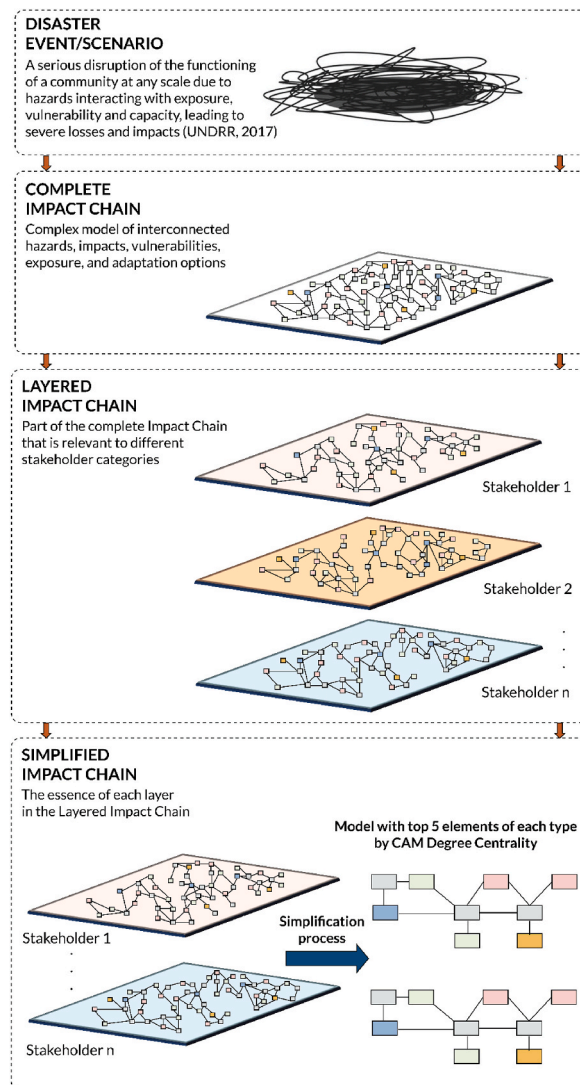


Fig. 4. Complete, Layered, and Simplified Impact Chain concepts.

In the Kumu platform, this phase was implemented by creating data fields named after the stakeholder categories listed in Fig. 3. These fields were rendered as columns in the table view of the model, and stakeholder attribution was achieved through filling in the stakeholder category fields with the exact name of that category for each relevant element. For instance, the First responders field was filled in with “First responders” for each element relevant to this group.

Next, this coded database was used to create the 7 layers (one for each stakeholder category in Fig. 3) of the Layered Impact Chain. This was accommodated in the Kumu architecture by setting up 7 control pipelines (called “filter controls” in Kumu [44]) that automatically filter the model to visualise only the elements (and the connections established among them) relevant for (based on the attribution phase) specific stakeholder categories, while hiding irrelevant elements and connections. The control pipelines were named after each stakeholder category and displayed as buttons in the lower-right of the Impact Chain visualisation panel (Fig. 5A). By clicking on their designated control pipelines, stakeholders had access to the model content (i.e., elements and connections) that was relevant to their expertise and professional responsibilities in the event of a multi-hazard disaster. The CSS-like code (modified for use in the Kumu platform using a forked PostCSS parser, [45]) of these control pipelines is provided in the Zenodo repository (<https://doi.org/10.5281/zenodo.18774181>), and it can be inserted in the Advanced Editor Mode of Kumu. Alternative implementation strategies were also considered and ultimately discarded, as described in Box 1.

To further streamline model navigation, we implemented two additional filter control pipelines. Accessible via buttons at the bottom of the view panel (Fig. 5A), these control pipelines allow stakeholders to visualise specific element and connection types across

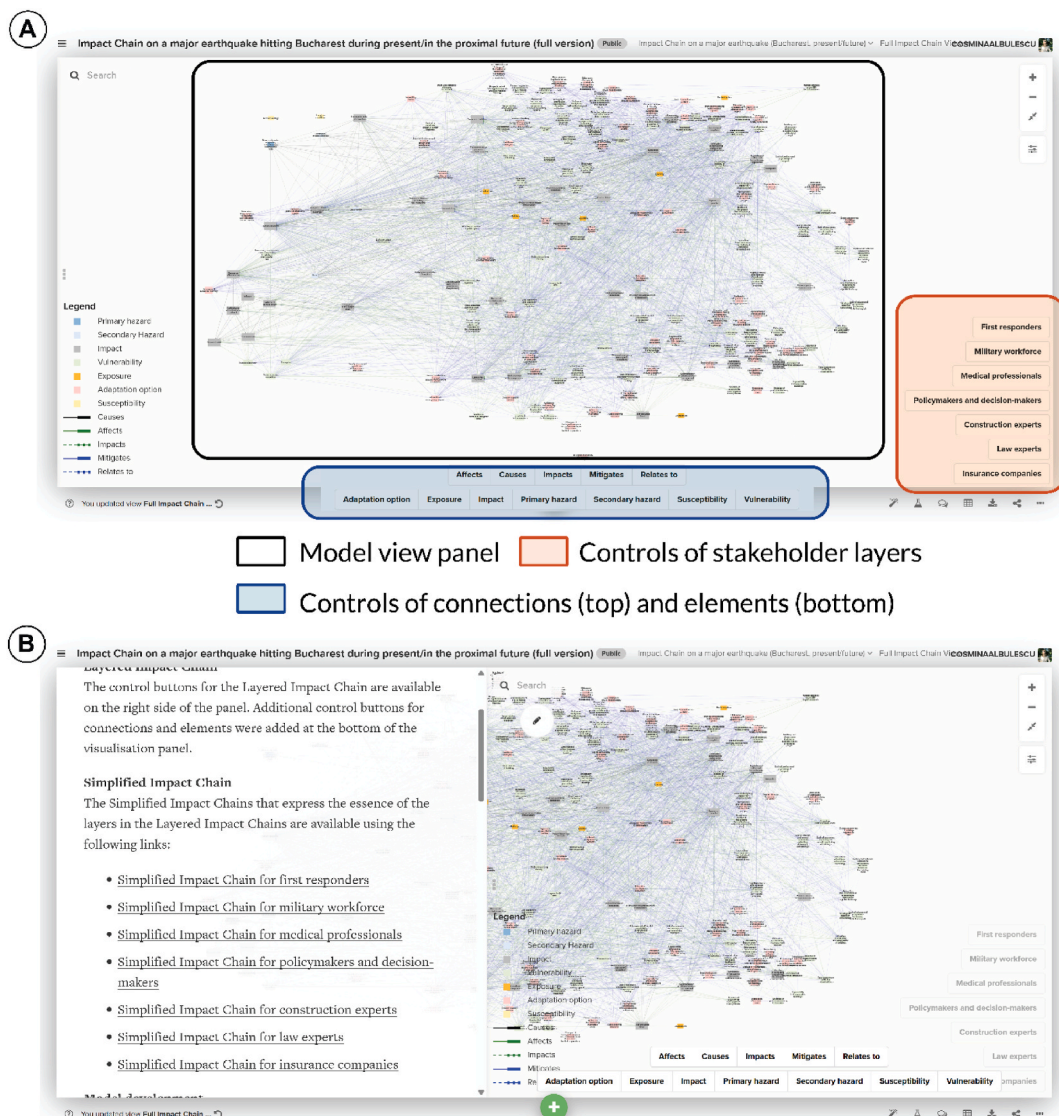


Fig. 5. A – Kumu visualisation environment of the complete and Layered Impact Chains, B – Kumu visualisation environment of the left side panel, including the links to the Simplified Impact Chains designed for the stakeholder layers.

all layers. For example, this enables policymakers and decision-makers to view only the vulnerabilities, impacts, and the “affects” connections established between them, instantly filtering out and visually removing from the model view panel (Fig. 5A) all other content. Such customised filter-based access to the elements and connections across the layers fosters critical thinking and can inform the elaboration of mitigation measures specific to DRM phases. For instance, by visualising and analysing vulnerabilities and the impacts they contribute to, authorities can focus future policies and action plans on the most influential such elements.

2.4. Simplifying the Layered Impact Chain

To transform each layer into a Simplified Impact Chain (i.e., to reduce it to its essence), we created a customised metric called CAM Degree Centrality. This was inspired by the Degree Centrality metric provided by Kumu, defined as “the simplest of the centrality metrics, counting the number of connections an element has” [46]. CAM Degree Centrality was adapted to include only high-importance connections, namely the “causes”, “affects”, and “mitigates” (CAM) connections. It excludes connections of secondary importance, such as “impacts” and “relates to”. Its computation was conducted using an R-script based on the tidyverse package [47] that uses the Excel file of the complete Impact Chain as an input file.

In the selection phase of core elements in each layer, we identified the top five elements of each type (i.e., hazards, impacts, exposed elements, vulnerabilities, and adaptation options) based on their CAM Degree Centrality. A binary code (1 for top five, 0 otherwise) was assigned to each element in a dedicated data field named for its specific stakeholder layer (e.g., top5_firstresponders, top5_militaryworkforce, etc.).

As CAM Degree Centrality does not include “impacts” connections that link impacts with the exposed elements subject to them, all exposed elements registered a 0 score. Their selection for the Simplified Impact Chains was established based on their inclusion into the layers specific to the stakeholder categories. For example, the Simplified model for medical professionals included the population and medical system as exposed elements, as only these were relevant for them (i.e., included in their specific layer).

The implementation of Simplified Impact Chains in Kumu differs from the process presented for the Layered model. To overcome the platform's restriction on duplicating element names within the same project, we created 7 separate Simplified Impact Chains (one for each stakeholder layer). These are accessible via external links provided in the general presentation of the complete Impact Chain, located in the left side panel (Fig. 5B) which is accessible via the Tab key. The Simplified models were created by exporting the complete Impact Chain as a JSON file that preserves the model's structure and style settings, importing it into 7 new projects, and then applying a filter control to display only the top five elements for each layer. The CCS-like code of these filters is openly available in the Zenodo repository (<https://doi.org/10.5281/zenodo.18774181>).

2.5. Validating the complete, Layered, and Simplified Impact Chains

To validate the complete, Layered, and Simplified Impact Chains we presented their Romanian-translated versions to the stakeholders invited at the Third Stakeholder Workshop for Bucharest Case Study organised in October 2025 as part of the PARATUS Project. The participants were already familiar with Impact Chain frameworks from two prior workshops, where they had reviewed and worked on small extracts of the complete multi-hazard chain. Participating stakeholders mirrored the categories for which the Layered and Simplified Impact Chains were developed (Fig. 3). To secure the evaluation of law experts, the military workforce (who were absent from the workshop), and more first responders, medical professionals, and construction experts, we organised special online sessions for them to evaluate the three types of Impact Chains following the original workshop structure.

The workshop started with the presentation of the complete multi-hazard Impact Chain, followed by the presentation of Layered and Simplified ones. Participants were divided into stakeholder-specific groups (Fig. 3) and asked to explore the complete, Layered, and Simplified Impact Chains together with their colleagues and on their own, using the provided laptops. Upon interacting with the models, the stakeholders were invited to fill in an online feedback survey on the three types of the Impact Chains. The survey included 9 Likert-scale items (3 for each model type) wherein respondents were asked to evaluate the chains in terms of:

Box 1

Less effective Kumu implementation strategies for Layered Impact Chains

Implementing the Layered Impact Chain via filter-based control pipelines is the most effective strategy, enabling stakeholders to navigate layers intuitively and efficiently without supplementary guidance. Alternatively, layers can be designed as separate map views which showcase (using showcase controls in Kumu) only the elements and connections relevant to specific stakeholders. Kumu map views are collections of decorations, filters, or other settings that change what is visible on the map and allow for style customisation [42]. This alternative approach was considered but ultimately discarded due to slow rendering times and a disjointed navigation experience, which would hinder stakeholder engagement.

Another considered strategy was to design the layers as independent Kumu maps belonging to the same project. This approach was also dismissed, as it would require duplicating the same elements across multiple maps that would serve as layers. This duplication causes the Kumu platform to experience data management issues and render the model unreliable.

- 1) understandability (i.e., how difficult/easy it is for the stakeholder to understand the model);
- 2) navigability (i.e., how difficult/easy it is for the stakeholder to navigate through/interact with the model);
- 3) usability (i.e., how difficult/easy it is for the stakeholder to use the model in their professional activity)

on a scale of 1 to 5 (where 1 indicates “very difficult” and 5 “very easy”).

Supplementary to this quantitative evaluation on the set criteria, stakeholders participated in focus groups to qualitatively evaluate the complete, Layered, and Simplified Impact Chain's relevance to their work experience and professional responsibilities. Guided discussions explored whether the Layered model included the most critical elements for the stakeholders and what might be missing. The collected insights served as a foundation for subsequent model refinements.

3. Results

This section outlines the structures of the complete, Layered, and Simplified Impact Chains, together with the stakeholder evaluation. The models are too convoluted to be reproduced as proper figures. Nevertheless, the chains can be visualised, interacted with, and downloaded using the links in [Table 2](#) and [Appendix 1](#).

In the Kumu environment, the default view represents the complete model, while the layers dedicated to different stakeholder categories ([Fig. 3](#)) can be accessed using the buttons in the lower-right corner of the panel view ([Fig. 5A](#)). The Simplified Impact Chains are available via external links listed in Kumu's left panel ([Fig. 5B](#)), which is actionable via the Tab key. Comprehensive descriptions of each element of the models, along with their respective references, are available at the provided links ([Table 2](#)) by clicking on one element (represented as a colour-coded box) at a time. The underlying model data (in .xlsx and JSON formats) and code can also be downloaded from this repository: <https://doi.org/10.5281/zenodo.18774181>.

3.1. Overview of the complete multi-hazard Impact Chain

The complete multi-hazard Impact Chain comprises 196 elements and 2795 connections. Its configuration is dominated by vulnerabilities (42.9%) and adaptation options (32.1%) ([Fig. 6A](#)). This shows that contributing stakeholders possess extensive expertise and knowledge regarding the factors and conditions that set up the stage for impacts before the hazards occur (i.e., vulnerabilities), as well as on the solutions to address them (i.e., adaptation options).

Prominent vulnerabilities (i.e., having the largest number of primary-importance connections) include the less supportive and potentially aggressive population; lack of trust in authorities; the negative effects and emotions of earthquake information provided by mass media over time; ineffective institutional communication; and the limited disaster planning, management, skills and training of public authorities. Key adaptation options concern the changes in the mentality of public authorities; the great capacity of first responders to develop creative solutions in crises and cope with new challenges; a proper coordination of seismic disaster management institutions; investments in research regarding seismic risk and vulnerability; and the elaboration of a unified, amended law that regulates SRR.

Accounting for 18.9% of all elements, impacts represent the model's secondary focus ([Fig. 6A](#)). Impact hubs include damage to buildings; economic loss; human casualties; injuries to people; and damage to emergency management buildings (including hospitals). There are under 5% hazards (i.e., the major earthquake as a primary hazard, and liquefaction; dam-break floods; and fires as secondary ones) and exposed elements (i.e., population; buildings; infrastructure; economy; environment; and medical system). Susceptibility (1.02%) encompasses environmental vulnerabilities such as tectonic and local site conditions.

In the multi-hazard complete Impact Chain, the network of connections is dominated by two primary types: “mitigates” (42.9%) and “affects” (34.9%) connections ([Fig. 6B](#)). The remaining connections are less prevalent: “causes” makes up 12% of the total, while “relates to” and “impacts” are the least common. This distribution suggests the model's structure prioritises protection-oriented interactions and the influence of vulnerability on impacts over simple cause-and-effect pathways established among hazards and impacts.

Table 2

Access links to the complete, Layered, and Simplified Impact Chains. The stakeholder-dedicated layers in the Layered Impact Chain are actionable through the buttons in the lower-right of the Kumu visualisation panel. The hyperlinks of these models are also listed in [Appendix 1](#) in their complete URL format to ensure continued access.

Impact Chain	Link
Complete Impact Chain	Link
Layered Impact Chain	Link
Simplified Impact Chain for first responders	Link
Simplified Impact Chain for military workers	Link
Simplified Impact Chain for medical professionals	Link
Simplified Impact Chain for policymakers and decision-makers	Link
Simplified Impact Chain for construction experts	Link
Simplified Impact Chain for law experts	Link
Simplified Impact Chain for insurance companies	Link

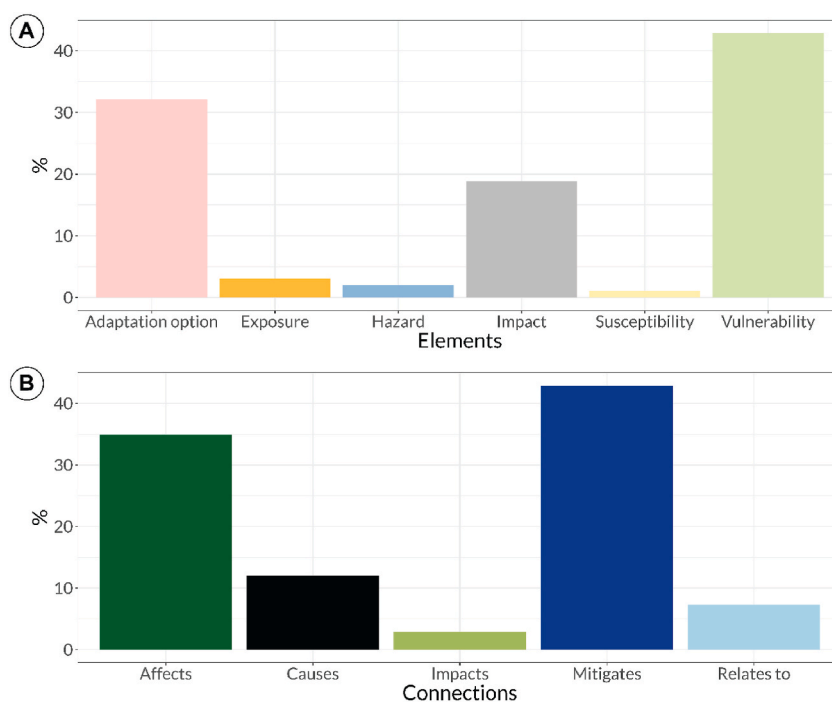


Fig. 6. A – Elements and B – connections included in the complete multi-hazard Impact Chain.

3.2. Overview of the Layered Impact Chain

The Layered Impact Chain comprises stakeholder-dedicated layers that represent 38.77% to 75.51% of the complete model in terms of elements and 23.22% to 67.65% in terms of connections (Table 3). The most comprehensive layers are specific to policymakers and decision-makers and to first responders, while more specialised, less extensive layers are dedicated to law and construction experts. These configurations provide insights into the training, funding, and accountability of the contributing stakeholder groups, reflecting their priorities across DRM phases (i.e., preparedness, response, recovery). A detailed description of the content of each layer (Fig. 7A–G) is provided in Appendix 2.

Vulnerabilities are the dominant element across all layers except for medical professionals, representing at least a third of the total elements. Adaptation options come second across the chains, with high percentages (over 30%) for medical professionals, first responders, military workforce, and policymakers and decision-makers, and lower percentages for law experts (19.7%). Conversely, impacts are of greatest concern to the military workforce (27.6%) and medical professionals (24.7%) and are less significant for construction and legal experts (14.6% and 17.1%).

There is also a common core of 10 elements relevant for all stakeholder groups (i.e., included in all layers) (Fig. 7H). These include the primary and secondary hazards (30%), except for liquefaction, alongside key impacts (40%) such as damage to buildings; homelessness/displacement of population; road transportation disruption; and economic loss. The sole common exposed element is the population, and the only vulnerability of interest to all stakeholders is corruption. In terms of adaptation options, only one such element emerged in all layers: the Government funds for recovery. This configuration shows that each stakeholder group is concerned with its particular set of vulnerabilities and adaptation options, operating in silos although they have to address similar impacts.

Table 3

Details on the complete multi-hazard Impact Chain and the Layered Impact Chain. * reads “This layer represents x% of the complete multi-hazard Impact Chain in terms of elements/connections.”

	No. of elements	No. of connections	Percentage of the complete multi-hazard Impact Chain*	
			Elements	Connections
Complete multi-hazard Impact Chain	196	2795	100%	100%
Layer specific to first responders	139	1891	70.91%	67.65%
Layer specific to military workforce	98	1284	50.00%	45.93%
Layer specific to medical professionals	97	1308	49.49%	46.79%
Layer specific to policymakers and decision-makers	148	1822	75.51%	65.18%
Layer specific to construction experts	82	649	41.83%	23.22%
Layer specific to law experts	76	666	38.77%	23.82%
Layer specific to insurance companies	116	1155	59.18%	41.32%

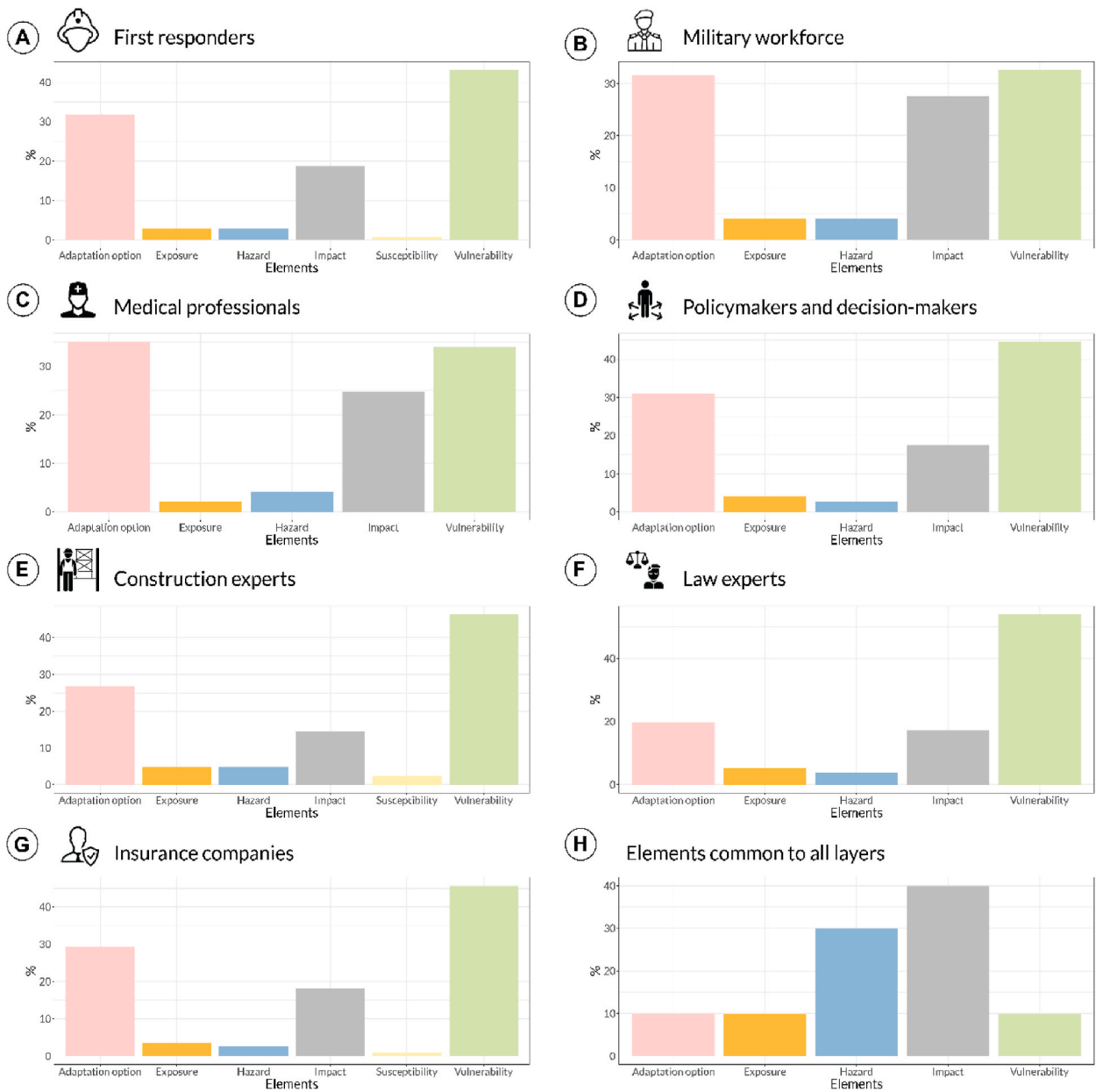


Fig. 7. Elements included in the Layered Impact Chain specific to A – first responders; B – military workforce; C – medical professionals; D – policymakers and decision-makers; E – construction experts; F – law experts; G – insurance companies; H – Elements included in all the layers.

Nevertheless, collaboration is more common among stakeholders with similar backgrounds, such as first responders and the military workforce. Another highlight is that corruption is a pervasive, cross-cutting problem that indirectly contributes to (multi-)hazard impacts.

3.3. Overview of the Simplified Impact Chains

The Simplified Impact Chains created for each stakeholder category (Fig. 3) reduce the complete model to 10.71-12.75% of its content in terms of elements and 3.25-4% in terms of connections (Table 4). These Simplified models include only the most interconnected elements (top 5) of each type, according to their CAM Degree Centrality. The content of the Simplified Impact Chains and its detailed analysis is provided in Appendix 3. It should be noted that while reducing stakeholder-dedicated layers to their essence, Simplified Impact Chains prioritise highly interconnected elements and omit less-connected but potentially critical elements.

Although the Simplified Impact Chains are also specific to different stakeholder categories, these models are ultimately based on

Table 4

Details on the Simplified Impact Chains. * reads “This Simplified Impact Chain represents x% of the complete multi-hazard Impact Chain in terms of elements/connections.”

	No. of elements	No. of connections	Percentage of the complete multi-hazard Impact Chain*	
			Elements	Connections
Simplified Impact Chain specific to first responders	24	104	12.24%	3.72%
Simplified Impact Chain specific to military workforce	23	98	11.73%	3.50%
Simplified Impact Chain specific to medical professionals	21	100	10.71%	3.57%
Simplified Impact Chain specific to policymakers and decision-makers	25	112	12.75%	4.00%
Simplified Impact Chain specific to construction experts	25	91	12.75%	3.25%
Simplified Impact Chain specific to law experts	23	103	11.73%	3.68%
Simplified Impact Chain specific to insurance companies	23	91	11.73%	3.25%

the same complete model. This can cause their contents to partially overlap, especially when examined by element type. For instance, the primary and secondary hazards appear in the Simplified Impact Chains for first responders, military workforce, medical professionals, policymakers and decision-makers, and construction experts (Appendix 3), while law experts and insurance companies exclude liquefaction.

Overlaps also occur at the impact level: first responders, military workers, medical professionals, and policymakers and decision-makers prioritise damage to buildings (including critical emergency management buildings); economic loss; human casualties; and injuries. Law experts consider similar impacts, excluding injuries and adding the disruption of businesses, while insurance companies remove damage to critical emergency management buildings and add business disruption. Construction experts present a more differentiated top 5 impacts: damage to buildings (including critical emergency management buildings); economic loss; homelessness/displacement; and road transportation disruption (Appendix 3).

The most interconnected vulnerabilities also show convergence and differentiation. First responders, medical professionals, and policymakers share communication problems with the public; the distrust of population in public authorities; a less supportive population; limited disaster planning, management skills, training of public authorities; and the negative effects of mass media coverage regarding earthquakes (Appendix 3). Military workers exclude institutional communication and population's distrust, but add the lack of decision-making support and limited backup power. Law experts share several vulnerabilities but emphasise building ageing and degradation; low preparedness among the population; and socio-economic inequalities. Insurance companies and construction experts highlight the poor understanding of seismic risk; the lack of information support; and either limited backup systems (insurance companies), or the precarious state of infrastructure (construction experts).

Susceptibility elements (i.e., local site conditions, tectonic settings) are relevant only for first responders, construction experts, and insurance companies, influencing building and infrastructure damage.

Adaptation options partly converge across Simplified models dedicated to different stakeholders: medical professionals and military workers share mitigation measures like the changes in the mentality of public authorities; contingency plans for additional support; the proficiency and creative capacity of first responders; support provided by volunteers or NGOs; and the proper institutional coordination; first responders add investments in research on seismic risk and vulnerability. Policymakers and decision-makers focus on the elaboration of a unified, amended law that SRR and the enforcement of seismic design regulations. Law experts and insurance companies emphasise similar adaptation options (e.g., the aforementioned legal reforms, institutional coordination, power backup systems, and research investments), while construction experts prioritise regulatory enforcement (Appendix 3).

3.4. Stakeholder evaluation and feedback

The complete, Layered, and Simplified Impact Chains were evaluated by the targeted stakeholder categories (Fig. 3) in terms of understandability, navigability, and usability. It is important to note that the small sample sizes within these groups limit definitive interpretation (Appendix 4). This should therefore be considered a preliminary evaluation that does not support comparison across stakeholder groups. A broader assessment is needed to properly validate the models against the stated criteria.

Appendix 4 provides the evaluation ratings given by the 45 stakeholders that have evaluated all three types of models according to the stated criteria. The evaluation shows that both the Layered and Simplified Impact Chains were more favourably perceived by stakeholders compared to the complete model. Participants generally rated the Layered and Simplified models as easy to understand, navigate, and use, with policymakers and decision-makers providing lower ratings than other groups. The interpretation of these results is constrained by the uneven and frequently small sizes of the stakeholder categories, which means certain ratings constitute individual perspectives. Due to their small sample sizes ($n \leq 5$), the data from stakeholder categories such as military workers, medical professionals, construction experts, law experts, and insurance companies, do not provide a statistically reliable foundation for evaluating the three types of Impact Chains (Appendix 4).

The evaluation for first responders is the most salient due to their comparatively large sample size ($n = 21$). They rated both Layered and Simplified models as outperforming the complete Impact Chain across all three criteria. While the Layered Impact Chain was rated best for navigability (mean of 4.52), the Simplified Impact Chain scored highest for usability (mean of 3.95) and outranked the Layered Impact Chain for understandability (mean of 4.33 versus mean of 4.28) (Appendix 4). The complete Impact Chain received the lowest scores across all three metrics. Variance was moderate to high across all formats (standard deviations between 0.68 and

1.02), suggesting certain disagreement among first responders in their ratings. These ratings indicate that selecting only the relevant content and simplifying the format directly improves the user experience for this group, with a notable distinction: the Layered Impact Chain for exploring complex relationships and the Simplified Impact Chain for practical application.

Policymakers and decision-makers have the second largest sample size ($n = 7$). These stakeholders provided a notably more negative evaluation compared to other groups. Across all three Impact Chain models, their ratings are the lowest in the study. The complete model was rated with a mean understandability score of 2.71 (median of 3, standard deviation of 0.48) and a usability mean of 3 (median of 3, null standard deviation). The Layered Impact Chain showed minimal improvement or even slight declines, with a usability mean of 2.85. The Simplified Impact Chain received the group's highest scores, particularly in understandability (mean of 3.28, median of 3, standard deviation of 0.75), but it still barely surpassed a neutral rating. The variance for navigability was higher (standard deviation of 0.97) for both Layered and Simplified Impact Chains, indicating disagreement, while usability scores showed very low variance (standard deviation of 0.37) (Appendix 4), reflecting a consistent but weak consensus that none of the formats were highly useable.

As part of the evaluation process, stakeholders were invited to provide feedback on the elements that are relevant to their DRR/M interests and responsibilities but might be missing from the Layered Impact Chain. Only 11 of the 45 participating stakeholders provided such qualitative feedback. First responders mentioned the quantification of vulnerability, the role of civic spirit in mobilising public assistance during crises, and the integration of a description of the roles and tasks of first responders. Policymakers highlighted the connections established across sectors, which is highly relevant to the analysis of systemic risks. The representative of insurance companies noted the foundational role of education from early ages in building preparedness, which should be included as an adaptation option. Additional comments included requests for the inclusion of other hazards, such as pandemics, and for more detailed information on intervention forces and their specific roles, as well as on the impacts targeting buildings. Some respondents indicated that more time would be required to identify potential additions, while others stated that the Layered Impact Chain is complete. Only one comment from one medical professional stated that the Layered model was hard to follow and use into practice, recognising its merit for research and education. Nevertheless, there were also encouraging comments from first responders, highlighting the comprehensive identification of vulnerabilities and the fact that the Layered Impact Chain sets the stage for progress. Further positive feedback highlighted stakeholders' strong interest in building their own capacity to construct similar models.

4. Discussion

4.1. Layered and Simplified Impact Chains support participatory approaches and transdisciplinary perspectives

Recent decades have brought a growing consensus between scientists and practitioners on the need for participatory approaches and increased transdisciplinarity in DRR/M [13,48–50], especially in the context of increased frequency and impactfulness of multi-hazards [12]. This is reflected in the 4 priorities of the Sendai Framework for Disaster Risk Reduction 2015–2030 [5], with a particular focus on Priority 2: Strengthening disaster risk governance to manage disaster risk. A cornerstone of this strengthened governance is the whole-of-society approach, which fosters open dialogue and collaboration among stakeholders with different visions, expertise, resources, and technology [13,51], ultimately aligning with the shared responsibility of managing disaster risk across sectors and scales [5].

Co-developing solutions with stakeholders results in a better integration of theory and practice, bridging the gaps between science, policies, and practical solutions [52]. In addition, stakeholder engagement ensures that new conceptual and operational frameworks address real-world problems in a tailored way. Achieving this goal is contingent upon a salient understanding of stakeholders' needs on the ground, which has been reported as limited [12]. Moreover, to complete a full cycle of co-creation (i.e., from development to assessment and product use), stakeholders must shift from merely providing input and fulfilling consultation roles to actively evaluating the outcomes and recommending (re)calibration insights. To enable this, the co-developed tools must be accessible, aiming at diverse stakeholder groups [13,52], and designed to be easily integrated into existing workflows [12].

Advocating for increased stakeholder engagement in developing DRR/M solutions, we introduce Layered and Simplified Impact Chains as models that respond to these needs. The tools are designed to balance complexity and clarity, leveraging the dual role of stakeholders as co-creators and evaluators. Referring to the input generation role of stakeholders, Layered Impact Chains act as integratory tools that harmonise interdisciplinary perspectives and efforts, as stakeholders speak different "disaster languages", and all their valuable contributions can be reconciled and integrated into these models to obtain a picture as comprehensive as possible. Layered Impact Chains allow for the breakdown of this puzzle into sections designed to fit the needs, interests, and responsibilities of the targeted stakeholder groups, supporting the creation of enhanced DRR/M policies and practices across the DRM phases. Onwards, scientists can work at the boundaries of these perspectives, facilitating the co-development of more holistic DRR/M plans. Complementarily, Simplified Impact Chains address simple purposes, as they distil the stakeholder layers and bring front the key disaster components that must be addressed in the response phase.

Layered and Simplified Impact Chain also support the evaluation role of stakeholders, as they facilitate a focused understanding of large disaster-related information volumes, thus removing barriers and creating a seamless, human-centered experience that takes into account specific stakeholder visions and challenges. Nevertheless, Simplified Impact Chains systematically omit less-connected, but potentially critical elements, which may support a rather "symptomatic analysis". Therefore, Layered Impact Chains are better suited for nuanced DRR/M planning and the elicitation of deeper insights.

The need of such innovative tools that serve multiple purposes (i.e., streamlining complex disaster models, improving cross-sector collaboration and stakeholder involvement, and facilitating analysis) is highlighted by the challenges of multi-hazard risk management

identified by Šakić Trogrlić et al. [12]. Layered and Simplified Impact Chains address many of these interlinked challenges that cannot be tackled in isolation but under improved and focused collaborative environments:

Challenges in the governance of multi-hazard risk (e.g., siloed working and stakeholder engagement and participation [12]): Layered and Simplified Impact Chains tackle problems rooted in defective interinstitutional coordination and communication across scales, as they serve as instruments that harmonise different stakeholder perspectives and expertise on disasters, and create a shared platform for cross-sector stakeholder dialogue. This facilitates collaboration between scientists and practitioners but also among practitioners, with valuable implications for fostering conceptual clarity in multi-hazard risk understanding and governance (van Manen et al., 2025). For instance, the Collaboration-Support Module of Layered Impact Chains can help seize missed opportunities for potential synergies in interinstitutional or cross-sector collaborations [12].

Challenges related to knowledge on multi-hazard risks (e.g., critical gaps in understanding hazard interrelationships and the impacts of multi-hazard events, low awareness on multi-hazard risks [12]): Layered and Simplified Impact Chains map the interplay of (independent, simultaneous, or cascading) hazards, their (compounded) impacts, the underlying vulnerabilities, exposed elements, and associated mitigation measures, thereby advancing the spatio-temporal characterisation of the relationships established among disaster components. Layered models can be used to educate the public on the roles of different DRR/M institutions and to pinpoint opportunities for volunteer support. Together, the proposed models are instrumental in building awareness among stakeholders with limited prior exposure to multi-hazard risks.

Challenges regarding the existing approaches to disaster risk management (e.g., the single-hazard and single-sector focus, limited cross-sectoral interaction, and the inadaptability of existing tools and frameworks [12]): Layered and Simplified Impact Chains can integrate multiple hazards and sectors at a time, also proving instrumental in organising and visualising information on their interaction mediated by impacts, vulnerabilities, and adaptation options. This comprehensive integration capacity enables stakeholders to move beyond single-hazard/sector focus in their planning and supports the elaboration of policies and actionable plans that truly address multi-hazard dynamics, avoiding mitigation measures that work in asynergy [53]. The Collaboration-Support Module (Box 2) fosters collaboration across public and private sectors and encourages citizen participation [54], helping to build institutional capacity for multi-risk management in chronically siloed environments [12]. When combined with metrics-based analysis [23], the Layered models can also function as learning tools, highlighting stakeholder best practices (but also areas for improvement) that may inform and inspire others. Moreover, the inherent adaptability and customisability of Layered and Simplified Impact Chains address the limitations of rigid analytical tools, as additional stakeholder groups can be incorporated as needed.

Challenges related to the translation of science to policy and practice (e.g., the gap between science and policy/practice, conveying scientific knowledge, and the transition from conceptual understanding to practical application [12]): Layered and Simplified Impact Chains address the stated gaps between science and policy/practice by facilitating stakeholders' understanding of complex analyses on hazard or disaster events from the past or future, ultimately aiming to transfer such knowledge into DRR/M policy and practice. Layered Impact Chains cater to specialised professionals, while Simplified ones are suited for public outreach and education. Both models are developed under collaborative approaches that facilitate a two-way flow of information and create a positive feedback loop, allowing insights from policy and practice to inform science just as science informs DRR/M policy and practice.

4.2. Scientific and practical contributions

Layered and Simplified Impact Chains were specifically created to address the “trade-off between complexity and operationalisation” stated by UNDRR [6] in the foundational publication that introduced the Impact Chain methodology. Attempting to make Impact Chains manageable can come at the cost of simplifying complex systems [17,55,56] and potentially omitting critical connections, tipping points, or indirect effects. Layered Impact Chains escape this common pitfall, emerging as the solution to finding balance between preserving model complexity and enabling clarity. Continuing on the same line, Simplified Impact Chain reduces cognitive load by presenting only the core elements of the Layered model. These tools go beyond academic or conceptual exercises by streamlining stakeholders' understanding of complex Impact Chains and promoting their integration into actionable DRR/M plans.

Box 2

The Collaboration-Support Module of Layered Impact Chains

Layered Impact Chains include a Collaboration-Support Module which allows for the overlapping of two or more stakeholder-dedicated layers. This is particularly valuable in policy development settings, such as meetings that bring together policymakers and legal experts to strengthen DRR/M legal frameworks. In such contexts, the layer corresponding to policymakers and decision-makers can be activated alongside that of legal professionals, producing a visualisation that includes the intersecting elements (and their connections) of these two layers.

The Collaboration-Support Module can be broadened to include additional stakeholders. For example, first responders should also participate in the exemplified working sessions. Activating their dedicated layer adds an operationally grounded dimension to the analysis. The visualisation can then be further tailored to display particular types of elements. For instance, current preparedness gaps can be identified by control filtering for adaptation options and vulnerabilities, together with the “mitigates” connections established among them.

Their value becomes even more evident in cases where DRR/M institutions are understaffed, and risk analysis, adaptation planning, and monitoring are scaled back (Luckerath et al., 2023).

Layered Impact Chains and their Simplified versions overcome several key limitations of conventional Impact Chains:

- Conventional models show only one perspective on the hazard or disaster event under analysis, which tends to be comprehensive (and ultimately very complex) but unfiltered or unrefined. The proposed Layered Impact Chain overcomes this limitation not only by putting forward different stakeholder perspectives, but also by providing a Collaboration-Support Module (Box 2).
- Conventional models are often developed in isolation from formal planning cycles and may not align with existing policy frameworks, institutional mandates, or budgetary processes. This is explained *inter alia* by the fact that diverse stakeholder groups have diverging interests and opinions on the interplay among disaster elements [17,43]. By distilling complex models into parts (i. e., layers) that are most relevant to certain stakeholder groups, Layered Impact Chains foster enhanced understanding and navigability, ultimately supporting an increased adjustability and usability of the models. Grounded in statistics, Simplified Impact Chains facilitate initial engagement with the models and the development of basic model understanding and navigation skills, therefore setting a strong foundation for the participation of stakeholders in the full model development cycle.
- Conventional models lack standardised methods for validation, uncertainty analysis, or sensitivity testing [17]. The layering and simplification procedures presented in this study make them more accessible and therefore easier to evaluate. They also foster critical thinking and open dialogue, which are currently limited (or completely missing) from stakeholder presentations that involve results based on Impact Chains.

Looking ahead, the flexibility of Layered Impact Chains offers significant potential for integration with other methodological advances in disaster analysis. For instance, layering procedures can be applied to Enhanced Impact Chains [24], ultimately leading to vulnerability dynamics analyses tailored to the interests and vulnerability mitigation responsibilities of different stakeholder categories. As Enhanced Impact Chains integrate dynamic feedback loops (opposed to their conventional Impact Chains, [14,17,19,24]), their layering would transform the new models into streamlined dynamic models. Another future research avenue is to combine Layered Impact Chains with metrics-based analysis, such as the one introduced by Albulescu et al. [23], to understand what are the strong points and areas for future improvement in the DRR/M practices of various stakeholder groups. These integrations would offer robust, evidence-based guidance for strategic prioritisation and decision-making.

4.3. Limitations

To effectively operate with Layered and Simplified Impact Chains, users have to also be aware of their limitations. Although the present case study was designed with an intentionally comprehensive stakeholder selection process, it cannot claim it involved all relevant stakeholders (e.g., NGOs such as the Red Cross or organisations focused on vulnerable populations; utility companies; business and industry representatives; real estate and property developers; tenant associations; the media; historical preservation societies; vulnerable groups such as the elderly, marginalised ethnics, migrants, people with disabilities or who are chronically ill, single-parent families, etc.). However, a key advantage of Layered Impact Chains is that they are not constrained by a fixed number of stakeholder categories. Thus, future studies can integrate even more diverse groups.

Other limitations refer to the stakeholder evaluation process, wherein certain Layered and Simplified models have been evaluated by lower numbers of users compared to others (Appendix 4). Stakeholders explored the complete, Layered, and Simplified Impact Chains only within the constrained time of workshops, which did not allow them to experience how the models could be integrated into actual policy development or their regular workflows, or to comprehensively identify other relevant elements that can be added to the model. Also, future evaluations can integrate other criteria, such as long-term utility (the estimated lifetime of a model) or scalability. The evaluation can be improved by increasing stakeholder engagement through organising more workshops or focus groups.

While they escape key limitations of conventional Impact Chains, Layered Impact Chain still inherit certain of their shortcomings. For instance, Layer Impact Chains remain highly dependent on disaster contexts (including hazard settings and temporal and geographic scopes), which constrains their generalisability. Conversely, this context-dependence can also be viewed as a strength, supporting the elaboration of DRR/M policies and actionable plans tailored to local realities, as well as historical and socio-cultural backgrounds.

One major limitation of Simplified Impact Chains lies in their methodological tendency to prioritise highly interconnected elements, thereby systematically omitting less-connected yet potentially critical elements. For instance, Simplified Impact Chains exclude nuances that may prove instrumental for addressing resurfacing impacts (by first addressing the underlying vulnerabilities that contribute to those impacts). By failing to capture these nuanced influences, Simplified Impact Chains offer support only for a superficial analysis, addressing symptomatic effects while neglecting the root causes that allow impacts to resurface. This shortcoming may skew DRR/M policies towards being reactive and insufficient for fostering long-term resilience. To overcome this, we recommend to employ Layered Impact Chains for more analytical tasks, as they provide more nuanced perspectives on disasters and their unfolding.

A key challenge for both conventional and Layered Impact Chains is deciding how direct/indirect should be the cause-and-effect relationships included in the model. This setting dictates the extent of the chain, potentially emerging as a starting point for convoluted models. To address this issue, we established the “causes”, “affects”, and “mitigates” connections guided by the principle of empirical relevance to the case study. Also, we balanced realism and comprehensiveness by setting a larger indirect influence for the vulnerabilities that contribute to hazard impacts (i.e., the “affects” connections) and limiting the indirect causality at the level of hazard and

impacts (i.e., the “causes” connections) and adaptation options (the “mitigates” connections).

5. Conclusions

In this study we introduce Layered and Simplified Impact Chains as new models that can make large, complex Impact Chains more accessible and useful to diverse stakeholders with responsibilities in DRR and DRM. Layered Impact Chains rely on filtering controls applied to elements and connections that are relevant to different stakeholder categories. In contrast, the Simplified models create a more focused view by retaining only the most highly connected elements of each type and their connections, within each stakeholder layer. Both models showcase a story on how stakeholders organise themselves to face multi-hazard disasters, according to their training and DRR/M roles. By integrating stakeholder-generated input and refining the chains based on their feedback, the model development process achieves a full co-creation cycle. This increased stakeholder engagement and the user-centered design of Layered and Simplified Impact Chains can foster a greater adoption of these tools across various DRR/M workflows.

The key strengths of the proposed Layered and Simplified Impact Chain models can be summarised as follows:

- Layered Impact Chains function as integrative tools that align interdisciplinary perspectives and efforts. Given that stakeholders often use distinct “disaster languages”, these models provide a shared analytical framework through which diverse contributions can be reconciled and systematically integrated, thereby enabling the development of a more comprehensive understanding of (multi-hazard) disasters.
- By layering and/or simplifying complex Impact Chains, DRR/M stakeholders benefit from increased understandability, smoother navigability, and improved usability of disaster analysis models.
- The proposed models are highly versatile and enable multi-purpose application. They can be developed for any relevant stakeholders, considering that their roles dictate the focus of the layers, also considering different geographic, temporal, and (multi-) hazard settings.
- The Collaboration-Support Module (Box 2) represents a key feature for enhanced stakeholder engagement. This module allows multiple layers to be activated simultaneously, revealing the elements and connections at the intersection of these layers, and helping to identify shared interests, overlapping responsibilities, and critical knowledge and operational gaps.

To demonstrate their application and merits, we implemented the proposed models on a case study focusing on a multi-hazard disaster scenario relevant for Bucharest during present times or in the near future (i.e., a major earthquake and its secondary hazards). The complete model that served as a foundation for the Layered and Simplified ones was developed under a multi-method approach that combined desktop-based analysis with the expert workshop approach and expert judgement refinement.

The highlight of the case study analysis is that vulnerability was the dominant element across the stakeholder-dedicated layers in the Layered Impact Chain. This means that vulnerability emerges as a foundational concern, pointing out that most stakeholders view disasters through the lens of “What weaknesses exist now and could contribute to hazard impacts?”. In other words, stakeholders are deeply aware of the present issues that need to be solved to proactively mitigate the escalation of multi-hazard events into disasters. It is precisely this awareness that Layered and Simplified Impact Chains are designed to harness, providing the clarity necessary to translate this proactive mindset into practice.

Moreover, results from the application case study and insights from the involved DRR/M stakeholders show that the true potential of Layered and Simplified Impact Chains emerges when they are treated as adjustable tools that can accommodate new perspectives (e.g., referring to hazards that emerge and give rise to compounded impacts, shifts in institutional mandates or legal frameworks governing risk, cascading interactions, etc.). In this sense, Layered and Simplified models can function as controlled experimental tools that can be calibrated according to stakeholders’ interests or to visualise their intersection. Rather than merely making complexity more accessible or simplifying it, the proposed models can be used to interrogate it; for instance, by testing how perspectives on hazard/disaster events change according to different institutional configurations and experiences. By embedding this reflexive capacity (which is showcased through the Collaboration-Support Module of Layered Impact Chains) into DRR/M workflows, Layered and Simplified Impact Chains move beyond visualisation, organisational, and analytical power and can become instruments for iterative learning, strategic anticipation and collaboration, and institutional adaptation in increasingly challenging (multi-hazard and multi-) risk settings.

CRedit authorship contribution statement

Andra-Cosmina Albulescu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Iuliana Armaş:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation.

Authorship

Both authors contributed equally, with the concept of Layered and Simplified Impact Chains developed by A.C. Albulescu.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijdr.2026.106080>.

Data availability

The complete, Layered, and Simplified Impact Chains can be visualised, interacted with, and downloaded using the links in Table 2 and Appendix 1. The underlying model data (in .xlsx and JSON formats), code, and reference list can also be openly downloaded in JSON and XLSX formats from this repository: <https://doi.org/10.5281/zenodo.18774181>.

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