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Using multi-stakeholder causal mapping to explore priorities for infrastructure resilience to flooding

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A B S T R A C T

Urban resilience to natural hazards could make our cities less vulnerable to adverse weather events. However, the implementation of resilience actions is currently not effective, as mechanisms to facilitate collaboration among involved stakeholders are missing. This paper for the first time explores causal mapping as a method to disassemble major issues of urban resilience into a more manageable understanding, and thus identify key objectives, barriers and opportunities in thinking "resilient cities". In this study, a cognitive-mapping-based workshop was held to elicit information from stakeholders in the remit of urban resilience to flooding. The statements and connections identified during the workshop led a consolidated map, analysed using the StrategyFinder software. This analysis highlighted barriers related to data availability, silo-based approaches and lack of funding; it also evidenced shared goals, such as the need to protect the built environment and minimise impact from flooding. Overall, causal mapping resulted a powerful analytical tool for improving understanding of the complex dynamics of urban resilience, identifying key variables and relationships, as well as eliciting information from stakeholders. Furthermore, this approach facilitated systems thinking, communication and collaboration. This enhanced understanding is fundamental for advancing strategies for future planning, contributing to urban sustainability and liveability.

1. Introduction

Towns and cities have become increasingly exposed to natural hazards such as flooding, driven by climate change and urbanization [1,2]. The economic costs of flooding are substantial since they include direct damages to infrastructure, property, and crops, as well as indirect costs related to business interruptions, health impacts, and displacement of populations [3]. A total of 143 significant floods occurred in 2019, representing more than 45% of all climate-related adverse events, and were accountable for over 40% of total deaths in that year; the annual average losses caused by floods globally were estimated to be around US$40 billion in 2019 [4]. Cities play a crucial role in the modern society for a variety of reasons: they are centres of economic activity, cultural exchange, innovation, and social development. Contemporary cities serve as crucial nodes of infrastructure and connectivity, while also playing a vital role in impacting on environmental sustainability [5]. The role of cities are expected to increase as it is anticipated that the 68% of the world population is projected to live in urban areas by 2050 [6].

Goal 11 of the United Nations' Sustainable Development Goals (SDG11) is on Cities and Urbanization, and states to "make cities and human settlements inclusive, safe, resilient and sustainable" [7]. There is a compelling and urgent need for cities to increase their

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resilience to natural hazards, such as flooding, and decision-makers (such as city or county councils) are asking for practical tools. Urban resilience refers to the ability of a city or urban area to withstand, adapt to, and recover from shocks, stresses, and disruptions while maintaining its performance in delivering essential functions and supporting the well-being of its residents [8]. Urban resilience goes beyond mere survival or bouncing back to a pre-disaster state. It involves pro-active measures to enhance the long-term sustainability of a city, addressing both immediate and underlying vulnerabilities [9]. However, actual implementation of resilience actions in urban planning is not sufficiently effective [10]. Cities are complex systems of infrastructure, institutions, and communities [11,12]; this complexity requires clarity about barriers and goals, as well as the input of a range of actors (planners, authorities, modellers, etc.) [13]. recommended to strengthen urban governance by stepping up engagement with key city interest groups, to shape urban development through connected policies and collective actions. Currently, urban resilience is still generally tackled by a single institution alone, which has low transformational impact in working towards difficult goals [14]. This limitation opens a research window for more holistic and wide-ranging methods to elicit information for urban resilience.

Before we can start developing tools, we first need to understand the needs and perceptions of different stakeholders when looking to make cities more resilient. For example, how definitions, criteria, objectives, priorities, and issues may differ for each stakeholder along with their access to data and tools. The challenges associated with these differences are further complicated by the lack of sharing cross-organisational perspectives and interrelationship of the involved issues [15], too. Traditional activities to elicit information from stakeholders include ([16–19]: *(i)* via surveys and questionnaires (an example is [20]; *(ii)* via interviews (an example is [21]; *(iii)* via structured workshops (an example is [22]; or via a combination of surveys, workshop and focus groups (an example is [23]. In addition [24], applied serious gaming principles to elicit information from experts in infrastructure resilience. Alternatively [25], developed a Resilience Diagnostic Tool to translate general concepts of urban resilience to operational rules and criteria. Further methods can include also: focus groups [26], the Delphi method [27], or storylines [28]. Elicitation activities can then be based on various methods.

Problem Structuring Methods (PSMs) are a set of approaches and techniques used to help individuals and groups understand, analyse, and structure complex problems [29–31]. Among these, Strategic Options Development and Analysis (SODA) is a method functional to explore and evaluate various strategic options in problem situations [32]. It involves constructing cognitive maps, identifying different perspectives and objectives, and systematically analysing the consequences and trade-offs of different courses of action [33]. For Ackermann and Eden (e.g. [34]), cognitive mapping refers to a map based on one person, whereas causal mapping refers to map based on multiple people, but this terminology is not consistent in other authors' work. In this study, causal mapping and cognitive mapping are used as synonyms. The maps capture views of an issue into a model, which can be used as a tool for negotiation, change management or strategic thinking. The method also enhances the level of ownership and awareness for the problem, as well as revealing interdependencies among factors that may be hidden before the analysis.

In the literature, workshops based on the cognitive mapping approach are widely adopted for eliciting risks in project management from different stakeholders [35]. [36] developed a series of workshops to develop single cognitive maps about perceived failure reasons of complex megaprojects. In marketing management, interviews were adopted by [37] to develop three separated cognitive maps. In a later study regarding health management [38], combined individual maps realized during the interview process to develop a multi-level cognitive map. A similar approach was also used in supply chain management by [39]. In knowledge management, Spanellis et al. [40] used a dynamic model to obtain six cognitive maps: each map represented a different company and reflected the experience on knowledge creation of various individuals (of that company). Cognitive mapping has also been successfully applied in policy analysis to explore options and goals, such as for the UK Home Office Prison Department [34]. Furthermore [41], investigated the sustainable energy transition at national level using single maps of stakeholders' interests first, and then a combined map which highlighted the interrelations within political dynamics. Cognitive mapping was also used for elaborating secondary data (publicly available) to develop cognitive maps for "Remain" or "Leave" groups within Brexit [42,43]. Stakeholders' perspectives in various contexts, such as the aviation sector [29,44], have previously been effectively analysed using cognitive mapping techniques.

Despite many successful applications to complex contexts, the authors could not find any studies that apply specifically cognitive mapping to urban resilience for exploring stakeholders' knowledge and perception [45]. This paper demonstrates the application of causal mapping to urban resilience, adopting multi-level mapping, as opposed to the most common mapping of single individual or groups as highlighted by [29]; exploring the key objectives, barriers and opportunities in thinking of "urban resilience to flooding" for UK cities, as perceived by a selection of stakeholders. The paper addresses the following research question: how can causal mapping be applied to better understanding the barriers and opportunities in improving urban decision making and collaboration among multiple stakeholders? The study aims at identifying strategic aspects of implementing operational measures to bridge the gaps among intentions, policy and practice. To fulfil this aim, four objectives are pursued: *(i)* to briefly present the theory underpinning causal mapping; *(ii)* to apply causal mapping via a workshop with stakeholders to elicit information; *(iii)* to develop and interpret the obtained composite map; *(iv)* through discussion, to develop conclusions and recommendations. Outcomes are relevant for the wider community working on disaster risk reduction.

2. Methodology and data

Among the known PSM approaches, this paper aims to apply SODA's cognitive mapping [32] to capture the perspectives of multiple stakeholder groups on urban resilience. To carry out the exercise, we held a workshop bringing multiple key stakeholders together and asked them to map out the objectives, barriers and opportunities in urban resilience and their interconnections. By having workshop attendees divided up into multiple working groups, at the end of the workshop multiple causal maps were developed. After the workshop, these causal maps were consolidated into one single map and further analysed using StrategyFinder (www.strategyfinder.

com). A graphical summary of the study design of the proposed research method is shown by Fig. 1.

2.1. Cognitive and causal mapping

Co-creation methods with stakeholders can be useful mechanisms for enhancing multi-stakeholder cooperation, social innovation and capacity building for resilience [46,47]. In particular, causal mapping was found functional to support strategies in the aviation sector [29,44]. SODA and causal mapping are chosen because they operatively capture the causal relationships among elements, to identify the "consequences of knowing and the explanation of knowing to acquire knowledge as meaning" [48], in a field where their potential has not yet been explored. The final aim is to capture key information required to define an emergent strategy, within an "active process of strategising" [49].

A causal map consists of a network of nodes (statements) and directed arrows whose direction implies causality (i.e., "may-lead-to" relationship) [50]; Fig. 2). The map is built over an overarching question or statement. Firstly, participants write down their perceived goals or gaps around the question ideally as complete statements (e.g. "to work with lack of information" rather than "lack of information"). Secondly, they look for all the connections among them, creating a causal map. The consolidated map is thus a graphical representation that captures the complexity of a problem, by for example showing how goals or problems are inter-connected, as well as detecting emerging patterns [51]. The interpretation of the map will support the reading of this information.

In this work, the cognitive mapping approach is used to map the perspective of a participants' group; a workshop elicited the qualitative information from stakeholders, and facilitated their diagrammatic form of causal maps. In this study, the cognitive mapping process contains two steps. The first step consists in the development of separate causal maps for each group (four in total); the second step consists in the consolidation of the four maps into a single "composite" map. To combine the four maps, this study followed the four-step procedure by [52]; also adopted by [29]: *1)* identify and overlay similar elements; *2)* add extra causal links between overlaying elements; *3*) check that the map maintain the groups' hierarchies of links; and, *4)* analyse and interpret the obtained map (e.g. for loops, clusters and potent nodes).

The interpretation step *(4)* consists of defining macro themes, goals, patterns (e.g. feedback loops) and isolated concepts [46] which allows us to draw out actionable information. Structural properties [51,53] of the graphical layout are critical in the interpretation process, such as.

- *arrows:* causal relation (connecting cause to effect, activity to outcome) among elements;
- *"potent" or "central" nodes*: statements with many outward and inward links, likely to affect significant themes and chains of argument;
- *clusters of nodes:* "dense" (important) areas of one or more potent nodes, and satellited notes, likely to be macro-themes;
- *loops:* virtuous (positive, reinforcing) or vicious (negative, undermining) circles that highlight higher identification of causality or dependency;
- *tails:* statements with outcoming links only, these can be significant triggers, events or actions that affect many other items on the map (may be assumed as the start of the model);
- *heads*: statements with incoming links only, assumed as the end (goal) of the model.

These properties are used by this study to interpret the map via the software StrategyFinder (www.strategyfinder.com), that allows individuals or groups to create a causal model in a web-space. In addition to graphic displays, the software uses statistical analytics to advance our understanding of the maps realized (e.g. how many links a statement has). StrategyFinder can also identify vicious and virtuous cycles, central themes and potentially potent action, thanks to a series of inbeeded algorithms and mathematical methods. Alternative software to organize complex data into relationship maps includes Kumu (https://kumu.io/) or Causal Map (https://causalmap.app/), among others.

2.2. The workshop

Structured workshops aim at interacting with a group or groups of people, and are ideal to generate information and knowledge. The organisation of a workshop requires the definition of its goal (i.e. why the workshop is hold and what is of interest to achieve in it) and logistics determination (where and when, room booking, catering, health and safety, etc.), which could be more demanding as compared to interviews and questionnaires/surveys (see Sec. 1). The workshop can include different activities (e.g. roundtables) and tools (e.g. software, objects) according to the established goal and participants. In addition to the information produced by the specific

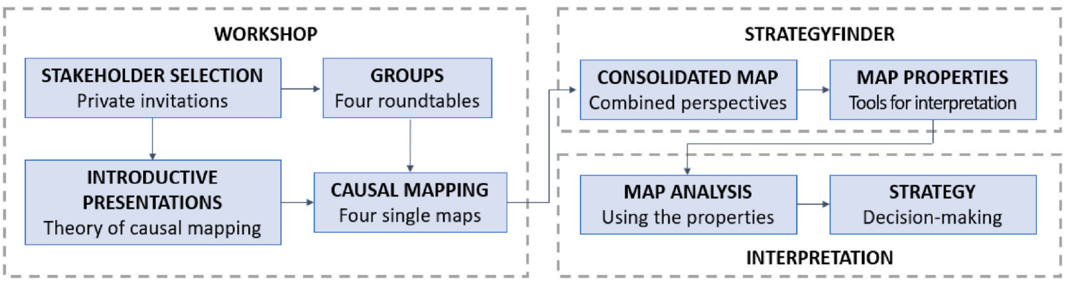

Fig. 1. Graphical summary of the proposed method.

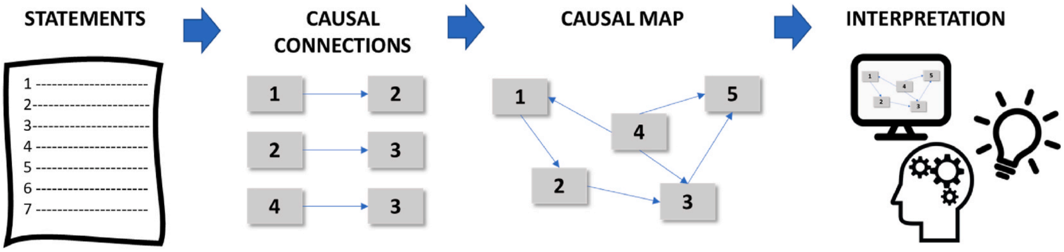

Fig. 2. A representation of the process of causal mapping.

activities, further information can be collected by observing and recording participants' comments; a record-keeper could help in this activity.

A cognitive-mapping-based workshop "Urban infrastructure resilience to flooding: building community event" was held on the November 30, 2021 in Bristol (Brunel Institute) to obtain primary data, with a diverse group of key stakeholders working on urban resilience to flooding in the South-West of England (UK). The event was attended by 23 invited participants in total; one academic per table acted as the facilitator, and four PhD students helped with the logistics and practical organization during the day. Stakeholders were categorised as: (1) Policy makers and governments, which include representatives of city and county councils, governmental departments - 6 participants; (2) Research community, i.e. representatives from universities and research institutions - 8 participants; (3) Practitioners and professionals, i.e. representative from civil engineering companies - 7 participants; and (4) Private business, which include consultants and free-lance individuals - 2 participants.

The workshop was organised into two parts: *(i)* morning session: introductory presentations, framing the problem and introduction of the casual mapping technique; and *(ii)* afternoon session: the "causal mapping exercise" to elicit the information from the stakeholders. For the mapping activity, participants were divided into four groups which were diverse for gender, affiliation and seniority. They were guided into a causal mapping exercise to reflect on issues and goals in the context of urban infrastructure resilience to flooding (Fig. 3).

Fig. 3. Photos of cognitive mapping process taken during the workshop. All participants gave consent to be photographed, with photos being allowed to be shared in public domains (e.g. social media).

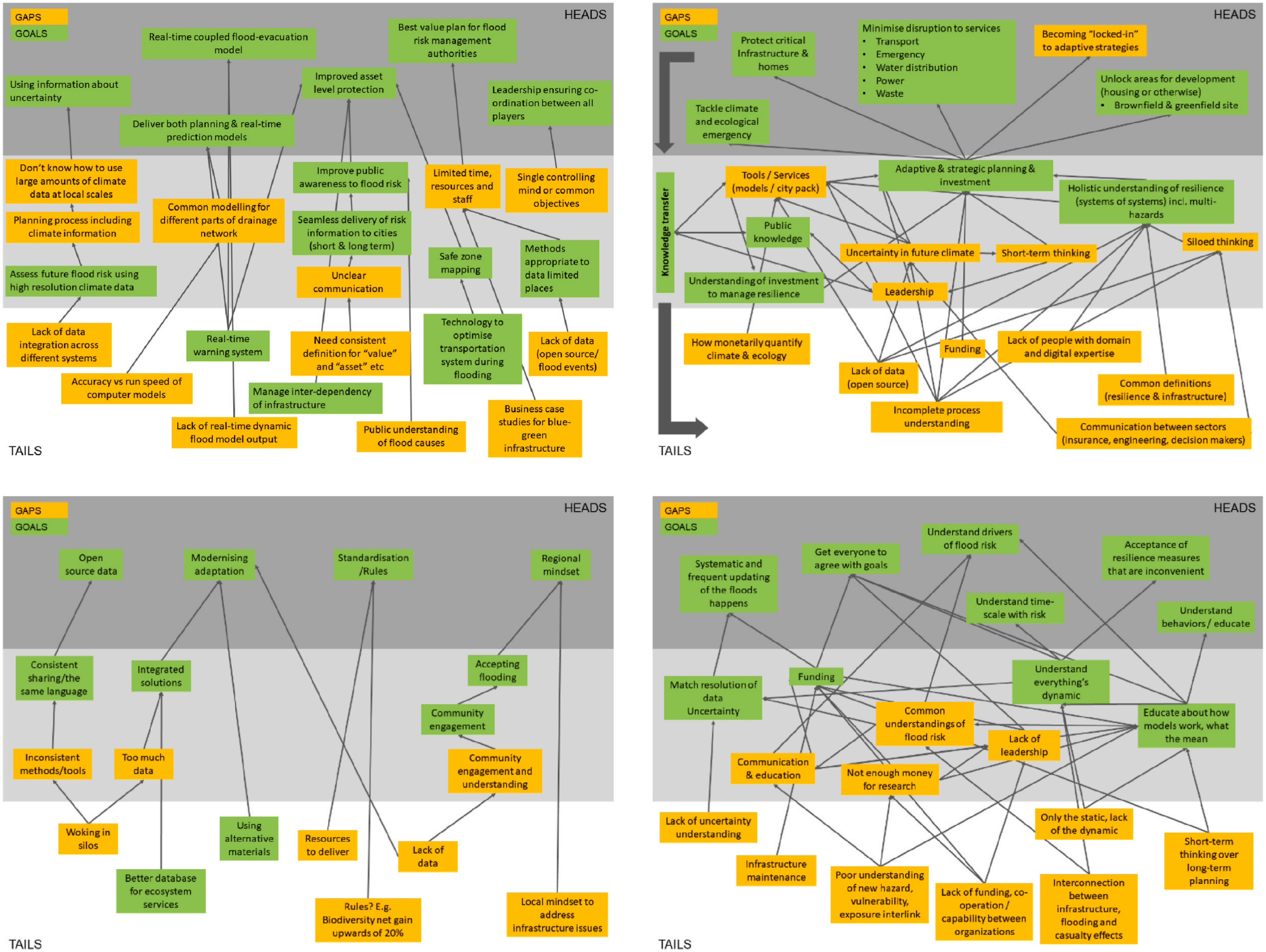

Fig. 4. The produced maps during the workshop, obtained from the hard copy of the roundtables.

Table 1
List of statements, and relative assigned theme. Colour legend: Data - yellow; Technical and technological knowledge - green; Leadership and relationships - blue; Modelling and tool - orange.

Statement	Theme	Note
1 to work with lack of data	Data	Tail
2 to quantify climate and ecology	Technical and technological knowledge	Tail
3 to gather funding	Leadership and relationships	-
4 to work in a condition of incomplete process understanding	Technical and technological knowledge	Loop B
5 to keep data open-source	Data	-
6 to cope with little funding	Leadership and relationships	Tail
7 to have staff with domain and digital expertise	Technical and technological knowledge	-
8 to lack of common definitions on resilience and infrastructure	Technical and technological knowledge	Tail
12 to communicate among sector (insurance, engineering, policy, etc.)	Leadership and relationships	-
13 to understand investments in resilience management	Technical and technological knowledge	-
14 to possess public knowledge	Technical and technological knowledge	Loop A
15 to produce tools/services (e.g., models, city pack)	Modelling and tools	Central node
16 to develop adaptive and strategic planning and investments	Modelling and tools	Central node
17 to account for uncertainty in future climate	Modelling and tools	-

18 to provide leadership among all players	Leadership and relationships	Loop A
19 to think in short terms	Leadership and relationships	Tail
20 to think in longer-terms	Leadership and relationships	-
21 to overcome siloed-thinking	Leadership and relationships	-
22 to account for a holistic understanding or resilience, e.g., system of systems and multi-hazards	Technical and technological knowledge	-
23 to tackle climate and ecological emergency	Modelling and tools	Head
24 to protect critical infrastructures and homes	Modelling and tools	Head
25 to minimise disruptions to services (transport, water, power, waste)	Modelling and tools	Head
26 to develop adaptive strategies	Modelling and tools	Head
27 to unlock "safe" areas for development (housing or otherwise), also in the future	Modelling and tools	Head
28 to transfer knowledge across sectors and institutions	Technical and technological knowledge	Loop A
29 lack of data integration across different systems	Data	-
30 to increase accuracy while limiting computing resources	Modelling and tools	-
31 to develop real-time warning system	Modelling and tools	Loop B

33 to manage inter-dependency of infrastructure	Modelling and tools	-
35 to work with lack of real-time dynamic data (e.g. flood outputs)	Data	-
36 to use technology to optimise transport system during flooding	Technical and technological knowledge	-
37 to define a business case for adaptation (e.g., blue-green infrastructure)	Modelling and tools	-
38 to include climate information into planning process	Modelling and tools	-
40 to model different parts of the network	Modelling and tools	-
41 to assess future flood risk using high resolution climate data	Data	Central node
42 to improve public awareness to flood risk	Leadership and relationships	-
43 to deliver risk information to cities	Leadership and relationships	-
44 to maintain clear communication with citizens	Leadership and relationships	Central node
45 to map safe zones of the city	Modelling and tools	-
46 to develop methods based on limited data	Data	-
47 to improve protection of assets	Modelling and tools	-
48 to deliver best-value plans for flood risk management authorities	Modelling and tools	Head

49 to use appropriate databases for data of ecosystem services	Data	Tail
50 to develop a societal mindset on infrastructure issues	Leadership and relationships	-
51 to engage the wider community	Leadership and relationships	Tail
52 to develop and share a consistent common language	Modelling and tools	-
53 to develop standards and rules	Modelling and tools	-
54 to understand the interlink among hazard, vulnerability and exposure	Technical and technological knowledge	Loop B
55 to improve/optimise infrastructure maintenance	Modelling and tools	-
57 to improve cooperation among organisations	Leadership and relationships	-
58 to consider the interaction among infrastructure, flooding and casualty effects	Technical and technological knowledge	-
59 to gather funding for research	Leadership and relationships	-
60 to deal with lack of leadership	Leadership and relationships	-
61 to train staff to use models and understand outputs	Technical and technological knowledge	Central node
62 to pair data resolution and uncertainty	Data	-
63 to develop a shared vision	Leadership and relationships	Head
64 to understand the drivers of flood risk	Technical and technological knowledge	-
65 to understand the risk timescale	Technical and technological knowledge	Head
66 to educate the general public	Leadership and relationships	-
67 to update/keep records of flood happenings	Technical and technological knowledge	Head
68 to accept resilience measure whose return is uncertain	Technical and technological knowledge	Tail
69 to conduct research	Technical and technological knowledge	-

The problem statement that was proposed to participants as the overarching question was: "*How can infrastructure resilience to flooding be improved in urban environments?*", with reference to their actual practice and experience (thus specifically for Bristol). Stakeholders' perceptions were expressed as statements, which were connected using principles of causality (i.e. X leads to Y; see Sec. 1).

3. Results

During the workshop, each group produced a causal map identifying key variables and relationships. These maps were then integrated into a consolidated map, which was analysed. Sec. 3.1 illustrates the information obtained from the workshop through the four causal maps; Sec.3.2 describes the analysis of the consolidated map and its interpretation.

3.1. Causal maps and data from the workshop

By linking statements (of goals and gaps) according to causal mapping principles (Sec. 1), the participants obtained the four maps of Fig. 4. Overall, 88 statements were collected, with an almost equal division between goals (no. 43 statements) and gaps (no. 45 statements).

The workshop statements were copied from the workshop posters into an electronic document; here, similar statements were uniformised while all the relationships (in/out arrows) annotated, to obtain a consolidated map (see the method by [52], explained in Sec. 1). For example, the statements "lack of data" and "little data" were consolidated into "to work with lack of data".

Those consolidated statements were clustered into the four themes according to their content: (1) Data; (2) Technical and technological knowledge; (3) Leadership and relationships; (4) Modelling and tools. They were also categorised according to the structural properties of Sec. 1, e.g. tail, head, etc. (Table 1).

The most of the statements are about "Modelling and tools" (34.5%), followed by "Leadership and relationships" (28%), "Technical and technological knowledge" (25%), and "Data" (12.5%). These "clusters" help to understand the broad categories of interest of stakeholders, since their thoughts were expressed into statements in these areas.

The consolidated statements and relative connections identified during the workshop are those used in this paper to produce the final consolidated map, which was reproduced as model in StrategyFinder for analysis and interpretation (Sec. 3.2).

3.2. Analysis of the consolidated map

One of the advantages of casual mapping is its visual representation of the causal relationships among variables, which allows to comprehend complex systems via interpretation analysis. It helps to identify the key components, connections, and feedback loops within a system, enabling a more intuitive understanding. We produced a consolidated map to offer such a global view (Fig. 5) of all statements and relative connections (Table 1) using StrategyFinder. The analysis of the map is based on the structural properties of the graphical layout, as described in Sec.1; Appendix A offers supplementary material from such an analysis.

A first step of this analysis was to identify the nodes which receive the highest number of in/out connections (central nodes; Fig. 6): the analysis shows the "busy areas" and is helpful because it highlights the areas that capture the attention and interest of workshop participants, thus potential priority areas. The main priorities of stakeholders resulted to be five central nodes: *to develop adaptive and strategic planning and investments* (16), *to produce tools/services* (15), *to maintain clear communication with citizens* (44), *to assess future flood risk using high-resolution climate data* (41) and *to train staff to use models and understand outputs* (61). Central nodes are quite equally distributed among the four themes.

These five priorities are interconnected. Staff training and risk assessment are the tails, while clear communication with the society and strategic adaptation plans can be seen as the heads of this specific group. This observation means that staff training and flood risk assessment could be the first objectives that can enable the final goal of developing adaptation plans and communication with citizens; in this process, a key driver is the development of tools and services (e.g. impact models), which allow to exploit staff's capacity for the development of adaptive and strategic plans.

View 15-44-61 (Fig. 11) shows that staff's skills are key for producing and delivering information. In this view no heads and two tails (1, 11) are included: this lack of end and paucity of beginning statements may signify that these three central nodes mostly affect priorities in the middle of the process. View 15-16-41 (Fig. 12) shows that tools, services and risk information are enabler of strategic plans for urban resilience. This sub-group includes two tails (1 and 9) and four heads (23, 25, 26, 27). Since 15 is already in the previous group (15, 44, 61). The tail 9 and the four heads are included because of adding 16 and 41. Thus, among the central nodes, *to develop adaptive and strategic planning and investments* (16) and *to assess future flood risk using high resolution climate data* (41) seems the most crucial in delivering the final goals within the whole process. The central nodes have been also analysed into two additional separated views (see Figs. 11 and 12 in Appendix A).

A second analysis included the identification of heads and tails, shown in Fig. 7. No central nodes are present among heads and tails, although being highly-connected elements; this means that the process itself (rather than the beginning or the end) is crucial and its elements should not be addressed in isolation.

Among the nine head statements, six (66.6%) belong to the "Modelling and tools" theme. Some head statements received more

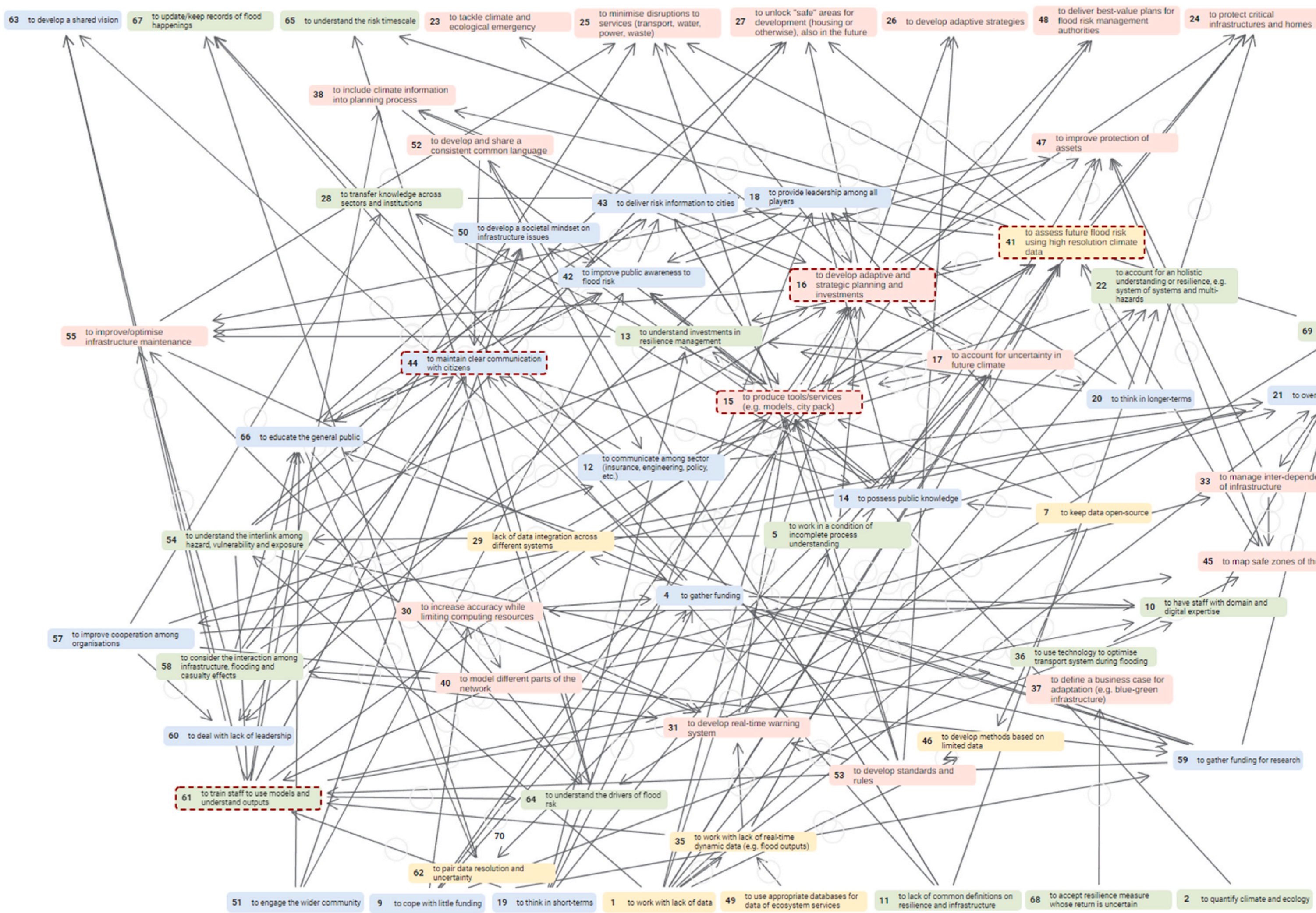

Fig. 5. The complete causal map in StrategyFinder. Colour legend: Data - yellow; Technical and technological knowledge - green; Leadership and relationships - blue; Modelling and tool - orange; the red dashed border indicates central nodes.

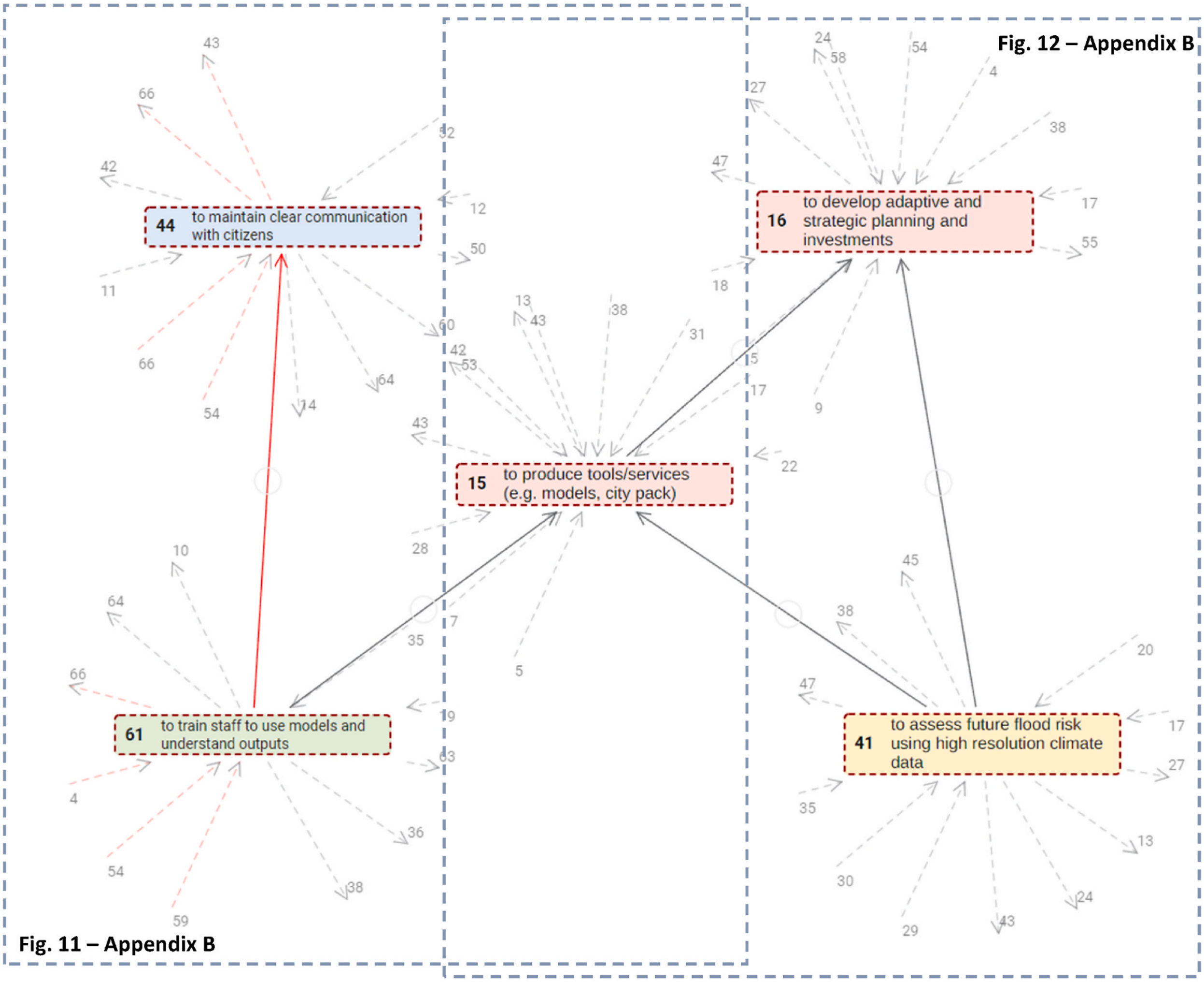

Fig. 6. Views of all the five central nodes; additional views are offered in Appendix A.

arrows (24, 25, 27, 63, 67), compared to others (23, 48, 65), which are less connected within the model. Heads point to the possible outcomes and impact of the explored transport resilience situation: *to tackle climate and ecological emergency* (23), *to protect critical infrastructures and homes* (24), *to minimise disruptions to services (transport, water, power, waste)* (25), *to develop adaptive strategies* (26), *to unlock "safe" areas for development (housing or otherwise), also in the future* (27), *to deliver best-value plans for flood risk management authorities* (48), *to develop a shared vision* (63), *to understand the risk timescale* (65) and *to update/keep records of flood events* (67) are thus the desired results. Looking at the most connected statements, regarding the heads the following statements resulted particularly important as final goals: *to protect critical infrastructure and homes*(24); *to minimise disruptions to services* (25); *to unlock "safe" areas for development* (27); *to develop a shared vision* (63). This reading means that the "true North" of stakeholders is indeed to protect the built environment, by being able to minimise impact and identify safe areas for future construction (e.g. out of the floodplain). In fact, these "ends" are the ultimate purpose of urban resilience, i.e. more robust cities and safer communities.

Tails are the drivers and triggers of actions and events since they affect the critical issues with respect to transport resilience. For the obtained map, the eight tail statements are almost equally distributed among three themes ("Leadership and relationships", "Data" and "Technical and technological knowledge"). Also in this case, some tails (1, 9, 11, 19, 51) have far more connections than others (2, 49, 68), thus likely of more relevance. *To work with lack of data* (1), *to quantify climate and ecology* (2), *to cope with little* funding (9), *to lack common definitions on resilience and infrastructure* (11), *to think in short terms* (19), *to use appropriate databases for data of ecosystem services* (49), *to engage the wider community* (51) and *to accept resilience measure whose return is uncertain* (68) resulted to be the starting points of a strategy of interventions. This observation means that the first steps of a strategy should account for tackling data and funding scarcity, while overcoming traditional silo-based approaches and a lack of operational definitions. These drivers are relevant because they affect what happens in the map: they are sustaining (directly or indirectly) central nodes, as well as they are connected with loops (e.g. data scarcity, see Loop B in Fig. 10).

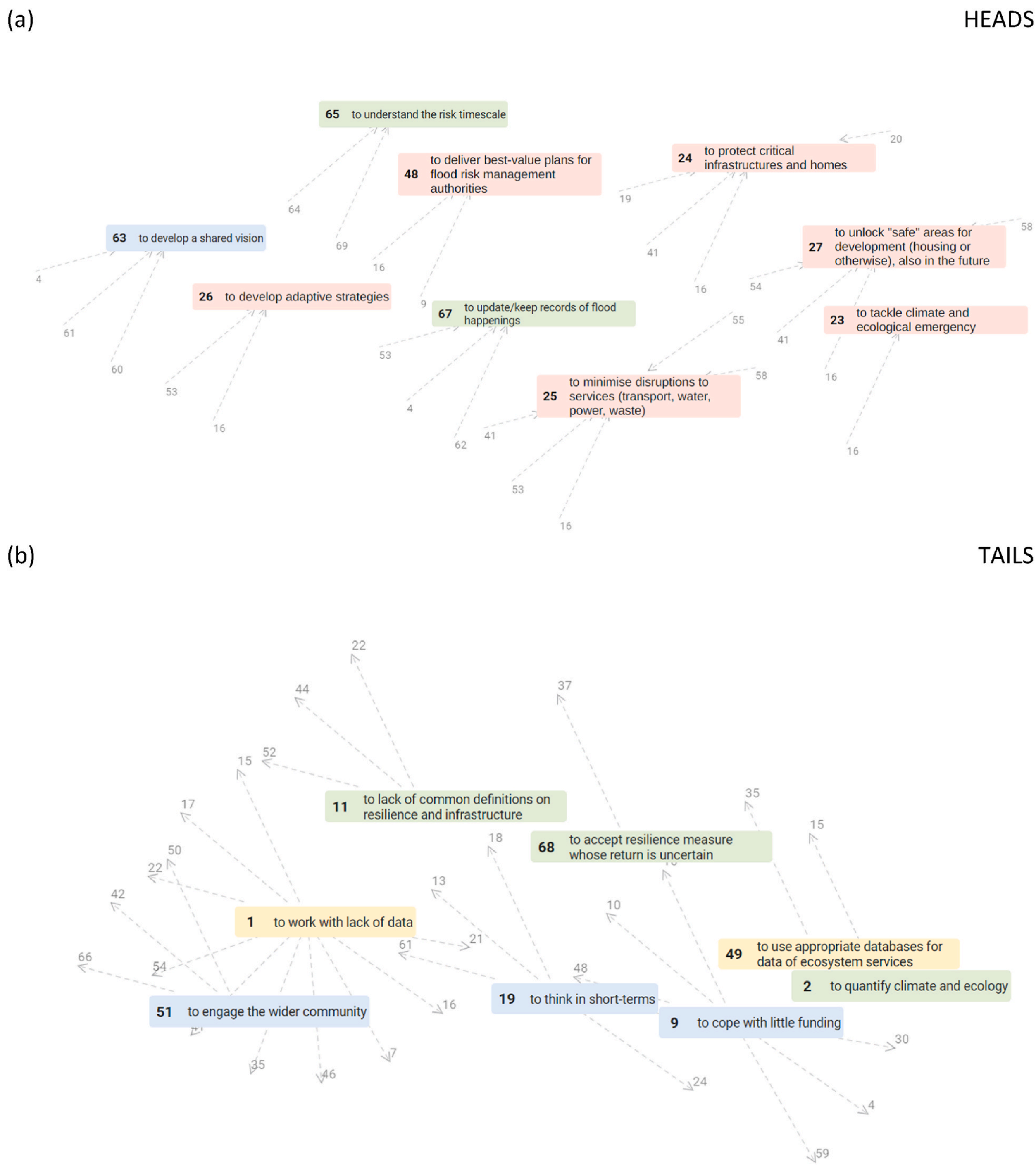

Fig. 7. Head (a) and tails (b) of the StrategyFinder's causal map.

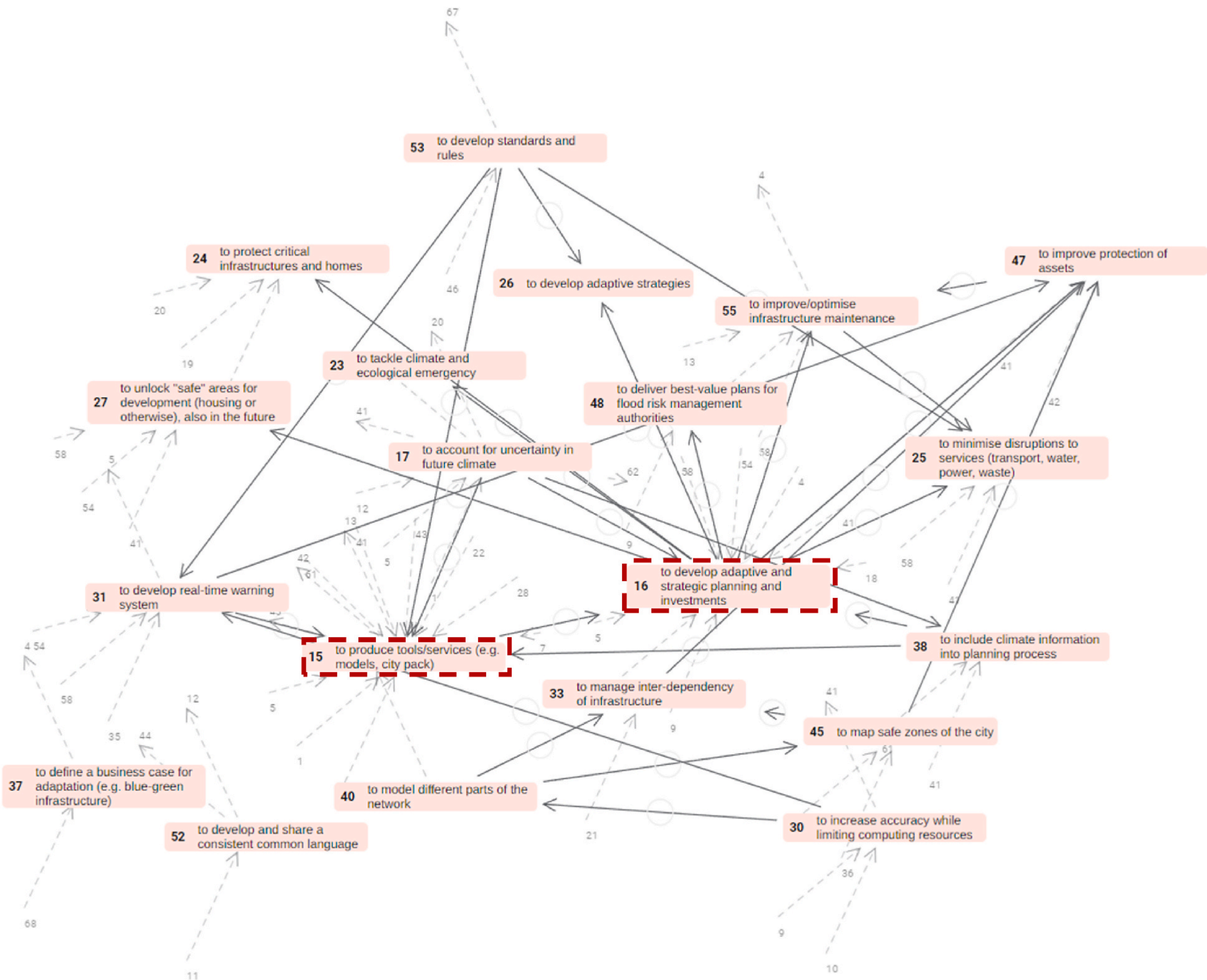

Fig. 8. The "Modelling and tools" cluster (red dashed border – central node).

A second step of the analysis exploited the four thematic areas to scrutinise the model into thematic clusters and create separated views (Fig. 8 as an example, all other views in Appendix B). Each thematic cluster has at least one central node, meaning that each area has transformational potential and at least one focused element to concentrate on.

The "Data" cluster includes eight statements, in particular the central one *to assess future flood risk using high-resolution climate data* (41). These statements highlight in particular a lack of or limited data (1, 29, 35, 46), the importance of high-resolution data (41, 62) and issues of data management (storage - 49, accessibility - 7). This highlight underlines the need to improve practices behind data collection and generation, as well as those of data management.

The "Technical and technological knowledge" cluster is a larger cluster of 16 statements, including the central node *to train staff to use models and understand outputs* (61). Six statements (2, 13, 28, 58, 67, 68) are not directly linked to the others. The "stand-alone" statements are indeed not strongly related to the others, and perhaps negligible if in need to simplify the map and the reasoning on it. The topic of knowledge and understanding results as those dominating the cluster, since eight statements (5, 11, 13, 28, 54, 58, 64, 65) contain issues about it (e.g. need to understand, lack of knowledge). A second emerging topic relates to staff capability and availability, with three statements (10, 36 and central node 61) about the skills or activities that are relevant for staff operating in urban resilience. This cluster highlights the relevance of being knowledgeable about data, processes and practice, thus the priority of training staff with the appropriate skillset (e.g. in operating impact models).

The "Leadership and relationships" cluster is another large and complex group, with 17 interconnected statements, where *to maintain clear communication with citizens* (44) is the central node. The engagement of the community plays a central role in this cluster, with five statements (14, 42, 43, 51, 66 and central nodes 44) remarking the relevance of communicating with citizens. Other emerging topics include funding (9, 59) and cooperation (12, 57). Finally, the presence of leadership is critical (18, 60, 63), especially if linked with a needed change of mindset and approach (19, 20, 21, 50). The key message that emerges from this cluster is that keeping the

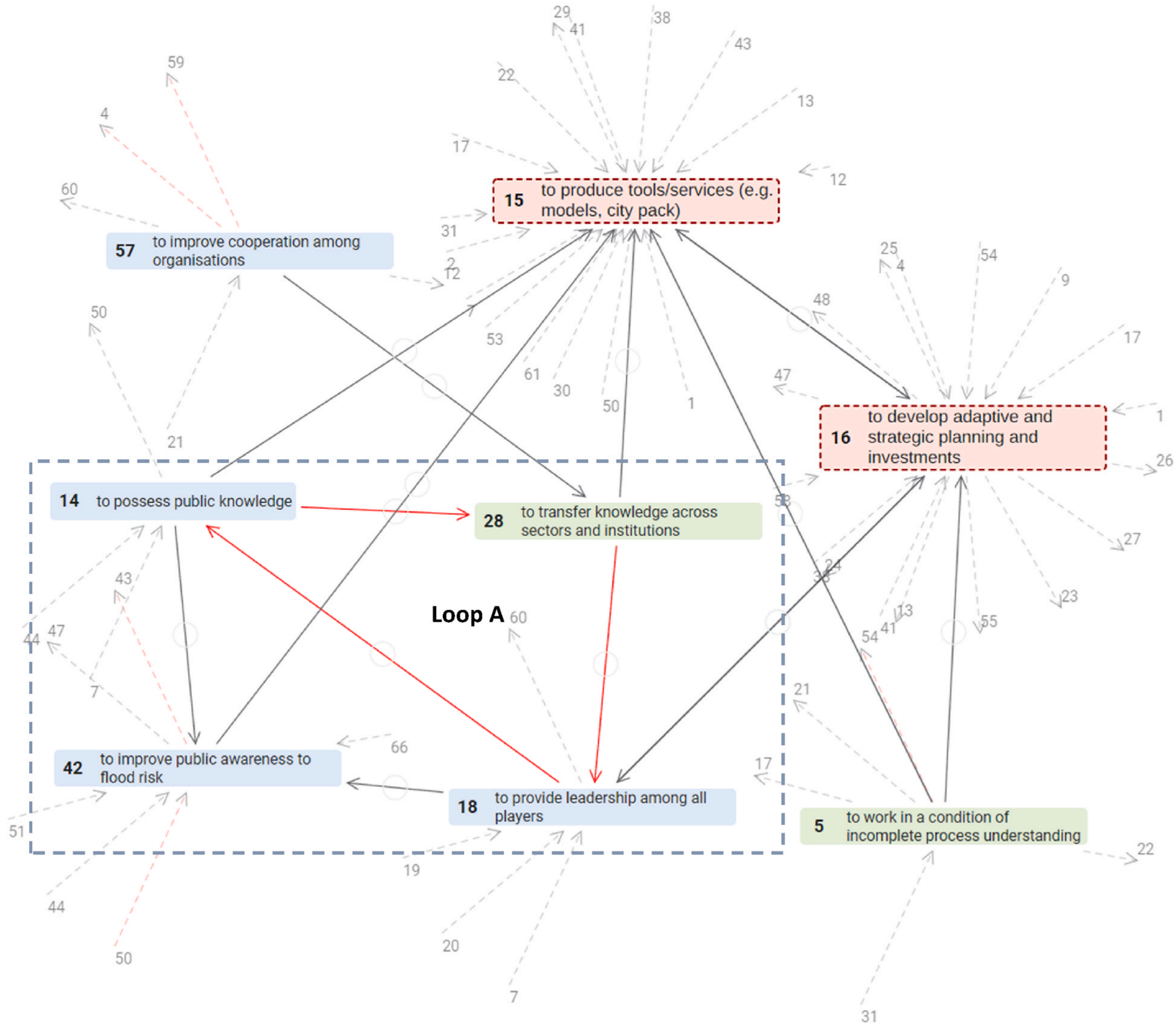

Fig. 9. Loop A: 14, 18, 28 (red dashed border – central node; no heads or tails, red arrows – loop).

community informed is important for stakeholders, and such communication is driven by leadership, and sustained by cooperation (among actors) and available funding (e.g. for "raising flooding awareness" campaigns).

"Modelling and tools" is the largest and most complex cluster, with 18 (out of 20; 37 and 52 are the isolated statements) interconnected statements (Fig. 8). It contains two central nodes, *to produce tools/service* (15) and *to develop adaptive and strategic planning and investments* (16). Emerging topics mainly include the built environment (homes, infrastructure) (24, 25, 27, 33, 40, 45, 47, 55), with the action goals of improving or developing capacity to improve urban resilience. They also include climate and extreme events (17, 23, 31, 38), such as the need to develop real-time warning systems and account for climate change. Finally, policy is another emerging topic (26, 48, 53, central nodes 15 and 16) which highlights the importance for stakeholders of developing standards, rules and services to implement actions. This cluster is the closest to the heads and indeed very relevant for the final goals. It confirms that tools/services and adaptive plans are central for stakeholders, and this centrality may be due to the fact that they lead to the aims of reducing disruptions and enhancing asset protection. Moreover, this cluster also shows some actions for information generation: considering available climate information, modelling infrastructure networks and mapping "safe areas" of a city are all key information that can help filling the data gap of the "Data" cluster.

Causal mapping also helps in identifying and analyzing virtuous or vicious loops within a system. By visualizing these loops, it is possible to realise how changes in one variable may influence others, and the system as a whole. Two self-contained loops were identified; in both loops, no heads or tails are present which means that they are more relevant in the central part of the development of a strategy. Capturing similar feedback loops is important because urban resilience is considered a strongly interconnected

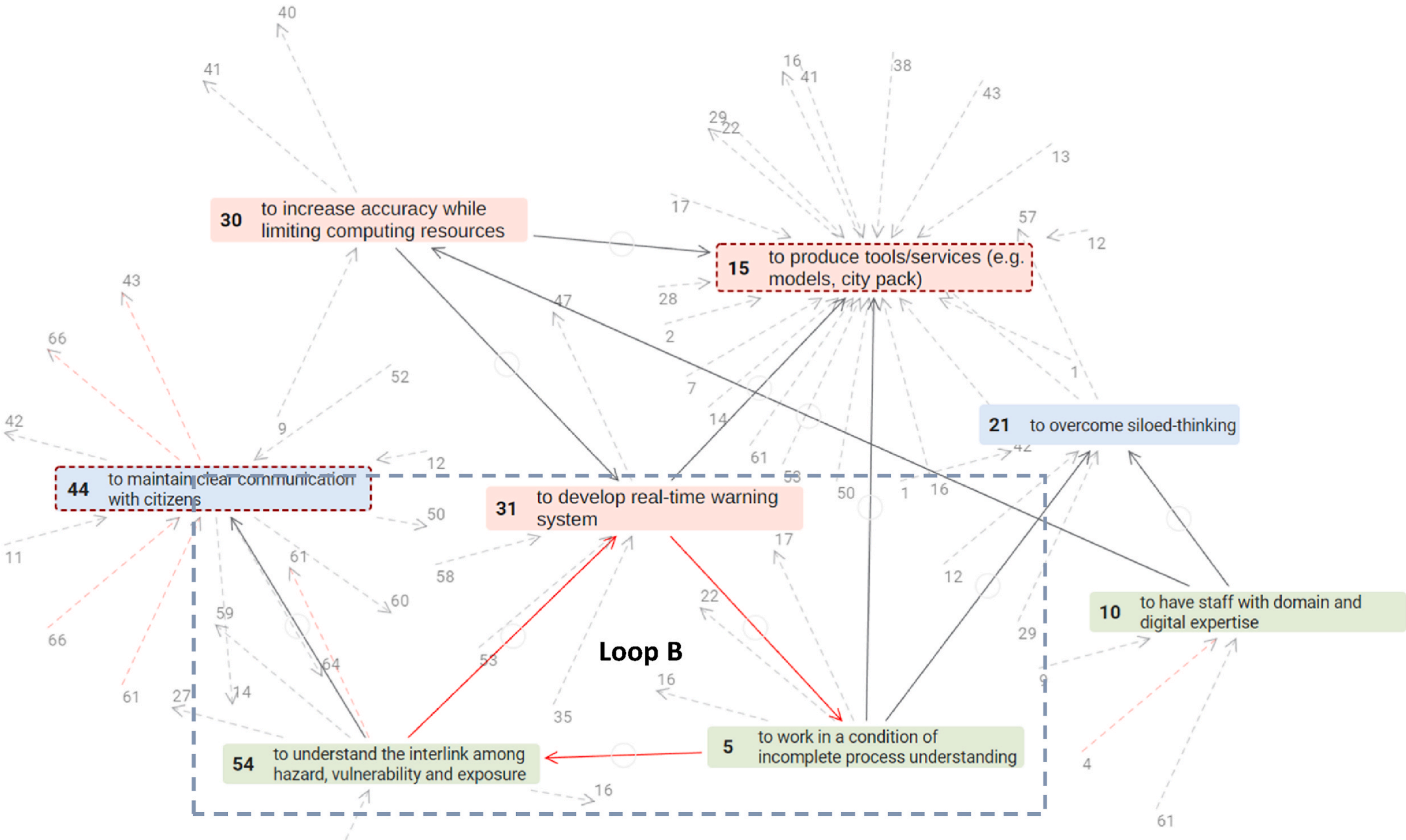

Fig. 10. Loop B: 5, 31, 54 (red dashed border – central node; no heads or tails, red arrows – loop).

phenomenon; in this case, loops include indeed complicated connections, with multiple nested loops (see Appendix A) and thus their interpretation is not straightforward. Loop A (14-18-28) in Fig. 9 is mainly about “Leadership and relationships”, and participate to reinforce two central nodes (15, 16). It shows that public knowledge, knowledge transfer and leadership are reinforcing, while requiring multi-institutional cooperation among stakeholders. This loop is a virtuous cycle because stronger leadership can support public knowledge which can facilitate the knowledge transfer across sectors and institutions; this knowledge transfer can enhance leadership (e.g. leaders with a more holistic background), re-starting the loop.

Loop B (5-31-54) in Fig. 10 is mainly about “Technical and technological knowledge”, with connections to “Leadership and relationships” and “Modelling and tools”. It participates in reinforcing two central themes (44 and 15); especially, the production of tools/services (15) receives contributions from two members (5, 31) of the loop. This relevant aspect signifies that tools/services development can be improved by better real-time warning system and with the assessment of the unknows of the underlying process. This loop can be seen as a vicious cycle because the absence of a complete knowledge of the underlying processes undermines the understanding of the three elements of risk (hazard, exposure and vulnerability), which in turn prevents from developing real-time warning systems; on the contrary, it can become virtuous with improved knowledge of the hazard progression, which will enhance the understanding of risk and enable the creation of real-time warning system. For example, the vicious loop can be prevented by improving information (quality and quantity) that support understanding of physical processes (e.g. urban runoff during flash floods).

4. Discussion and future research

This study aimed to explore the key objectives, barriers and opportunities in thinking about “resilient infrastructure” for UK cities, as perceived by a range of key stakeholders, by answering the question “How can causal mapping be applied to understanding better the barriers and opportunities in improving decision making and collaboration among multiple stakeholders to strengthen urban resilience?”. This study developed and analysed mental models of multiple participants of different affiliations working on improving urban resilience, by using causal mapping.

First of all, the broad validity of the workshop cannot be guaranteed because every situation is unique in relation to the context (e.g. stakeholders, issues of concern; [54]. It also recognized that facilitators might have influenced the dynamics at tables. However, the workshop structure and organisation are versatile, and can be tailored to suit different needs. For example, the causal mapping activity could be organised around scenarios-based questions, and participants could be engaged in discussing specific outputs (e.g. central issues) in a follow-up workshop or conversations. Furthermore, another PSM approach could be adopted for the workshop development, such as Strategic Choice Approach (SCA), which focuses more on uncertainties linked to working environment, related decisions, guiding values and disruptive events [54]; see Sec. 1).

Causal/cognitive mapping requires de-briefing and post-elaboration to extract information. The post-workshop stage could be improved by adopting a cross-validation process, as proposed by [55]; where multiple researchers cross-check the composite map to verify the correctness of the summary procedure. More importantly, the obtained results from the interpretation of the composite map would gain more validity and reliability if disseminated to stakeholders for feedback and discussion [29]. This dissemination and feedback may make the workshop more useful for stakeholders, enhancing and extending the learning process further [56].

This method also requires a careful selection of participants to involve a diverse and relevant pool of representatives [57]. Stakeholders’ identification as participants is key in achieving the goals of eliciting information and the interested reader can refer to the wide body of literature on stakeholder theory (e.g. [58]. Group activities could lead to group bias, whereas precedent single interviews could have mitigated the risk of individuals dominating the group [29]. Furthermore, stakeholder management is a delicate matter when eliciting information; for example, preserving anonymity is critical, as well as managing the complexity of inputs during conversations and activities [59]. Finally, principles of procedural justice theory could be considered in developing procedural rules within the workshop organisation to support individuals’ perspective and feelings [60].

4.1. *Insights about the workshop approach*

The context of urban decision-making is complex since it requires collaboration between businesses, academia, different levels of government, non-profit organizations, public, and other stakeholders [61]. At the end of the workshop, feedback forms were distributed and filled by 21 (on 23) attendants. In particular, causal mapping was appreciated for helping to analyse the problem and for allowing the discovery of something new. Top-scored items included “Making connections with new people” and “Engaging and varied activities”. It was also suggested to “Make causal mapping more applied to identify ways forwards within the group/more focussed question” (Participant 12). Further comments also included appreciation like “Very well organised and lively interaction” (Participant 19), and willingness to follow up “to explore further collaboration opportunities” (Participant 3). On the basis of the feedback received, the study also confirmed the usefulness of workshops in enhancing stakeholders’ networking and problem ownership (e.g. [62]. Participants found causal mapping useful and stimulating, in accordance with existing works [36,53,54,63].

In this study, stakeholders understood the workshop as a mean to gain awareness of best practice, but also as a platform for working effectively and across disciplines. Their answers evidenced that participants were overall happy and found the causal mapping exercise useful, engaging and accessible. According to the received feedback, the workshop was found useful to address a complex matter and co-develop a deeper understanding for identifying existing issues and potential future actions as a diverse group, transforming perspectives into a holistic view of the problem. Lastly, the enhanced and enriched ownership of the problem "urban resilience" is an important result *per se*, since it can drive more informed decision-making in the future. This insight contributes to evidence that this work (and relative workshop) can be taken as reference for future events that look at resilience as a multi-faceted and multi-actor issue. Future events may also include members of public, i.e. lay members.

4.2. Insights for urban resilience

Politics of urban resilience in which knowledge is co-produced ideally leads to more useable science [64]. Causal mapping is a well-established technique and its literature is rich in applications within complex problems (e.g. [29,46]; see Sec. 1). Resilience literature overlooks the multidisciplinary and complex nature of urban resilience [65], and innovative methods to deal with urban complexity are needed [66]. This paper does not aim to bring change or innovation to the causal mapping technique itself, rather it aims to introduce it as a new method to work with stakeholders within the urban resilience community.

This study applies casual mapping to urban resilience for the first time; it explained the method, which is then demonstrated for an exemplar application of urban resilience to flooding. Thus, it can be used for reference for future and larger exploration of the field. In this field, the causal mapping method satisfies the need of adopting an holistic approach, to critically thinking through resilience [67]. In fact, it has the potential to capture elements from the political context, trade-offs, interconnections, and multiple scales, necessary for urban plans and interventions (*ibid*).

The obtained results of this study offered a practical contribution to the field of urban resilience by applying the methodology in a multi-stakeholder setting. The composite cognitive map showed a strong stakeholder inclination of focusing thoughts on "Data", "Technical and technological knowledge", "Leadership and relationships" and "Modelling and tools" (thematic clusters). These four clusters have not been identified before as operational areas for disassembling urban resilience as the literature currently offers more theoretical (and wider) multi-dimensional framework (economic, environmental, social and institutional dimensions, e.g. [68]; [69]).

The map was also functional to identify main challenges (data availability, silo-based approaches and lack of funding), as well as goals (the need to protect the built environment and to minimise impact from flooding). These challenges and goals are not new, and well-aligned with existing works (e.g. [70,71]). The analysis highlighted the relevance of being knowledgeable about data, processes and practice, thus the priority of training staff with the appropriate skillset (e.g. in operating impact models). Staff's skills and capacity to develop tool and services based on high-resolution data for decision-making (e.g. operational to support adaptation plans), in fact they resulted among the main drivers. This finding has not been previously specifically recognized, since current literature usually is more focused on policy mechanisms [29]. The analysis also revealed that the engagement of the community plays a central role, especially in association with available funding, multi-institutional cooperation and leadership. The relationship between resilience and leadership is a contemporary sub-topic, on which literature has recently started to focus (e.g. [72]). This study confirmed that understanding how to enable the public sector to lead holistic solutions to deliver resilience in cities is worth exploring.

Practical implications from results pinpoint that strategies for urban resilience can be articulated using the structural properties of the map (e.g. heads, tails), to propose a strategic vision for adaptation and mitigation plans. With reference to this case study, such a strategy could begin with a short-term vision based on available knowledge, data and finance, which the community is aware about and engaged with (tails). These resources shall be used to train members of staff to produce appropriate tools/services for developing new data and advanced adaptation plans; in parallel, citizens should be kept informed and involved (central nodes). Particular attention should be given to knowledge transfer among institutions and disciplines (Loop A), and to the understanding of underlying technical processes (Loop B), as main enablers of urban resilience. The target of these actions could be the emergence of a shared vision of a resilient city, which drives interventions towards minimising disruptions due to flooding and a more robust built environment (head).

In this paper, the application of causal mapping to urban resilience was particularly functional for: *(i)* visual representation, through a composite map with the capture of all stakeholders' perception on the matter; *(ii)* systems thinking, by capturing interactions; *(iii)* identifying feedback loops, for understanding reinforcing or balancing effects; and *(iv)* communication and collaboration, for a shared understanding of the matter. In future application, the method could be further developed to also embrace scenario analysis and actual problem solving/decision-making. The outcomes from the application of causal mapping could be used to delineate an informed holistic strategy for tackling the resilience of urban environments [69]. This point highlights that causal mapping is helpful to explore visions and pathways systemically in the field of urban resilience, in addition to identify challenges and goals. Thus, this study brings new contribution to current debates about the need for integrated planning processes and policy-working across multiple layers, scales and sectors [73].

5. Conclusion

In a context of global changes, cities need to increase their resilience to natural hazards, such as flooding. However, actual implementation of resilience actions in urban planning is currently limited, and a comprehensive platform where all involved stakeholders can collaborate together is required. Problem Structuring Methods (PSMs) are an appropriate approach for tackling this gap, in particular causal mapping is functional for disassembling major issues into simpler elements. The study shows the following gaps: *(i)* how to enhance urban resilience is still unclear and current measures unsatisfying; *(ii)* cognitive mapping has not been specifically applied to urban resilience before; *(iii)* multi-level cognitive mapping is limited and more application is recommended. The gaps led to the research question: "How can causal mapping be applied to understanding better the barriers and opportunities in improving decision making and collaboration among multiple stakeholders to strengthen urban resilience?".

In this work, the cognitive mapping approach was used to map the perspective of a participants' group in a workshop; the single maps of groups were then combined into a consolidated map, obtaining a multi-level cognitive map. The analysis and interpretation of the map was based on cognitive mapping measures, such as central nodes, heads, tails and loops (using the software StrategyFinder). The analysis highlighted:

- the presence of barriers in relation to data availability, silo-based approaches and lack of funding;
- the identification of shared goals, such as the need to protect the built environment and minimise impact from flooding;
- the emergence of a preliminary strategy to improve urban resilience.

The identified strategy suggested that available knowledge, data and finance could be used to train members of staff to produce appropriate tools/services for developing new data and advanced adaptation plans, while they keep the society informed and involved. In addition, knowledge transfer among institutions and disciplines, and the understanding of underlying technical processes could be assumed as main enablers of urban resilience.

The importance of this work resides in its contribution to the urban resilience literature, by providing the novel application of causal mapping in the field. This paper showed that causal mapping is relevant for urban resilience since it can effectively support relevant stakeholders through visual representation and system thinking of perceived barriers and goals, while enhancing communication and collaboration. In particular, the emerged preliminary strategy could be a basis for research and development in the context of urban resilience.

Future research could focus on developing the technique and results further, by:

- targeting scenario analysis or specific context of decision-making (e.g. what-if scenarios);
- enhancing the pre- and post-workshop stages, by respectively improving stakeholder management and adopting a cross-validation process of primary data (e.g. dissemination of and feedback on findings);
- including in the workshop members of public, for community engagement;
- providing recommendations separately for each stakeholder.

In conclusion, causal mapping can be applied successfully and with interesting results for exploring barriers and opportunities in improving decision-making in the context of urban resilience, and our workshop's outcomes highlighted its usefulness in both theoretical and practical terms.

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.

Data availability

Data will be made available on request.

Acknowledgement

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Appendix A

This Appendix offers additional outputs from the analysis of the composite map with StrategyFinder.

Fig. 11 offers a view on the interconnection of central nodes "*to train staff to use models and understand outputs*" (61) leads to both *to produce tools/service* (15) and *to maintain clear communication with citizens* (44), which means that staff members with adequate skills are needed to both develop tools and disseminate outputs to the society.

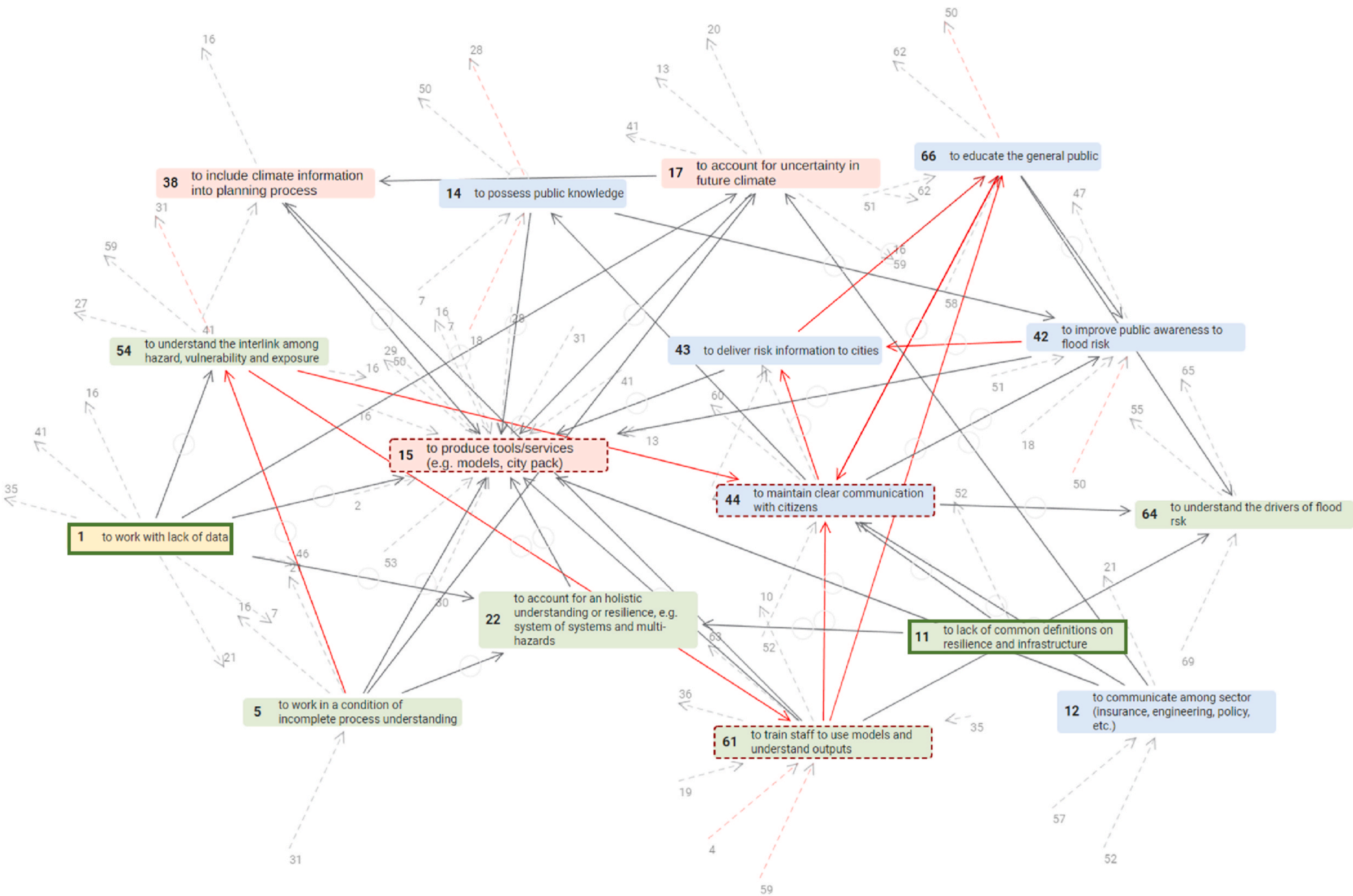

Fig. 11. View on central nodes 15, 44 and 61 (red dashed border – central node; no heads; green border – tail).

The view of Fig. 12 shows the interconnection of central nodes 15, 16 and 41. *To produce tools/service* (15) and *to assess future flood risk using high-resolution climate data* are causally connected to *develop adaptive and strategic planning and investments* (16), which means that the availability of dedicated tools/services and risk levels for urban flooding would lead to the capability to develop adaptive and strategic plans. There is a two-way connection between 15 and 41, thus these two statements are mutually reinforcing: in fact, information about flood risk is essential for producing tools and service, and *vice versa* specific tools are needed to estimate flood risk.

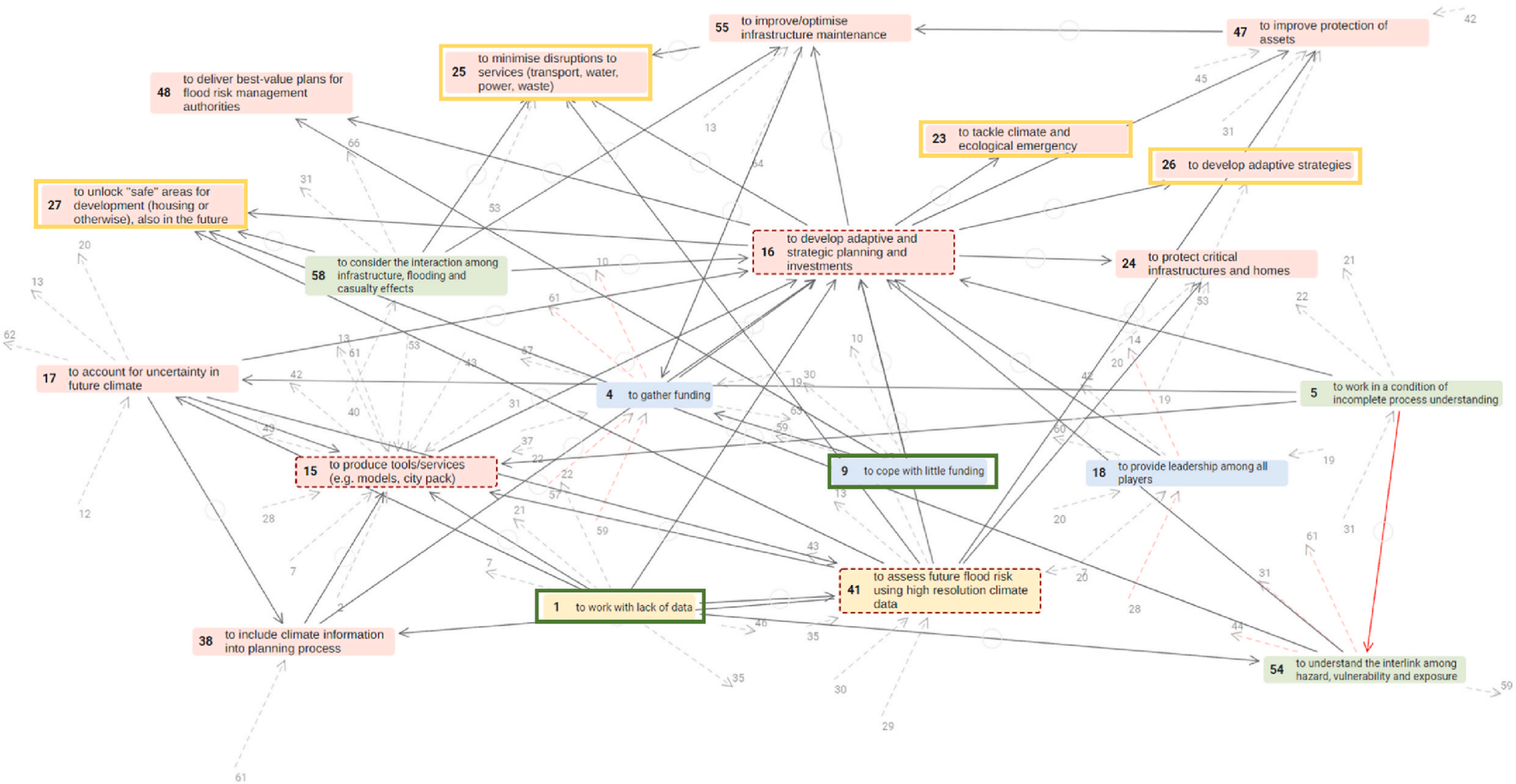

Fig. 12. View on central nodes 15, 16 and 41 (red dashed border – central node; yellow border – head; green border – tail).

Fig. 13 shows the “Data” cluster, which includes eight statements, in particular the central one *to assess future flood risk using high-resolution climate data* (41).

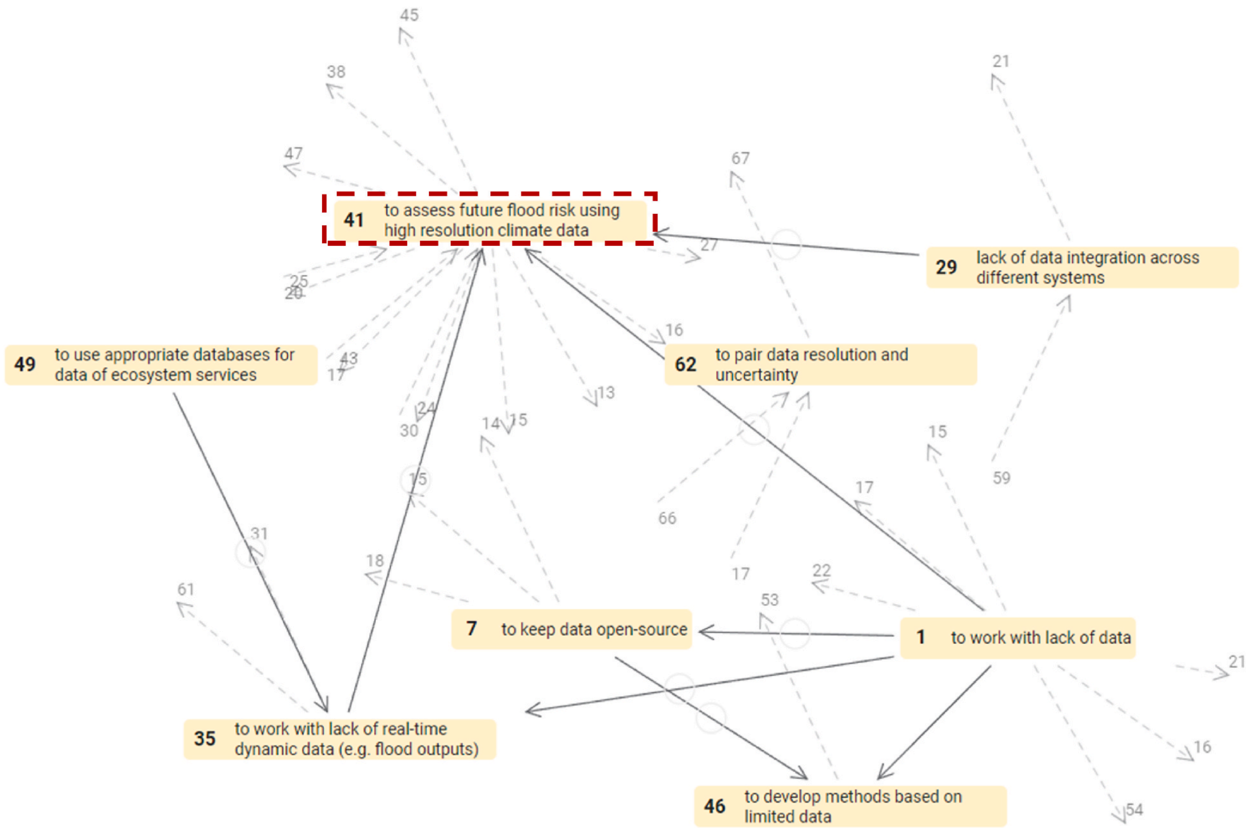

Fig. 13. The "Data" cluster (red dashed border – central node).

Fig. 14 shows the “Technical and technological knowledge” cluster, which contains 16 statements, including the central node *to train staff to use models and understand outputs* (61).

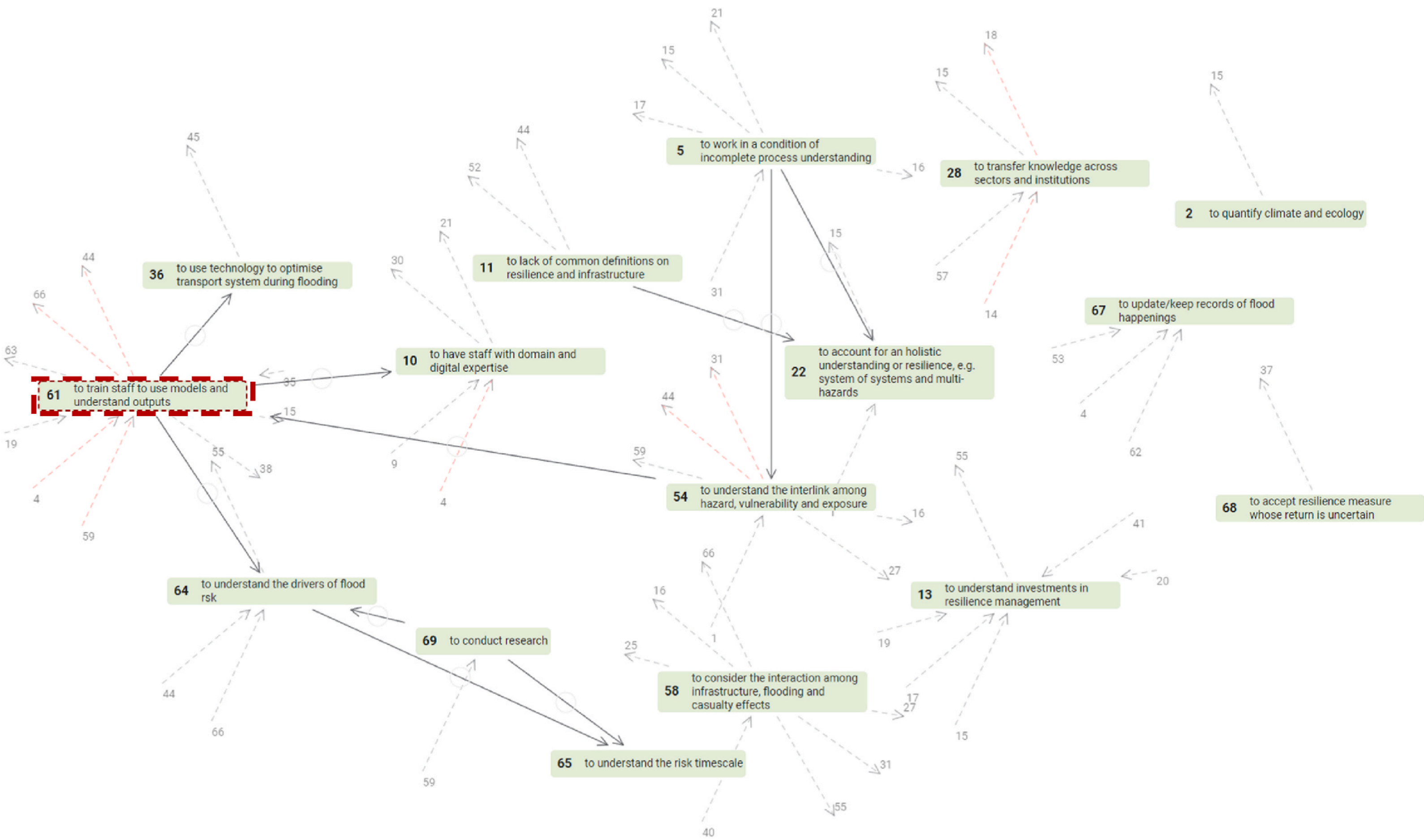

Fig. 14. The "Technical and technological knowledge" cluster (red dashed border – central node).

Fig. 15 shows the “Leadership and relationships” cluster which contains 17 statements, where *to maintain clear communication with citizens* (44) is a central node.

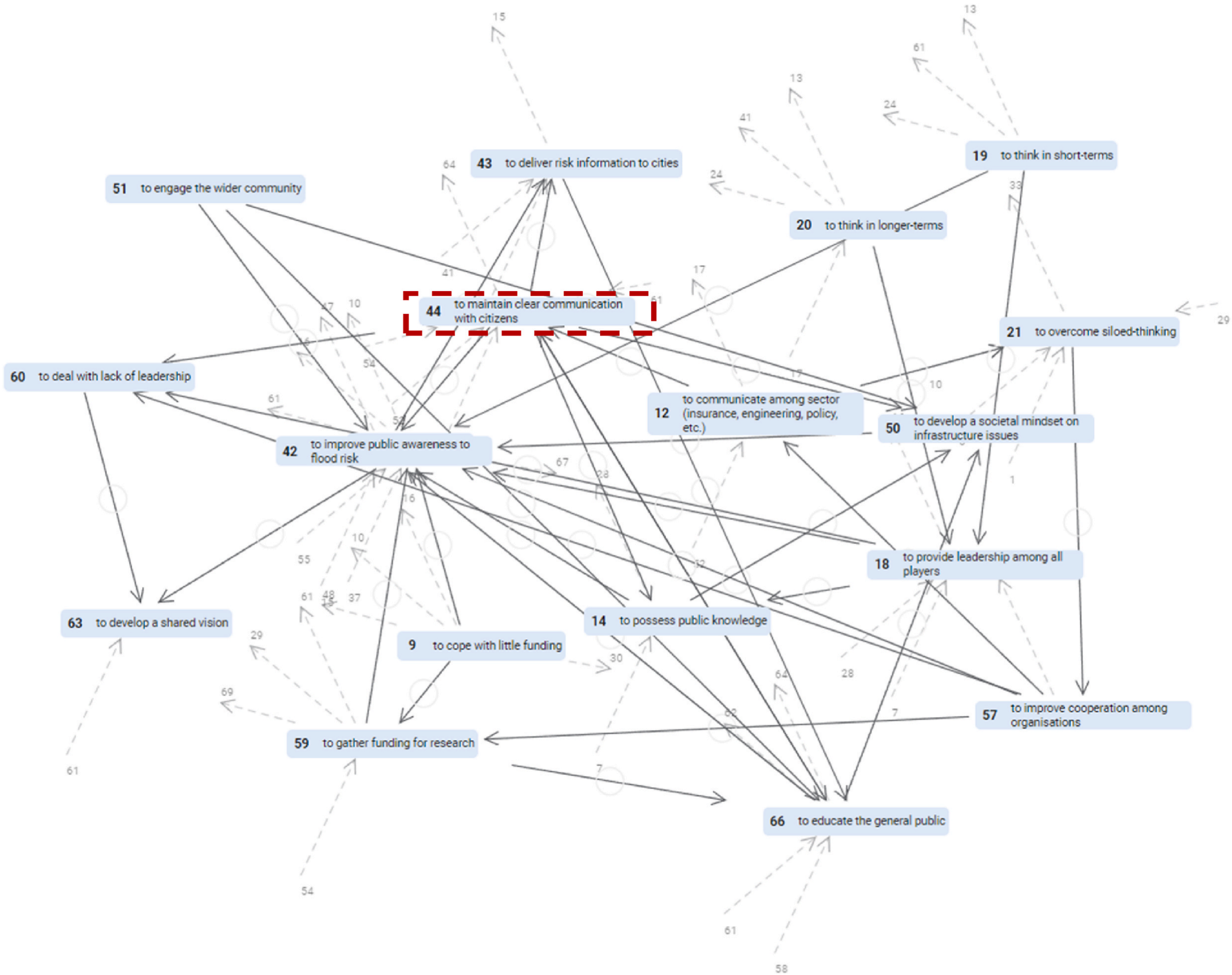

Fig. 15. The “Leadership and relationships” cluster (red dashed border – central node).

Fig. 16 shows all the (nested) loops present in the model.

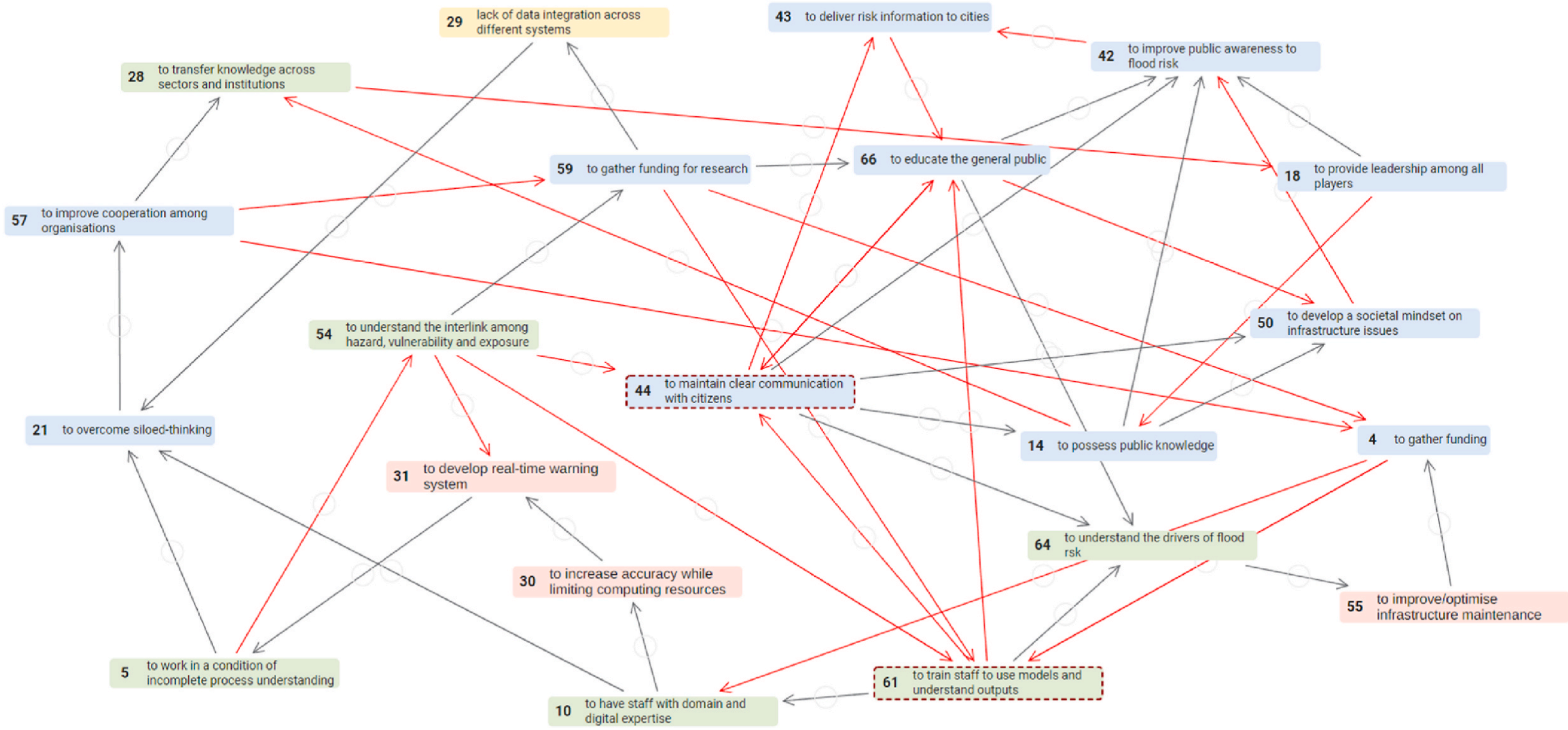

Fig. 16. All loops in the composite map (red dashed border – central node; red arrows - nested loops).

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