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Developing a performance evaluation functional model for cities impacted by a natural hazard: application to a city affected by flooding

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Abstract

The experience feedback on a crisis that hit a city is frequently used as a "recollection" tool. However, it may not be held in itself as a tool for analyzing a city's performance. The city, considered as a complex system, was modeled using a functional analysis method. Based on such modeling, two risk analysis methods (Failure Mode and Effect Analysis and Event Tree Method) were deployed and adjusted. Lastly, a qualitative reasoning model had been used for get the scenario modeling of the urban crisis. Such functional model was deployed on a case study.

1 Introduction

For the past decades, growing urbanization and industrialization gave rise to a sharp increase in harmful disastrous events, thereby demonstrating the city's higher exposure to major risks, e.g. flood risk (Ashley et al., 2007). In addition, the climate change anticipates a substantial escalation and increase in frequency for a number of natural hazards (Muller, 2007). Cities, now particularly vulnerable, need to get hold of new tools that will guard them against future disasters and improve their performance facing such hazards. The RESILIS project – technical urban systems governance for a resilient city – funded by the French National Research Agency, addresses such issues and aims at improving urban system resilience to natural or anthropogenic hazard-driven crisis. All works described herein were conducted as part of the RESILIS project and focus on developing a performance evaluation model for cities.

Improving the performance of crisis-stricken cities is a key objective for crisis management stakeholders in the city. Such an improvement cannot succeed without a better understanding of how urban systems behave when hit by a crisis. For that reason, performing a detailed review of urban crisis experience feedback is essential. Such experience feedback will help examine all failures occurring during a dreaded event, analyze the different scenarios and draw meaningful conclusions. Based on such analyses, the city should be able to improve its protection, prevention and crisis management performance, in the event that a similar event were to impact the considered urban system again. However, in order to learn from urban crisis experience feedback, a methodology must be clearly set up so as to make the experience feedback a formal one, provide a model for the impacted city's failures, and understand the failure processes as well as the sequences and causal relationships thereof. This is not a negligible issue since urban systems appear particularly complex due to their many constituent subsystems, and the multiple organizations and governance (Lhomme et al., 2013; Toubin et al., 2012). The main scientific issue pertains to developing a model that might reproduce the complex operation and deficiencies of urban systems. An underlying issue relates to modeling the experience feedback on crisis-stricken urban systems. The purpose is to analyze urban crisis case studies, understand the failure processes thereof and picture them on a homogenous model.

The primary objective of this research is to develop a model that would allow modeling the crisis-stricken cities performance. Reference work searches did not reveal many models for urban system modeling existing in technical literature, except researches undertaken by research teams working in the urban engineering and more particularly in the field of urban resilience (Campanella, 2006; Serre et al., 2012). The resilience concept is initially a derivative term of the ecology (Holling, 1973) and has evolved significantly since the past 30 years (Folke, 2006; Gallopín, 2006). The recognition of this concept has increased across the disciplines that human and ecological systems are interlinked and that their resilience relates to the functioning and interaction of the systems rather than to the stability of their components or the ability to maintain or return to some equilibrium state (Klein et al., 2003). Thus, considering the city as a system, urban resilience can be defined according Campanella as "the capacity of a city to face devastating event reducing damage at minimum" (Campanella, 2006). Concerning the natural hazards and more particularly, for the flood hazard, resilience concepts are comprised of individual preventive and emergency measures at building scale and a land use policy to adapt building activities to floods (Pasche and Geisler, 2005). A resilient concept was applied to flood risk management by adopting a systems approach (De Bruijn et al., 2005). System approach tends to overcome these segmentations and level of complexity. Indeed, a system approach proposes a common language for different disciplines and can be considered a good way to study complex system (Batty, 2009). The research work of Lhomme are based on this approach and he defines urban resilience as "the ability of a city to absorb disturbance and recover its functions after disturbance" (Lhomme et al., 2011). He used a system model for studying cities and for modeling their functions. This model seeks to assess the resilience level of the urban networks. Indeed, the urban networks play an important part in crises and not always for positive aspects. For instance, the reliability and rapid restoration of the electric grid in particular necessary to support the needs of the population within the disaster area effectively (Winkler et al., 2010).

In this study, for the assessing the performance of a city affected by a natural hazard, in other words, for the assessment of its resilience to face a crisis, we are interested to all components city system including technical networks. Our suggested model uses functional analysis methods intended for understanding how the systems do work (Baroth et al., 2013), risk analysis methods designed for modeling complex systems and qualitative reasoning models (Forbus, 1996) and adopting a representation of failure sequences in the form of causal graphs (Forbus, 1996) that will help achieve a high abstraction level to represent the systems.

The second objective is to model urban crisis case studies. After reviewing past experience feedback, the purpose is to suggest a methodology that will help build up the failure scenarios that occurred in the cities of interest. Such models and methods would bring a major asset to the different management services and crisis management stakeholders in the relevant cities. These would help improve our understanding of urban system failures and eventually improve the urban system safety so as to mitigate the impacts stemming from crisis.

This is an innovative research project as it uses functional analysis, risk analysis and qualitative reasoning models and applies them to urban engineering. Adjusting such methods will result in developing a functional model that would outline the performance of a crisis-stricken city, and showing how helpful it would be for analyzing an urban crisis experience feedback. This aspect is described in the first section herein. The second section establishes the developed model. The model will be applied to the case study of an urban crisis caused by flash floods. The considered case study relates to the city of Nîmes (France), which was struck by a major runoff flooding in 1988. Such application will show how much can be learnt from such a model about the weak points to be improved in an urban system. The third section herein is specifically address the considered case study. Based on the different suggested models, the urban system's strengths and potential improvements are described in this section.

2 Developing a performance evaluation model for crisis stricken cities

A system's performance is defined according to its capacity to perform as per its assigned functions in specific operating circumstances (Peyras et al., 2006). Therefore, a city's performance should be assessed by reviewing its propensity to be operational, prevent human and minimize financial losses during a crisis. An in depth review of the failures in a city struck by natural, technological or industrial disasters turns to be of substantial help to understand the city's failure modes and thereby improve its performance in subsequent similar hazardous situations. On that account, the purpose herein is to develop a methodology that will help assess the city's performance when faced with an external hazard, analyze the failures of a crisis stricken city, determine which components are more efficient and which are most critical, in order to improve the city's performance in any subsequent similar situation.

2.1 Performance evaluation model development procedure for crisis-stricken cities

A city is a complex system for it has many a constituent subsystem and there are multiple interactions between those subsystems and the city's outer environments (Serre et al., 2011). Consequently, risk analysis methods used in industry to identify risks and model the complex system functions are considered relevant for modeling and analyzing how a crisis-stricken city operates (Baroth et al., 2013; Modarres, 1993). Also, qualitative reasoning models are deemed relevant for representing urban crisis (Forbus, 1996).

Such methods have been used in the past as part of civil engineering projects (Peyras et al., 2006; Serre et al., 2008). These were also applied to urban engineering with regard to technical networks (Serre et al., 2011).

The suggested procedure for building up a functional model that will outline the performance of a crisis-stricken city may be summarized in four steps: (i) from the functional analysis, the urban system and subsystems' functions is determined; (ii) from the Failure Mode and Effect Analysis (FMEA), information on failures occurring in an urban system due to a dreaded event is organized; (iii) from the Event-Tree Method (ETM), a representation of all potential scenarios is suggested, including the scenario resulting from experience feedback, as a sequence of failure modes; (iv) from qualitative reasoning models with causal graph modelling, a dynamic and gradual failure model is suggested for urban system failure scenarios.

2.2 Developing a performance evaluation functional model for crisis-stricken cities

2.2.1 Functional analysis applied to cities

The functional analysis consists in two stages: the external functional analysis, including analyzing the system within its environment and the internal functional analysis, including a structural analysis of the system, i.e. identifying its various constituent subsystems, and exploring the subsystems functions (Baroth et al., 2013). Many functional analysis methods are suitable for industry, services or organizations. It was decided to rely on the APTE method as successfully used and applied to civil engineering systems (Curt et al., 2010; Peyras et al., 2012).

In functional analysis, two categories of functions are considered in the functional reflected the actions of the system: principal functions and technical functions. The principal functions convey the purpose of a system's action. Technical functions derive from how the system reacts to stresses set by external environments. Functional analysis also uses functional block-diagrams (FBD), which is a representation of the system and external environments, highlighting the following (Baroth et al., 2013).

In functional analysis, the desired spatial granularity needs to be determined. It is suggested that three levels of granularity should be differentiated for urban systems. Higher granularity is the spatial scale used to perform an external functional analysis of the urban system as a whole. For internal functional analysis, the intermediate granularity was selected so as to describe each subsystem in the city. Lower granularity will help understand how some specific urban subsystems work.

The external functional analysis aims at defining the system to be reviewed, its limits and interacting external environments (Baroth et al., 2013). When applied to cities, the system is regarded as consisting of the urban system delineated by its administrative boundaries. The urban system interacts with external environments, including: neighboring cities, rural areas, outer technical networks (power, water, telecommunications, transport networks, etc.), environmental factors (meteorology, seismic situation, etc.), governance, etc. The FBD of a generic urban system is shown on Fig. 1. The external functional analysis will determine the principal functions: "ensure cultural, political and economical cohesion, thereby enabling men to live together as a society" and "ensure that incoming and outcoming material, such as information, energies, foodstuffs, materials, etc., may travel to and from the system". The functional analysis also determine urban systems technical functions: "protect inhabitants", "protect resources", “control flows”, “resist to outer network failures”, “ensure equipments are safe and properly maintained”, “comply with and enforce all major decisions”, “contribute to national economical growth”, “fit in geopolitical trends”, “feature equipment enabling access to information sources”, etc.

An internal functional analysis was performed for a typical urban system. It is suggested that four large categories of subsystems should be differentiated: technical networks, housings, businesses and public infrastructures. Such categories, referred to as grade 1 categories, may be detailed as grade 2 or grade 3 categories. Table 1 below shows how the city is structurally subdivided into different subsystem categories. The principal functions and the technical functions have been highlighted from FBD.

As an example, the FBD for the “Drinking Water Supply (DWS) technical network” is shown on Fig. 2. From such FBD, the DWS technical network principal and technical functions may be differentiated and highlighted. Principal functions are “provide drinking water supplies to housings, businesses and public infrastructures” and “protect the city in case of fire”. Technical functions are “resist to mechanical loadings” and “resist to failures from other technical networks interrelated with DWS water supply network”.

All the results from the internal functional analysis are compiled in a functional analysis table detailing all the principal functions and the technical functions of a city’s constituent subsystems. Table 2 provides a sample of such functional analysis table for DWS technical network subsystem. For an analysis of other urban subsystem functions, please refer to the RESILIS project (www.resilis.fr).

In this article, we will focus on six main functions which must maintain a suitable level of performance when a dreaded event impacts a city:

- the function “convey and/or drain off flows” for “water” technical network,
- the function “provide flows” (power flows, natural gas flows, district heating flows) for “Power” technical network,
- the function “provide flows” (communication flows: broadband, wireline telephone or mobile telephone services) for “telecommunications” technical network,

- the function “meet the needs for travel” (for road and railway transport) for “transport” technical network,
- the function “ensure”: “ensure accommodation” for housings, “ensure their economical and social duties are performed” for businesses and “ensure and serve a public interest purpose” for public infrastructures,
- the function “resist to mechanical loadings” for all subsystems.

Finally, the functional analysis drawn up for a typical city may subsequently be applied to a specific city case study through adjustments and quick streamlining. Therefore, this is a generic functional analysis that may apply to most urban systems.

2.2.2 FMEA applied to cities

The FMEA is one of the most frequently used risk analysis methods in industry. It is regulated by many a guide and standard, which are usually drafted for each specific industrial situation: NF X 60-510, CEI 812-1985, MIL-STD-1269 A, etc. The FMEA is an inductive method for analyzing the potential failures in a system (Modarres, 1993). Each component is consistently and consecutively considered and their failure modes (lost or impaired function) and effects are analyzed. FMEA analysis results are outlined on tables specifically designed for the system type of interest. An FMEA procedure will include (Baroth et al., 2013; Modarres, 1993) a system functional analysis then a systematic research for failure modes and effects thereof.

In order to be applied to urban engineering and serve the purpose herein to provide a model for urban system performance and failure scenarios during crisis, an FMEA is to undergo a number of adjustments. To that end, and to show the causal connections between phenomena and failure modes during urban crisis, each parameter in the FMEA table and how they are achieved is precisely defined: cause, failure mode, effect. The suggested FMEA analysis includes the following:

- subsytems;
- subsystem main and technical functions, provided by the functional analysis;
- subsystem failure modes, matching a function's failures and/or damages;
- possible causes of failure, originating from either the strength and/or location of the given external mechanical loading, or the failure of a subsystem interacting with the analyzed subsystem;
- possible effects of failure.

For instance, the "DWS technical network" subsystem's technical function is to "resist to mechanical loadings", hence the failure mode thereof: "did not resist to mechanical loadings". A possible cause of such failure is "damaged DWS pipes". Consequently, the effect of such failure is that inhabitants (housings, businesses and public infrastructures) have no longer access to drinking water. This example is reported on Table 3 below as an FMEA table.

Unlike in industry, where FMEA is used as a tool to identify a system's failure modes, the FMEA is used herein to identify failure modes, the causes and effects thereof of crisis-stricken urban systems. Thence, the FMEA method is applied in retrospect with a view to highlight the failure modes, and the causes and effects thereof, as part of urban crisis case studies.

Such an unusual application and adjustment of FMEA has been developed based on information provided by urban crisis experience feedback. At the end of FMEA, all the city's subsystems failure modes, causes and effects are known in connection with an urban crisis as detailed in experience feedback.

2.2.3 ETM applied to cities

Based on failure mode identification, the failure scenario modeling methods are used to build up the sequences of failure modes that may lead to system failure. There are different methods for modeling the risk analysis, one of the main being the ETM.

The purpose of the ETM is to model the sequences of failure modes within a system. The sequence of events on the tree is inductive, from the initiating event to the final events (Baroth et al., 2013; Modarres, 1993). The tree is chronologically developed according to how each modeled subsystem behaves.

As part of our study on urban systems, the ETM will be developed after the FMEA method has been applied. Indeed, all failure modes that occurred during an urban crisis are known. The ETM will then help model the chronological and functional sequence of failure modes as identified during this urban crisis.

Let us consider as an example an urban system hit by a severe flooding, for which the successive sequence of impacted subsystem failure modes is to be modeled. More specifically, three impacted urban subsystems are in focus: electrical power technical network, DWS technical network, and housings. Failure of the functions “provide electric power” and “resist to mechanical loadings” of the electric power technical network lead to a defaulting technical function (“resist to power outage”) of the DWS technical network. Subsequently, a failure of the latter results in the failure of the function “ensure suitable accommodation for inhabitants” of the “housings” subsystem. Ultimately, the flooding scenario for such urban crisis consists in the sequence of three failure modes: (i) failure of the electric power technical network that was flooded, (ii) failure of the DWS technical network due to power outage, and (iii) disrupted power and drinking water supply services to dwellings. The sequence of failure modes in the urban crisis example is modeled on Fig. 3 as a scenario.

In the end, the ETM allows us producing a sequence of the subsystems failure modes according to their functional and chronological occurrence. Thus, an event-three consists in modeling an urban crisis as a functional scenario with sequenced urban subsystem failure modes.

2.2.4 Modeling crisis-stricken cities through qualitative reasoning models

The dynamic quality-based models issued from qualitative reasoning models will help develop dynamic models in order to reproduce the systems’ behaviors from their causal relationships: any event (e.g. a P phenomenon occurring in an urban system) impacting a variable (e.g. an urban subsystem's F function) will spread to other variables (other phenomena and functions in cities) having a causal connection thereto, through causal paths (Forbus, 1996). Propagation may be simulated using quality-based and dynamic transfer functions with time as parameter.

Of all dynamic quality-based models, the directed graph dynamic causal model is most relevant for modeling an urban crisis scenario based on given experience feedback. Indeed, it will help show the dynamic and gradual change in impaired functions and subsystems over time. Also, redundancies may thereby be incorporated into the scenarios (introducing multiple identical phenomena in the scenario model) in order to take loop and non-linear scenarios into account.

Figure 4 gives an example of dynamic causal diagram considering the experience feedback on a flooding event impacting an urban system and, more specifically, the impact of such event on the "electric power technical network" subsystem.

3 Applying the performance evaluation functional model for flood-stricken cities

The functional model developed to evaluate the performance of crisis-stricken cities is applied to a case study pertaining to the city of Nîmes (France) after the October 1988 floodings. The event is first described and subsequently modeled following the above procedure: functional analysis, FMEA, ETM and causal model. Finally, the urban crisis is analyzed based on the model results.

3.1 Event description and experience feedback analysis

The information description is based on reference work searches that helped draw up an experience feedback analysis grid on the 1988 runoff floodings in Nîmes as part of the RESILIS project. The various pieces of information derived from a number of essays and books, for instance (Fabre et al., 1994) were summarized so as to describe the event and the 1988 flooding hazard impact on Nîmes and its subsystems.

A runoff flooding occurred on 3 October 1988 within Nîmes catchment area. This rain and storm event took place between 04:00 and 12:00 UTC. It produced a 300 to 420 mm overflowing nappe, with an estimated 100 year return period, which caused a runoff flooding, especially as it had rained heavily for several days before 3 October 1988. These previous rainfalls caused ground saturation, hence the substantial increase in runoff. Such natural event was widely exacerbated by the city's urban structures. Indeed, the thalweg beds located up the city of Nîmes had been narrowed by road infrastructures and housings. Thalwegs would flow down the city centre through pipes that were either undersized or cluttered up by technical networks. And the thalweg outlets down the city were blocked by road or railway embankments. Therefore, Nîmes and its dwellers ended up trapped by water. The flooding event in Nîmes had disastrous outcomes. Regrettably, there were several casualties, 30 individual dwellings were destroyed and about 2000 had their finishings damaged, causing 45 000 disaster victims out of which 200 had to be rehoused. 450 to 700 businesses were also damaged. The crisis management public infrastructure buildings were flooded (command post for organization of civil security response in the prefecture, service departmental to fire and rescue, departmental center operational to fire and rescue, emergency ambulance service, police station), as well as the city's utility services (electric power, telecommunications, DWS, road transport). The estimated global disaster cost was FF3.3 billions. Nîmes was not prepared to respond to such a large-scale crisis: there was no prevention plan except for the weather report, no hydraulic protection works or structures capable of responding to such a severe flooding event, no flood forecast system since there is no large watercourse flowing through the city, no delineation regulation applied to areas liable to flooding and no specific crisis management procedure. The city of Nîmes had to deal with an unexpected and large-scale event without any specific protection or adaptation resources available.

3.2 Functional analysis of 1988 flooded Nîmes

3.2.1 Identifying the subsystems impacted

With intermediate granularity, Nîmes impacted subsystems during flooding were determined based on the experience feedback (see Sect. 3.1). Those are described on Table 4 below showing all 10 impacted subsystems.

From such subsystems and by reviewing the event description contained in the experience feedback on the 1988 floodings in Nîmes, the performance evaluation functional model for crisis-stricken-cities would be applied.

3.2.2 Identifying the main functions of subsystems impacted

By analyzing the event in Nîmes and considering the functions identified during an urban system generic functional analysis (Sect. 2.2.1), the main functions impacted during urban crisis were determined.

The first is “provide drinking water” (to convey drinking water flow): due to the flooding event which began at 06:45 UTC on 3 October 1988, the drinking water supply was cut off as of 09:30 UTC, affecting 50 % of city dwellers. The impacted function during crisis was not ensured across the system.

The second is “ensure communication and information” (to provide telecommunications flows): this function was ensured in Nîmes by two technical subsystems: “the wireline telecommunications technical network” and “the local radio telecommunications technical network”. Four telephone exchange offices were flooded due to runoff flooding. Such flooding resulted in 60 000 users having their telephone communications cut off. In addition, the police telecommunications network was also cut off, thereby hindering communication in crisis management and emergency response operations. The “ensure information communication” function was indeed impacted by this event, although the second “local radio telecommunications technical network” subsystem remained in running order.

The third is “meet the needs for travel”: this function, ensured by Nîmes “road transport technical network”, was impacted by the flooding event due to the damaged road system. Indeed, roads were destroyed over 30 km, resulting in restricted access to housings for crisis management stakeholders.

The fourth is “ensure accommodation and sheltering for people”: this function is ensured by all public buildings in the city, especially during urban crisis. A large number of constructed entities were impacted by the flooding event, resulting in people losing their homes, jobs and access to public interest services for a variable length of time.

The main technical function involved in urban crisis is “resist to floodings”.

3.3 FMEA applied to subsystems impacted by the event

Once all functions impacted by the urban crisis are known, the FMEA analysis helped highlight failure modes, and the causes and effects thereof on subsystems impacted by such urban crisis. FMEA is applied only to subsystems involved in the crisis event, as determined by the functional analysis (see Sect. 3.2.1).

Table 5 below provides sample results for the “DWS technical network”. This table indicates that the function “provide DWS to housings, businesses and public infrastructures” of the drinking water supply technical network has the following failure mode: “does not provide drinking water to 50 % of the city”. This failure mode has the following cause: “50 % of Nîmes drinking water supplies are cut off” and has the following effects: “50 % inhabitants, including housings, businesses and public infrastructures, have no longer access to drinking water due to their geographical location”.

The FMEA table was used for modeling failure modes, failure causes and effects of the subsystems (10 subsystems) impacted by the flooding in Nîmes. The subsystem principal and technical functions were analyzed in the FMEA table. From such functions, the failure modes and the causes and effects were determined based on information provided by Nîmes crisis experience feedback. Information contained in this experience feedback was subsequently organized and classified in the FMEA table.

3.4 ETM applied to Nîmes crises

The ETM is used to model the different failure scenarios of the October 1988 urban crises in Nîmes, in linking the different failure mode sequences.

The initiating event of the ETM to be considered is runoff flooding. As described in Sect. 3.2.1, the flooding event in Nîmes impacted ten subsystems. The 10 subsystems require that the urban crisis should be modeled with regard to 4 main functions: (i) "provide drinking water", carried out by drinking water supply technical network (DWS), (ii) "ensure communication and information", carried out by telecommunications technical networks (wireline telephone and local radio services), (iii) "meet the needs for travel", carried out by road transport network, (iv) "ensure accommodation and sheltering" for people, carried out by constructed entities. A model for the failures occurring in Nîmes was subsequently sought for each of these 4 main functions using the ETM per the procedure set forth in Sect. 2.2.3.

We present in the article the modeling of the failure of the main function "provide drinking water". Event-tree modeling the "DWS technical network failure" involves the following subsystems: electric power technical network, drinking water supply technical network, decision-making crisis management public infrastructures, operational crisis management public infrastructures (Fig. 5).

The ETM made it possible to highlight the different potential scenarios, in a flood crisis-stricken city, induced by various sequences of failure modes, for each one of the four urban subsystem main functions. The ETM model proposed is a generic event-tree for urban crisis affecting any one of the considered main functions, and may therefore apply to a large range of cities that were or might be subjected to this type of crisis. In each event-tree, the procedure helped determine how the city of interest would behave in the event of a crisis, and such behavior was identified and modeled using one of the event-tree scenarios.

3.5 Modeling the city of Nîmes during the 1988 runoff flooding using the directed graph dynamic causal model

The directed graph dynamic causal model helps show the dynamic and gradual change in impaired functions and subsystems over time. It demonstrated the impact of an initiating event (*P* as phenomenon) on one or more variables (*F* as function), and how it would spread to other variables (other phenomena and functions in the city) having a causal connection thereto through causal paths.

With regard to the experience feedback on Nîmes, a directed graph dynamic causal model may be developed considering the sequence of subsystem failures as suggested in the event-trees (see Sect. 3.4). In this respect, this model provides a dynamic perspective on the scenario occurring in Nîmes from 3 to 4 October 1988. On Fig. 6, the DWS technical network section demonstrates that, faced with the runoff flooding phenomenon that occurred on Monday 3 October 1988, the function "provide drinking water" proved fairly efficient. Indeed, despite an external contamination and the network partial cut-off for 50 % of the city, the crisis management public infrastructures managed to handle the technical network failure. People were supplied with substitute drinking water as soon as the following morning (Tuesday 4 October 1988). The city's performance for this main function is therefore regarded as medium.

Therefore, the directed graph dynamic causal model shows the global scenario derived from the experience feedback on the considered case study, including each relevant subsystem specific scenario. The scenario is then more specifically defined by describing all phenomena at stake as a result of the failure modes. Unlike the ETM, the dynamic causal model does not highlight the different potential scenarios resulting from an initiating event. For that reason, a scenario's criticality may not be assessed against a whole set of potential scenarios.

4 Discussion

An analysis of each event-tree helped to compare the main function failure scenario that occurred in 1988 in Nîmes with other potential scenarios. This was meant to highlight all critical parameters as well as the city's performance factors against the considered main function failures. Then, recommendations may be directed at the city in order to improve its performance when faced with similar hazards. The goal is to reach towards the least detrimental scenario.

Scenario showing how the function "provide drinking water" may be affected is analyzed hereafter. Such affected main function is highlighted by the performance evaluation functional model applied to crisis-stricken cities through event-tree showing the failure of the DWS technical networks.

The event-tree showing the DWS network failure provides a model for the different potential scenarios in a flooding hazard-stricken city. These different scenarios may result in the failure of the function "provide drinking water", with the following subsystems being involved: electric power technical network, DWS technical network (carrying out the main function), decision-making crisis management public infrastructures, and operational crisis management public infrastructures.

Scenario #5 (see Fig. 5), of all possible scenarios, is the one derived from the experience feedback on the 1988 floodings in Nîmes. Indeed, the 1988 crisis gave rise to DWS being cut-off for 50 % of the city due to the drinking water supply technical network contamination on 3 October 1988 at 09:30 UTC. However, the crisis management public infrastructures duly carried out their functions with respect to such failure. Substitute drinking water was quickly supplied to inhabitants on Tuesday 4 October 1988, as shown in scenario #5 event-tree through the sequence of failure modes regarding: "resist to contamination" and "ensure undisrupted service" technical functions for the DWS technical network; "decide on implementing substitute drinking water supply" technical function for decision-making crisis management public infrastructures;

"ensure substitute drinking water supply" technical function for operational crisis management public infrastructures.

The failure of the function "provide electric power" carried out by the electric power technical network might have resulted in the failure of the function "provide drinking water" of the DWS technical network. Yet, as described in the experience feedback on Nîmes crisis, the electric power technical network was cut off as a preventive measure before the drinking water supply technical network cut-off. The experience feedback does not provide any further information indicating that the electric power technical network was involved in the DWS technical network failure. Still, the defaulting electric power technical network might have caused the DWS technical network to fail, as described in scenario #13 on Fig. 5.

In light of the different scenarios shown on Fig. 5, it may be inferred that the most critical scenarios are related to defaulting crisis management public infrastructures. As a matter of fact, a situation will be deemed under control when crisis management public infrastructures are able to respond, by carrying out their functions, to other urban subsystem failures. On that account, the most critical scenario – scenario #8 – would be the turn of events occurring on Monday 3 October 1988, when no decision or emergency response operation had been considered so far to respond to the DWS network failure.

The city of Nîmes can be viewed as a good performer in responding to their defaulting DWS technical network, by calling on their crisis management public infrastructures for action.

The city's performance with regard to the defaulting "to provide drinking water" function would most likely be improved with a faster response from crisis management public infrastructures. Indeed, the technical function "to decide on implementing substitute DWS" for decision-making crisis management infrastructures and the function "To ensure substitute DWS" for operational crisis management infrastructures should have been carried out on Monday 3 October 1988 instead of Tuesday 4 October 1988. A better performance in Nîmes would also imply securing the DWS technical network against the flooding phenomenon in order to reduce the length of technical network cut-off.

5 Conclusions

The functional model developed with a view to evaluate a crisis-stricken city's performance comes down to five basic steps: (i) performing a "generic" functional analysis for an urban system. Such analysis includes, on one hand, an external functional analysis showing all items outside the urban system as well as the principal and technical functions thereof and, on the other hand, an internal functional analysis defining each subsystem's main and their functions. The "generic" functional analysis underlines the main functions required by the system to work properly; (ii) having an experience feedback on an urban crisis; (iii) analyzing failure modes and effects using the FMEA method based on the experience feedback on the city of interest; (iv) modeling different potential failure scenarios for the different potential sequences of failure modes, based on the initiating event and using ETM; (v) representing the dynamic and gradual change in failed functions and subsystems as described in the experience feedback using a directed graph dynamic causal model. Such representation will also offer a global perspective on the scenario that occurred during the urban crisis of interest.

This urban crisis experience feedback analysis tool helps modeling the performance of a crisis-stricken city. With this tool, all crisis management stakeholders will be able to focus both on their technical systems and buildings performance or weak points, and on their decision-making and operational resource performance or weak points when faced with a crisis. Therefore, the purpose of this model is to help the various stakeholders in a hazard-stricken city to better prepare for a similar hazard occurring in the future. Also, applying a crisis-stricken city's performance model to experience feedback will let the lessons learned from such modeling extend to other cities liable to similar hazards. Most lessons learned will stem from the ETM where trees are, in this tool, generic trees representing urban crisis that impact a specific main function and involve specific subsystems. These may therefore apply to a large range of cities that were or might be subjected to this type of crisis, without further extension to other subsystems. It should also be noted that this performance modeling tool for crisis-stricken cities applies to any types of hazards, should they be natural or technological. Lastly, the performance modeling tool for crisis-stricken cities is limited, as it would show the city's weak points only based on previous experience feedback. As a matter of fact, this tool may not be used to implement proactive crisis management procedures based on hazards the city has never experienced before.

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Table 1. City structural breakdown.

#	Grade 1 category	#	Grade 2 category	#	Grade 3 category
1.	Technical networks	1.1	Water	1.1.1	DWS
				1.1.2	Sewage and storm water
		1.2	Power	1.2.1	Electric network
				1.2.2	Natural gas network
				1.2.3	District heating system
		1.3	Telecommunications	1.3.1	Broadband
				1.3.2	Wireline telephone services
				1.3.3	Mobile telephone services
		1.4	Transport	1.4.1	Road
				1.4.2	Railway
2.	Housings	2.1	Mobile		
		2.2	Individual		
		2.3	Group		
3.	Businesses	3.1	Services		
		3.2	Manufacturing industry		
		3.3	Stores		
4.	Public infrastructures	4.1	Decision-making crisis management infrastructure		Urban system administration (city hall)
		4.2	Operational crisis management infrastructure		Police, security, emergency response services...
		4.3	Infrastructure dedicated to vulnerable inhabitants		Health (hospitals, retirement homes...)
					Education (childcare centers, primary schools, secondary schools, high schools, universities)
					Specific accommodation (hostels, prisons...)
		4.4	Other public services		Welfare benefits
					Housing allowances
					Business support
					Record keeping
					Legal & judicial matters...

Table 2. Functional Analysis Table for DWS technical networks.

# and sub-systems	Main functions	Technical functions
1.1.1 Water Technical Network: "DWS"	*To convey flows:*	*To resist mechanical loadings (multi-hazards)*
	To provide drinking water supplies to housings, businesses and public infrastructure	*To resist* (piping) seismic loadings
	To protect in case of fire	*To resist* external contamination: To ensure water drinkability *To ensure* undisrupted service, *To resist* power outage (by providing a backup generator for instance) To last a long time

Table 3. Sample FMEA applied to Drinking Water Supply Technical Network.

#	Subsystems	Functions		Failure modes	Potential causes of failure	Potential failure effects
		Main functions	Technical functions			
1	DWS technical network		To resist mechanical loadings	Did not resist mechanical loadings	Damaged supply pipes	Inhabitants have no longer access to drinking water (housings, businesses, public infrastructures)

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Table 4. Subsystems impacted by flooding event in Nîmes (1988).

Classification (#)	Impacted subsystems
1.	Electric power technical network
2.	DWS technical network
3.	Road transport technical network
4.	Wireline telecommunications technical network
5.	Local radio telecommunications technical network
6.	Housings
7.	Businesses
8.	Decision-making crisis management public infrastructures
9.	Operational crisis management public infrastructures
10.	Public infrastructure dedicated to vulnerable inhabitants

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Table 5. FMEA table for Nîmes during the 1988 runoff flooding event: sample DWS technical networks.

#1	Subsystems	Functions		Failure modes	Potential causes of failure	Failure effects
		Main	Technical			
2.	DWS technical network	*To provide* DWS to housings, businesses and public infrastructure		Does not provide drinking water (50 % of the city)	50 % of Nîmes DWS are cut off	50 % inhabitants, including housings, businesses and public infrastructures, have no longer access to drinking water due to their geographic location
			To resist (piping) mechanical loadings (water pressures)		Damaged network	
		To protect in case of fire				
			To resist external contamination: to ensure water drinkability	Did not resist external contamination: non-drinkable water	Flooded network = contaminated water over 50 % of the city	
			To ensure undisrupted service	Did not ensure undisrupted service	Electric power technical network was cut off	
			To resist power outage (by providing a backup generator for instance)			
			To last a long time			

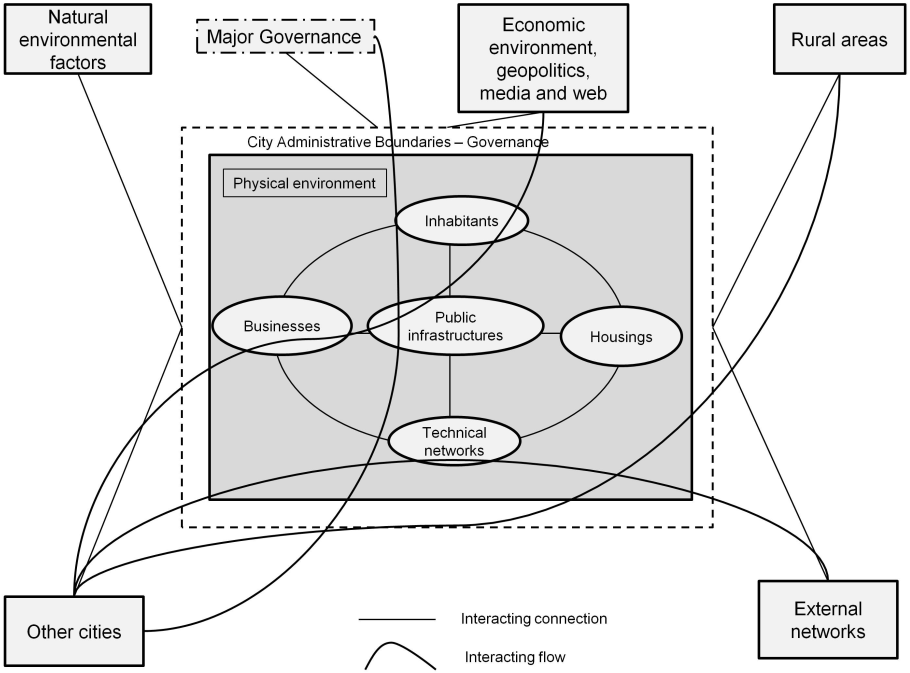


Figure 1. Urban system FBD.

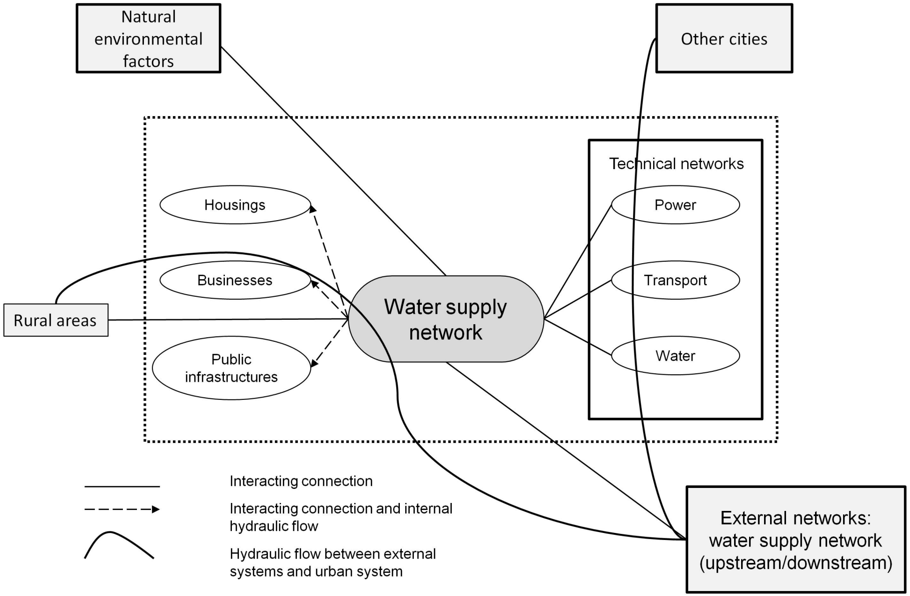
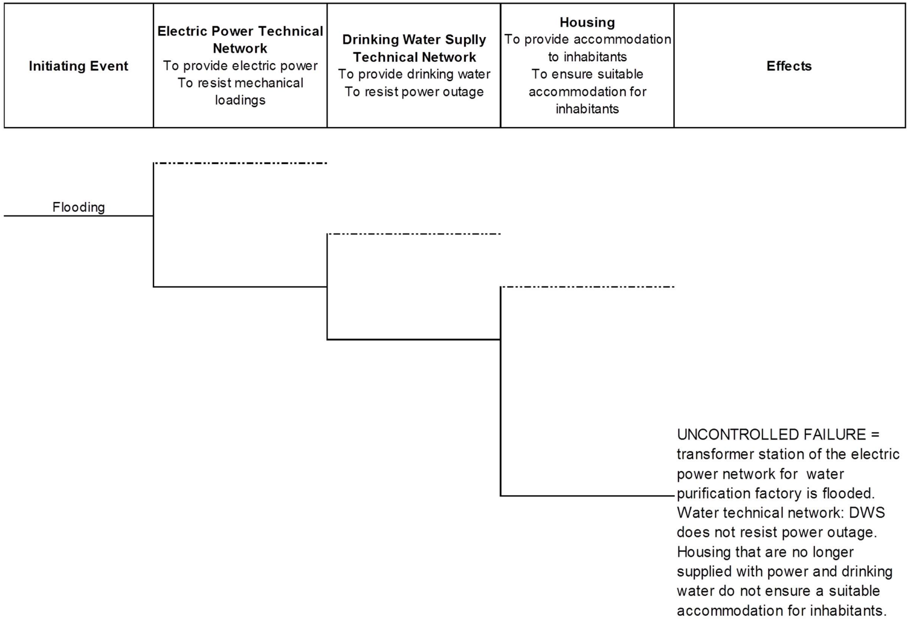


Figure 2. FBD for water technical network: DWS.



UNCONTROLLED FAILURE = transformer station of the electric power network for water purification factory is flooded. Water technical network: DWS does not resist power outage. Housing that are no longer supplied with power and drinking water do not ensure a suitable accommodation for inhabitants.

Figure 3. Sample ETM: application for water technical network: DWS.

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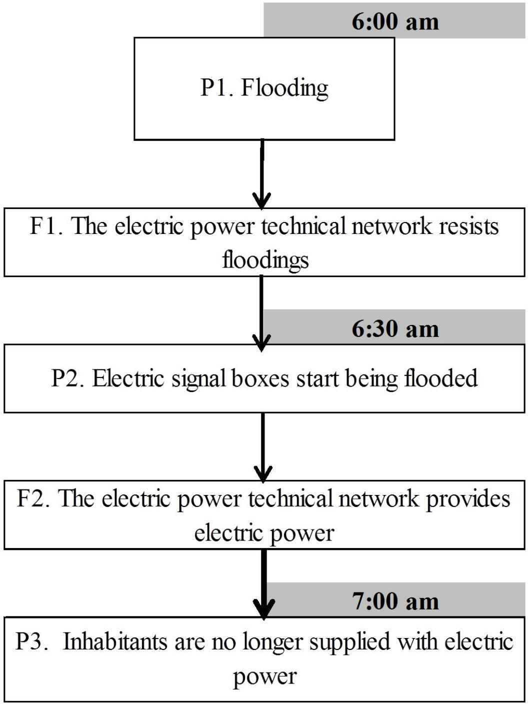
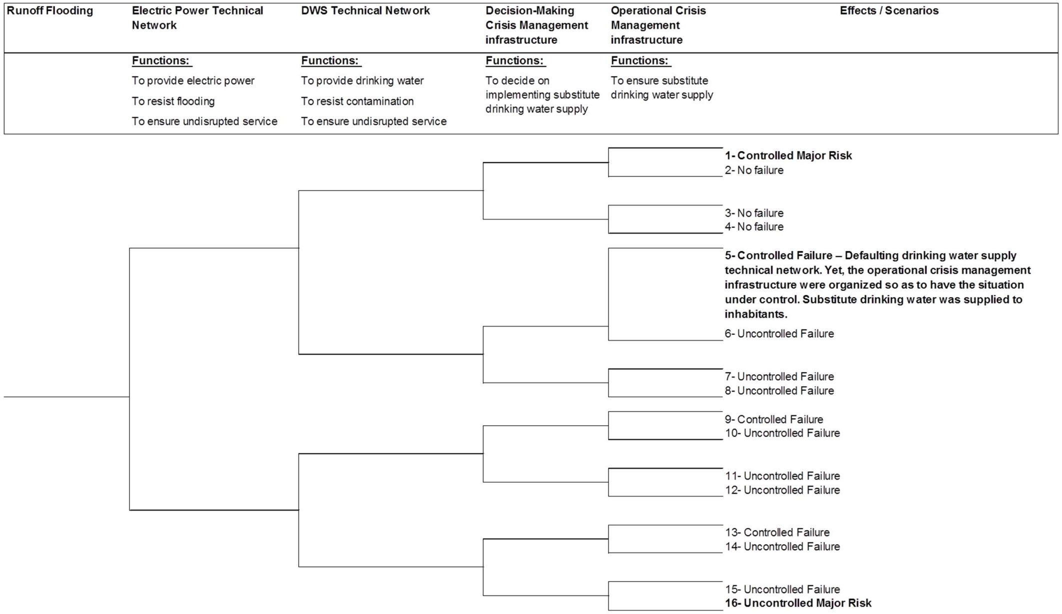


Figure 4. Sample dynamic causal graph application.



5- Controlled Failure – Defaulting drinking water supply technical network. Yet, the operational crisis management infrastructure were organized so as to have the situation under control. Substitute drinking water was supplied to inhabitants.

Figure 5. Event tree representing the DWS technical network failure during the 1988 flooding in Nîmes.

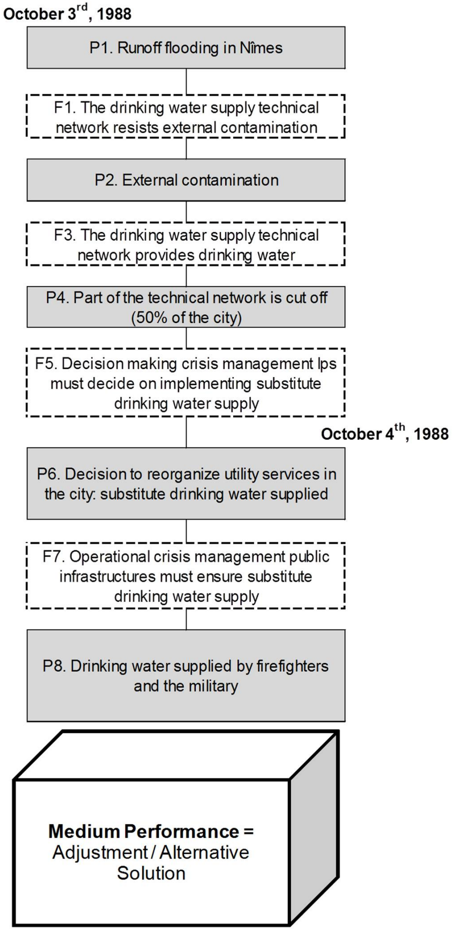


Figure 6. Representation of directed graph dynamic causal model for the 1988 crisis scenario in Nîmes, regarding DWS and road transport technical networks.