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A Simulation-Based Framework for Assessing Crisis-Response Capacity of Public Authorities and Emergency Response Organizations: A Heat-Drought Case Study

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A Simulation-Based Framework for Assessing Crisis-Response Capacity of Public Authorities and Emergency Response Organizations: A Heat-Drought Case Study

Abstract

Public authorities and emergency response organizations must maintain essential services during prolonged, multi-hazard crises, yet operationally grounded methods for analyzing capacity bottlenecks remain scarce. This paper presents a modular simulation framework that couples (i) a network-based model of crisis effects and cascading infrastructure disruptions using the cascade simulation framework CaESAR with (ii) a discrete-event process model of organizational tasks, resources, queues, and inter-organizational dependencies. Preparedness measures are represented through explicitly parameterized modifiers of task frequency, duration, and resource demand. We demonstrate the framework using a prototypical heat-drought scenario combining wildfire, heat-related medical demand, drinking-water disruption, and heavy rainfall. The case study includes a fire brigade, an ambulance service, the Federal Agency for Technical Relief, and the Federal Office of Civil Protection and Disaster Assistance. Model parameters were informed by practitioner input and organizational documentation. The simulation identifies time-dependent resource bottlenecks and illustrates how alternative preparedness assumptions affect operational capacity. Given the synthetic nature of the case study and the model's only partial calibration, the results should be interpreted as a proof of concept rather than as an empirical estimate of a specific municipality's resilience. The framework provides a basis for systematic scenario comparison, sensitivity analysis, the future quantification of the coping capacity of public authorities, and the future derivation of validated resilience indicators for public-sector crisis management.

Keywords: municipal resilience; resilience framework; coping capacity; public authorities; extreme weather

1 Introduction

Public authorities and emergency response organizations are central to maintaining the stability and security of modern societies, particularly in an increasingly dynamic environment shaped by crises and disasters. Strengthening the resilience of public

administration is therefore essential for managing uncertainty and enhancing the coping capacity of public authorities and emergency response organizations. Resilience is a dynamic, interdisciplinary concept that has been applied across a wide range of fields Carpenter et al. (2001). In the context of socio-technical systems, Thoma and Scharte (2015) conceptualizes resilience as a cyclical process comprising five phases: i) preparation, ii) prevention, iii) protection, iv) response and v) recovery. This conceptualization informs the understanding of resilience adopted in this study. Building on this perspective, resilience is understood as a multi-layered capability operating at both the technical and organizational levels. It encompasses the ability to respond to shocks, disruptive incidents, evolving environmental conditions, and gradual systemic changes; to absorb and adapt to stressors and disturbances; to proactively prevent and mitigate impacts; to manage critical situations efficiently; and to recover swiftly Bruneau et al. (2003). Resilience assessments have been conducted across numerous domains, including urban areas Cimellaro et al. (2010), acute care facilities exposed to earthquakes Bruneau and Reinhorn (2007), transportation systems Tang et al. (2020), aviation Wong et al. (2020), power supply networks Sun et al. (2021) and healthcare systems Srivastava et al. (2024).

Resilience can be quantified using appropriate metrics, i.e. quantitative measures that capture the ability of a system to withstand, adapt to, and recover from adverse events Poulin and Kane (2021). Suitable resilience metrics should reflect system performance before, during, and after a disruption. They can help identify vulnerabilities, monitor performance over time, and inform the development of resilience-enhancing strategies. Defining such metrics requires information about the system itself, the characteristics and impacts of disruptive events, and the effects of recovery actions Trucco and Petrenj (2023). Because resilience is context-dependent, relevant metrics vary across systems, use cases, and geographic settings. A comprehensive assessment should therefore combine complementary indicators that capture multiple dimensions of resilience Guo et al. (2021). Consequently, several frameworks have been developed to assess and quantify organizational resilience Brown et al. (2017); Guo et al. (2021); McManus et al. (2008). Administrative resilience can be understood as a specific form of organizational resilience, referring to the capacity of public institutions to maintain essential functions, recover from disturbances, and adapt to changing environmental demands. Existing indicator-based frameworks for administrative resilience emphasize different aspects of this capacity, including continuity of operations, recovery, and adaptability. Accordingly, administrative resilience is commonly operationalized through indicators that capture both enabling capacities and actual performance during crises Li et al. (2026). However, existing resilience assessment approaches often provide limited support for analyzing the time-dependent interplay of cascading crisis effects, operational task demand, baseline workload, resource constraints, and inter-organizational dependencies. As a result, they provide limited insight into when and why public-sector organizations reach operational capacity limits during prolonged crisis scenarios.

This work addresses this gap by presenting a simulation-based approach for assessing the operational dimension of administrative resilience. The novelty of the proposed

two-step framework lies in coupling a cascade model of crisis effects with a modular discrete-event process model. The cascade model translates crisis propagation into time-dependent task demand, whereas the process model represents baseline workload, organizational tasks, queues, resource constraints, inter-organizational dependencies, and alternative preparedness measures. Linking both models enables the assessment of the capacity of public authorities and emergency response organizations to cope with crisis situations, accounting for both increased mission demand arising from crisis impacts on society and direct disruptions affecting organizational operations and resources. The study addresses the following research questions: (i) How can cascading crisis effects be translated into time-dependent mission demand for public authorities and emergency response organizations? (ii) How can resource constraints, baseline workload, and inter-organizational dependencies be represented in a modular discrete-event model? (iii) Which operational bottlenecks and preparedness sensitivities can be identified in a prototypical crisis scenario?

The study is designed as a practitioner-informed proof of concept and focuses on the operational capacity dimension of administrative resilience rather than on a comprehensive assessment of it as a whole. The framework is demonstrated using a prototypical heat-drought scenario and is not intended to provide empirical validation or predictive results for a specific municipality. Instead, it evaluates the internal behavior and practical applicability of the modeling concept, including time-dependent workload patterns, resource bottlenecks, and the effects of alternative preparedness measures.

The practical application process of the presented approach is structured into several stages. First, users identify crisis scenarios that are relevant to their organization and for which resilience needs to be evaluated. Subsequently, scenario-specific tasks are documented, including interdependencies with other authorities and estimated processing times. To capture baseline operational load, routine tasks and their typical processing durations are also recorded, thereby representing the organization's normal activity level. At this point, incident statistics can be used to characterize the workload of emergency response organizations, whereas the workload of public administrations can be represented by caseload and process statistics, including the volume, type, processing times, and resource requirements of administrative cases. In the next step, users specify the resources available to their organization and, where possible, those of relevant partner institutions. In cases where precise data are unavailable, estimations may be used. Furthermore, organizational response strategies under conditions of overload are defined, including mechanisms such as task prioritization, the mobilization of external support, or the reduction of service levels. The process is complemented by the identification of relevant indicators for effective prevention with regard to the selected scenario. These indicators cover both characteristics of the geographic context, such as infrastructure conditions and population vulnerability, and internal organizational factors. Finally, the collected information is integrated into the simulation model. Scenario severity can be varied to assess organizational performance under different levels of stress. Systematic variation of model parameters and resource availability subsequently enables the identification of critical vulnerabilities.

The remainder of this paper is organized as follows: Section 2 outlines the two-step simulation framework for modeling crisis propagation and organizational capacity utilization. Section 3 presents an exemplary case study evaluating authority performance during a multi-hazard heat-drought crisis. Section 4 summarizes key findings, addresses implementation challenges, and outlines future developments.

2 Simulation framework

The use of simulation tools to model and analyze the system resilience for various extreme scenarios constitutes a central methodological approach across numerous sectors of critical infrastructure. Simulations enable the representation of complex system behavior under disruptive conditions, facilitate the identification of interdependencies, and allow for the systematic investigation of potential system responses under varying external influences Ouyang (2014).

In this work, the simulation approach consists of two steps. First, a network-based cascade modeling is employed to depict the direct effects of the extreme event on the administration under study as well as its consequences for the region under the authority's responsibility, especially regarding disturbances of critical infrastructures. Such disruptions can lead to severe consequences with significant impact on the society Brown et al. (2017), e.g. lost communication or power services, putting heavy pressure on public administrations to repair and mitigate them. Second, a process-based model of the administrations under consideration is used to analyze the consequences of direct damages and increased workload caused by the extreme event. The model provides a prediction of the time-dependent resource utilization and allows to quantify the effects of mitigation measures implemented to prevent organization overload.

2.1 Modeling of Crisis Effects

In context of the simulative assessment and quantification of the resilience of critical infrastructures against extreme event numerous qualitative, semi-quantitative and quantitative methods exist, e.g., graph-based, empirical, or agent-based models. To simulate the direct effects of severe events this work employs the CaESAR (Cascading Effects Simulation in urban Areas to assess and increase Resilience) framework Srivastava et al. (2024, 2022); Finger et al. (2017). This simulation tool is highly suitable for computing cascading effects within potentially heterogeneous systems and especially across system borders to cover the effects of interdependencies. Within CaESAR, the system under investigation is represented as a network consisting of nodes and edges. Nodes correspond to relevant system components, while edges capture physical as well as causal dependencies between them. Nodes (and edges) can fail by direct impact through an event or indirectly through their connections Ouyang (2014). When nodes or edges in the model network are disrupted, CaESAR computes how these disturbances propagate through the network, thereby simulating cascading effects.

In consequence, CaESAR allows to resolve the system resilience over time. After the crisis event impinges on the interdependent system elements, it may provoke direct effects leading to subsequent damage propagation. After applying the cascading effects within the system, the full impact on the system processes is given and the system

loses functionality. Cascading can happen time-delayed, such that the system reaches the state of lowest functionality, with respect to the given damage event, maybe not immediately but only after some time. Besides the damage cascading, CaESAR also simulates the restoration of the system. Here, it is assumed that all system components have a certain repair time that needs to pass after being damaged before the functionality is restored. These processes take part until the system is fully functional again. Based on this evolution, CaESAR evaluates the impact on the system over time. This simulation can be performed for varying crisis severity and can include or ignore relevant damage mitigation strategies so that numerous different scenarios can be considered and compared.

2.2 Administration process modeling

The process model is implemented as modular simulation pipeline, see Fig. 1, that translates structural agency information into performance and resilience metrics, e.g., the time-resolved availability of relevant resources. The response behavior of the considered authorities on the effects of relevant crisis, see Sec. 2.1, is modeled using the Python-based discrete-event simulation library simpy. The approach is based on a systematic identification of several authority characteristics including:

- Official responsibilities of public authorities;
- (Inter)dependencies with other authorities;
- Available institutional resources;
- Potential measures for improving preparedness and response capacity.

To respect the relevance of inter-agency interactions, the investigated network of public administrations is implemented as a class that collects all relevant organizations with their distinctive resource pools and interdependencies. It is possible to initialize multiple agency instances of the same type, e.g., several fire brigades, simultaneously. Organizations are able to interact autonomously with their available resources. Consequently, organization-specific functions can be implemented to model responses to internal states, such as the availability of personnel within a particular category, as well as to external conditions, including the operational status of other organizations. In addition, interactions and dependencies between different authorities and emergency response organizations can be represented within the model. Besides durable resources, like vehicles or personnel, consumable materials can also be covered by defining rules for their replenishment. This resource category aggregates all goods that are subject to wear, depletion, or replacement over time and therefore need to be replenished after operations. The level of detail can be adjusted as needed. For instance, specific critical consumables may be identified and modeled individually in order to simulate their availability and potential shortages in greater detail.

Once an organization is generated within the model, an initial stock level is specified for each of its resources. Resource quantities can be adjusted over time to represent changes in operational capacity, such as varying availability of personnel or the destruction of vehicles during the simulated scenario. The replenishment of consumable supplies can be implemented, for example, through a dedicated function that increases the available stock by a predefined amount during each simulation step. The

replenishment rate is determined by input parameters and can therefore be adjusted to reflect different logistical capacities or supply conditions. Once a predefined maximum stock level has been reached, no further replenishment is carried out, ensuring that resource inventories remain bounded and consistent with realistic storage or procurement constraints. This approach enables the simulation of continuous supply processes while accounting for practical limitations in resource availability and storage capacity.

Once the organizations, their interdependencies and resources are set up, a comprehensive catalogue of missions and tasks can be defined by analyzing the different responsibilities for the scenario under consideration. Figure 1 illustrates at the bottom the fundamental logic underlying each mission type. At first, the incident, leading to the triggering of a certain mission, is reported, i.e., the organization needs to detect that some task needs to be done. To fulfill its duties, the organization assigns the necessary resources to the task, those resources are then occupied and only become available again once the task is completed (assuming they are not consumables). By applying this common structure, different types of operations can be represented in a consistent manner while still accounting for the specific responsibilities, capabilities, and resource requirements of the respective organizations. Besides missions and tasks arising from the crisis scenario, it is also possible to define a baseline operational load by collecting routine tasks and missions, e.g., normally occurring building fires that occupy fire brigade capacities. This baseline is relevant to correctly estimate authority capacities that cannot be expected to contribute to crisis management, i.e., it might happen that some organization is already fully occupied by its regular tasks so that any major crisis directly overwhelms it.

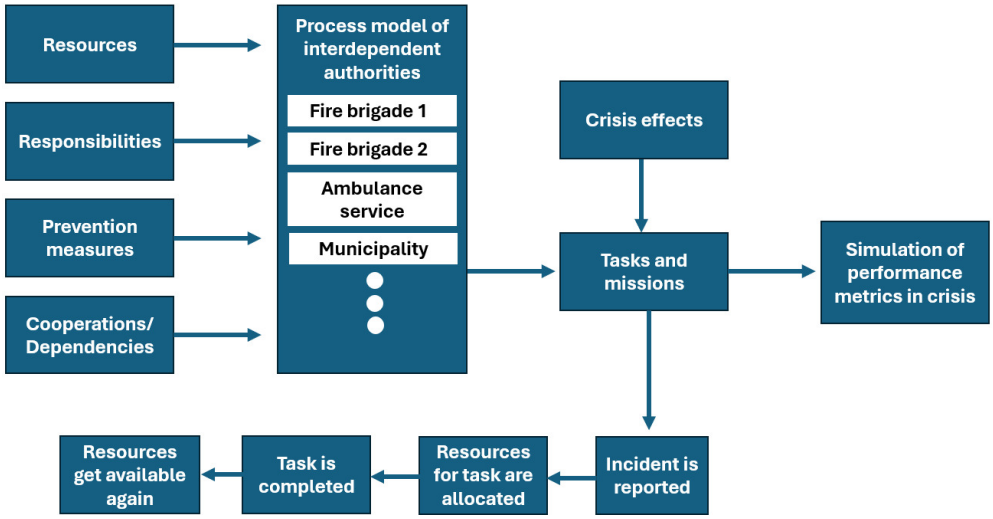


Fig. 1: Visualization of the process modeling approach and the processing of missions and tasks. Depending on the characteristics and requirements of a specific mission type, additional intermediate process steps may be included.

Besides investigating the direct crisis management, the model also covers crisis preparation measures. Those measures are incorporated into the simulation through a structured scoring approach. At this point it is assumed that each measure is assigned to one of three functional categories:

- attenuation: reduction of tasks generated by the crisis aspect targeted by the prevention measure;
- acceleration: missions/tasks are finished faster;
- efficiency: less resources are needed per task.

For each measure k, an "implementation quality score" s_k between 0 (absent or poorly implemented) and 10 (optimal) is specified. Then, a relative weight n_k is assigned, this number describes how relevant measure k is compared to all other measures targeting the same crisis aspect i. The selection of measures, as well as the assignment of implementation quality scores and relevance weights, should be based on structured input from practitioners familiar with the respective organization and crisis context. These inputs are therefore treated as expert-informed model parameters rather than objectively measured values. The $[0:10]$ score is a deliberately simple and arbitrary semi-quantitative scale chosen to transfer qualitative judgments ("good" or "bad") into numerical values. To avoid double counting, candidate measures should be reviewed for conceptual and operational overlap before they are included in the model. Measures that address the same underlying capability may be merged, distinguished more clearly, or their dependencies documented explicitly. Disagreements of practitioners about the appropriate score or relevance of a measure may provide valuable alternative parameterizations for sensitivity analyses. Self-assessment bias remains a potential limitation, particularly when practitioners assess measures implemented within their own organization. To mitigate this risk, elicited scores and weights should be checked wherever possible against documentary and operational evidence. In any case, the resulting scores and weights should be interpreted as context-specific scenario assumptions rather than exact empirical measurements.

Fig. 2 show an exemplary selection of preparation measures, their scores and their weights as they can be be found in the current version of the graphical user interface (see section 4). For crisis aspect i, the weighted mean implementation score is then defined as

$$\bar{s}_i = \frac{\sum_k n_k \, s_k}{\sum_k n_k}, \tag{1}$$

For each affected parameter type p (mission frequency, task duration, or resource demand), a maximum achievable relative reduction $\rho_{i,p} \in [0,1]$ is specified. The preparedness modifier is then calculated as

$$m_{i,p} = 1 - \rho_{i,p} \left(\frac{\bar{s}_i}{10} \right), \tag{2}$$

and the respective baseline parameter $x_{i,p,0}$ is transformed according to

$$x_{i,p} = m_{i,p} \, x_{i,p,0}. \tag{3}$$

This formulation allows the influence of preparedness to be calibrated separately for each parameter type. A broad range of heterogeneous preventive measures, such as public heat awareness campaigns, drinking water conservation strategies, forest fire early detection systems, or evacuation planning during a heat wave (see below), can be incorporated in a generalized and computationally tractable manner. Although the current formulation retains a common functional form for $m_{i,p}$, parameter-specific values of $\rho_{i,p}$ allow the effect sizes for attenuation, acceleration, and efficiency to be calibrated independently. The development of fully distinct functional forms for $m_{i,p}$ is, if it turns out to be needed, left for future work.

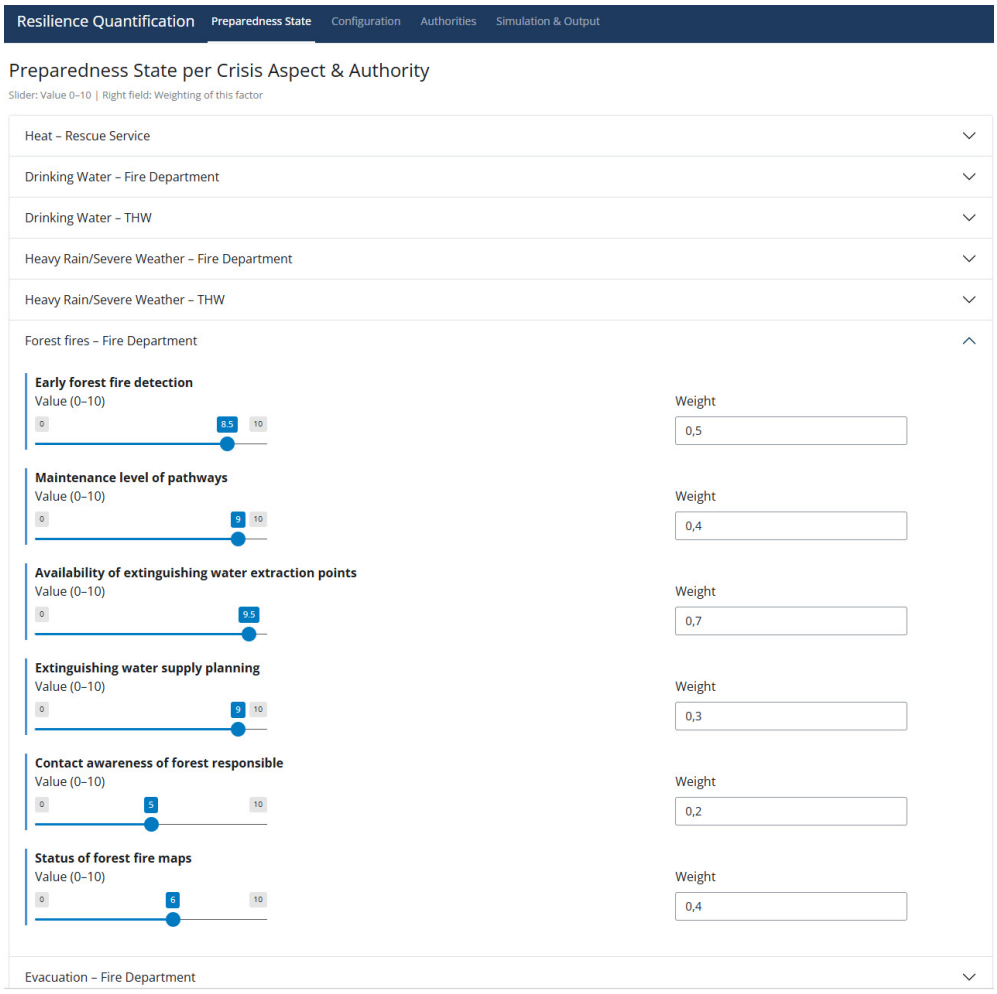


Fig. 2: Example of the graphical user interface for process modeling, showing crisis preparation measures intended to accelerate forest fire extinguishing by the fire brigade. The scores and weights are set for illustrative purposes.

To conclude this section, it should be noted that the approach is designed to be extensible. Additional authorities, system components, and scenario aspects can be integrated as soon as they are identified as relevant. This ensures that the model remains adaptable and capable of capturing the complexity of real-world disaster management systems.

3 Application

Having specified the modeling approach, this section presents an exemplary application to a heat-drought crisis affecting a network of public authorities and emergency response organizations.

3.1 Heat–Drought Crisis

To support its work, the XXX project (project anonymised for draft submission) developed a prolonged heat–drought crisis scenario in a German context. In the following, this scenario is used to illustrate the application of the modeling procedure introduced above. The scenario is largely synthetic and should not be interpreted as a forecast. However, it is informed by past observations, including events associated with the heatwaves and droughts of 2003 and 2018. Additionally, reports on German forest fires in the years 2018 and 2022 were included as data sources Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (o.D.). Using all this information, the heat drought crisis was set to span a substantial period of time, reaching from March until October, see Fig. 4. A monthly granularity was adopted for the event chronology.

Taking into account the responsibilities of the authorities considered (see below), the following aspects of the heat-drought crises were examined in the modeling of this paper:

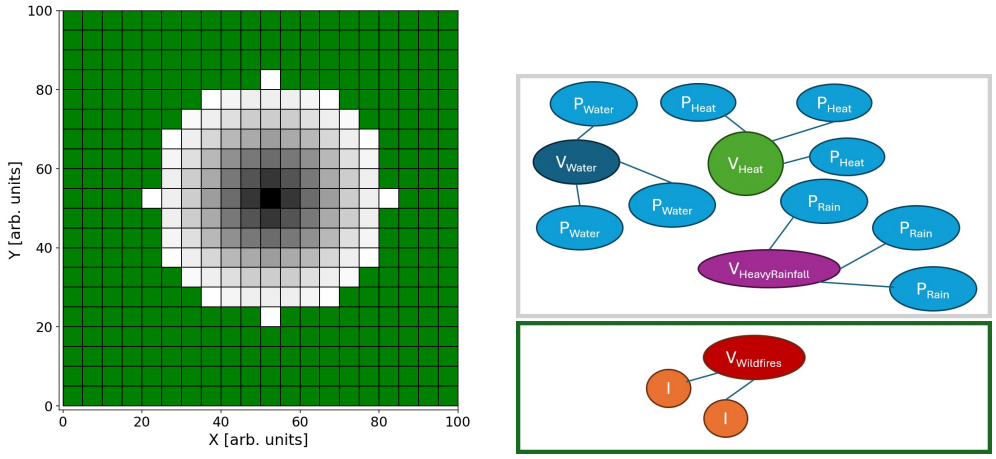
- The occurrence of forest fires in two periods (mid March to early may and mid June to early September);
- One prolonged period of extreme heat leading to an increased incidence of medical emergencies (early June to early August);
- One period of disruptions and shortages in drinking water supply (mid July to early October);
- One period of heavy rainfall events towards the end of the scenario, potentially causing flooding (early September to mid October).

In a first step, the effects of these crisis aspects on an exemplary model region were simulated based on the framework introduced in Sec. 2.1.

3.2 Simulating the effects of the heat-drought crisis

Ideally, the simulation (or any other alternative estimation) of the effects of the crisis under investigation can be designed in a scalable manner, allowing for the representation of both low-intensity and high-intensity scenarios. Such scalability enables the systematic mapping of different development pathways and contributes to a semi-automated quantification of resilience. In this work, the CaESAR framework, see

Sec. 2.1, is applied since it provides these scalability capabilities. The crisis aspects defined above are assessed for a prototypical model city, see Fig. 3a, which exhibits vulnerabilities against all of them.



(a) Spatial layout and population density

(b) Exemplary node structure

Fig. 3: Model city with a densely populated urban core surrounded by a forested area. a) Model city (white/grey) with a forested surrounding area (green). x and y coordinates are given in arbitrary units. The shading of the white areas represents the population density of the settlement zones, with a densely populated urban core and more sparsely populated peripheral areas. b) Node and dependency structure within the CaESAR model network for an exemplary city (top) and forest cell (bottom) of a), where P = Population, V = Vulnerability, I = Infrastructure Building in the forest. For each City Cell (grey) there is a node (V_{Heat}, V_{Water}, $V_{heavyrainfall}$) at which, depending on the population density, between 2 and 25 nodes P_i are attached. For each Forest Cell (green), there is a '$V_{wildfire}$' node to which between 0 and 3 'local infrastructure' nodes are attached.

The model city consists of settlements zones (white cells in Fig. 3a), it is assumed that the population density increases to the center. The city is surrounded by forests (green cells in in Fig. 3a) that are prone to fires during a heat-drought crisis. Traffic networks connecting the city to the surrounding are not depicted since, e.g., road blockage due to wildfires are not considered in the exemplary calculations of this work. Based on the cells of the model city, the CaESAR network is defined as follows.

For each urban grid cell, a node representing the population's vulnerability to extreme heat was introduced, see Fig. 3b. To each of these nodes, "population nodes" were attached, scaled proportionally to the local population density, ranging from 25 in the city center to 2 in peripheral areas, following a linear decrease. These population nodes are connected to their respective parent nodes via network edges. In a

similar manner, to each urban grid cell a node representing the vulnerability to disruptions in drinking water supply was assigned. Again, population nodes proportional to the population density were attached to these nodes. Furthermore, following the same principle as described above, a node representing vulnerability to heavy rainfall events was defined for each urban grid cell. We note that the assumed direct relationship between population density and vulnerability to the scenario effects is a simplifying assumption. When applying the approach to real urban environments, additional factors, such as district-specific heat vulnerability, should also be considered.

For each forest grid cell, a node representing the vulnerability to wildfires was introduced. These nodes, whose number depends on their proximity to the urban area, were linked to "infrastructure nodes", representing buildings that can be found in the forest. Their number ranged from 3 near the city boundary to 0 at greater distances, again with a linear decrease. An example is shown in Figure 3b.

Besides the definition of the network model, CaESAR requires the specification of the disturbance events. Based on the temporal structure of xxx's (project anonymised for draft submission) heat–drought scenario, those disruptions were defined for predetermined time intervals:

1. At the onset of the severe heatwave causing medical emergencies, all urban nodes representing heat vulnerability are damaged for a duration of 3.5 months. The resulting impacts cascade to the associated population nodes
2. With the emergence of disruptions in the drinking water supply, a defined percentage (10 % in the example results shown in Fig. 4) of the corresponding urban nodes is damaged for a duration of 1.5 months.
3. At the onset of heavy rainfall events, a percentage (2 % in the example results shown in Fig. 4) of the relevant urban nodes is damaged per simulation time step. Each affected node is subsequently protected from further disruption for a period of one week.
4. During two forest fire phases, a percentage (2 % in the example results shown in Fig. 4) of the forest nodes is damaged per simulation time step (representing wildfire ignition). The resulting impacts cascade to the dependent infrastructure nodes that need to be evacuated due to the forest fire.

All concrete numbers are set for illustrative purpose and should not be understood as any type of prognosis or forecast. While the scenario consequences are represented in a simplified manner, both the severity and the impacts of each disturbance can be adjusted sufficiently to generate a range of internally consistent stress-test scenarios. Figure 4 presents the aggregated results of the simulation, illustrating the percentage of undamaged network nodes over time. For this aggregation, all network nodes were assigned equal weight. The simulation is conducted with a temporal resolution of one hour and covers the period from March to October. The different phases of the scenario are highlighted through color-coded markers: red indicates the start of the two forest fire phases, green marks the onset of the severe heatwave leading to medical emergencies, blue represents emerging disruptions in drinking water supply, and purple corresponds to heavy rainfall. The results show an escalation in the second half of the

simulation period. This intensification is primarily driven by the concurrent occurrence of multiple crisis aspects, leading to overlapping disturbances.

Please note that model city and disturbance schedules are deliberately synthetic. Percentages of damaged nodes, event durations, and mission-trigger coefficients (see below) were selected to create a plausible stress test rather than to reproduce a historical event. Consequently, resulting absolute mission counts and resource shortages must not be interpreted as forecasts for any specific municipality. The case study is used to test model logic, identify bottleneck mechanisms, and illustrate sensitivity to assumptions. Empirical application requires local calibration against incident statistics, deployment records, staffing schedules, infrastructure data, and structured expert elicitation

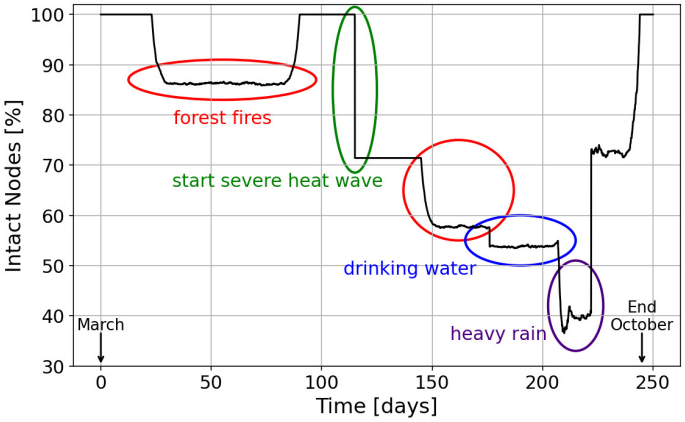


Fig. 4: Result of the CaESAR simulation for the city model. The colored ellipses indicate the effects of the different crisis aspects. The simulation time step is one hour.

Based on this (scalable) representation of the effects of the heat-drought crisis, the next section investigates the subsequent modeling of public administrations following the approach described in Sec. 2.2.

3.3 Authority process model

The network of public authorities that needs to solve tasks associated with the heat-drought crisis modeled above consists of

- One fire brigade
- One ambulance service
- The German THW (Federal Agency for Technical Relief) and
- The German BBK (Federal Office of Civil Protection and Disaster Assistance).

While the first three authorities represent organizations for direct emergency response, the BBK is only indirectly involved into overcoming the challenges posed by the crisis.

To parametrize the process model version of the different organizations, the practitioners of XXX (project anonymised for draft submission), the fire brigade of the city of Dortmund (FwDo), the THW, and the BBK, populated structured tables documenting agency-specific tasks (differentiated into prevention and response phases), relevant resources, and potential improvement measures for the heat-drought crisis. This initial data collection was augmented with other sources circulating within the organizations which was useful to harmonize nomenclature and task definitions with already existing conventions. FwDo provided vehicle inventories as well as the official fire protection and emergency medical services demand plans for Dortmund. Those sources were used to parametrize the fire brigade and the ambulance service. THW referenced publicly available documentation [1] on its specialist units, including planned personnel strengths and assigned equipment and was used to parametrize the THW in the model. Tab. 1 provides an overview over the collected data.

Table 1: Information on the inputs used to parameterize the organization-specific process models.

Model input	**Information type**	**Source**	**Providing organization**	**Comment**
Prevention and response tasks	List/Definition	Practitioner elicitation, organizational documentation	FwDo, THW, BBK	Dependent on the completeness/validity of documentation.
Relevant resources	List + Numbers/value ranges	Practitioner elicitation, organizational inventory lists	FwDo, THW, BBK (partly)	Actual availability may vary over time.
Potential improvement measures	List/definition	Practitioner elicitation	FwDo, THW, BBK	Assessments reflect personal perspectives and scenario-specific assumptions

Using this data collection and these sources, authority-specific resource lists were constructed. Due to the length of the complete list, only an overview is provided here; the full information is available in the Supplementary Information (SI). For the fire department, 27 different resources were identified, including, e.g., fire-fighting vehicles and different types of personnel. For the ambulance service, 17 resources were identified, including ambulance vehicles, paramedics and emergency doctors. For the THW, 86 different resources were identified. This comparatively large number reflects the fact that the THW is equipped to respond to a wide range of crises, i.e., it has to be more versatile than, for example, an ambulance service. The BBK was assigned

[1] https://www.thw.de/DE/Im-Einsatz/Einheiten-Fachgruppen/Einheiten-Inland/einheiten-inland_node.html

5 resources, each one of them corresponding to one internal functional areas that solves certain tasks in case of a heat-drought crisis. Again, it should be noted that the BBK does not directly intervene in the model city shown in Fig. 3a; rather, it will support local crisis management by processing data, informing the population and by the coordination of resources if needed to support local crisis management.

For fire brigade, ambulance service and THW, consumable materials are modeled as a single aggregated resource (per organisation) that depletes during missions and is replenished at configurable rates up to a defined maximum. Two proof-of-concept autonomous organizational behaviors have been implemented: the aforementioned automatic replenishment of consumables with fixed rates, and automatic requisition of auxiliary personnel by the BBK when the free capacities of a given type of personnel falls below a defined threshold. The latter process includes a configurable activation delay as well as an effectiveness parameter indicating how many auxiliary forces are needed to replace one regular staff member.

Also based on the data collection and sources, crisis-specific mission types as well as routine tasks and mission were derived for each organization. Again, only an overview is given here; the full information is available in the Supplementary Information (SI). For the fire department, the resources needed per missions follow primarily a "vehicles + crew" logic, derived from staffing conventions. For example, fire fighting vehicles are expected to be crewed by six firefighters while command vehicles only by two. In total, twelve mission types were defined, including generic ones like the deployment of a firefighting or a turntable ladder vehicle and crisis-specific ones, especially in context of the drinking water disturbances. For the ambulance service, eight mission types were defined, for example the deployment of an ambulance vehicle. Regarding the THW, it was assumed that the deployment of each of the 42 specialist units represents a natural definition of THW tasks. Only one generic task depicting the deployment of THW personnel and one transportation vehicle was added to reflect missions outside the specialist unit logic. For BBK, five task types were defined, each representing the deployment of one worker of the different personnel types.

Preventive measures have been defined for all crisis aspects considered. For heat-wave related ambulance service demand, measures include public awareness campaigns, preparation of social care facilities or the provision of cooling facilities. It is worth noting that the responsibilities for such preventive measures lie with municipal health and planning authorities. The ambulance service itself has barely any influence on the preparation level of the local population regarding heat waves, highlighting the interconnected nature of public authorities. Nevertheless, a resilient ambulance service must be able to operate effectively under prevailing conditions; preparedness measures beyond its direct control should therefore also be considered. For drinking water supply failures, measures include water conservation and climate adaptation effectiveness, again measures that are not under direct control of, e.g., fire brigade or THW. For storm and heavy precipitation events, measures address operational training effectiveness and road network condition. For wildfire scenarios, measures include early detection systems, access road condition, firefighting water availability, evacuation planning, and familiarity with forest management contacts. Here, the direct influence of the fire brigade on the measures is relatively high, compared to the other crisis

aspects. For the BBK, given that it is not directly responsible for hands-on disaster mitigation, an own set of preventive measures was defined. They address coordination efficiency and availability of technical support tools.

Having defined the public authorities with their resources, missions/tasks and relevant prevention measures, it is now possible to simulate the authories' behavior for the heat-drought scenario.

3.4 Simulation of authority performance

The time evolution of the heat-drought crisis visualized by Fig. 4 was translated into time-varying mission generation rates for each organization. To do so, the number of affected network nodes representing the vulnerabilities regarding the different crisis aspects are counted per timestep and further processed as follows.

To get the time-dependent number of heat wave related ambulance service missions $n_H(t)$, the number of affected network nodes for the heat wave $N_H(t)$ was multiplied by a (configurable) base trigger rate g_H and the corresponding prevention factor m_H yielding

$$n_H(t) = N_H(t) \cdot g_H \cdot m_H \tag{4}$$

Each generated mission starts with the emergency call processing at the dispatch center. Subsequently, the ambulance service mission is executed, consisting of the deployment of one ambulance vehicle and two paramedics. In some cases (defined by the probability p_{doctor}) the mission also includes the deployment of an emergency doctor (including the appropriate vehicle).

Disturbances of the drinking water supply leads to tasks for THW, i.e., the deployment of suitable specialist units, that are supported by missions for the fire brigade, contributing some vehicles for transportation tasks and workforce. The number of missions per timestep $n_D(t)$ is determined via

$$n_D(t) = N_D(t) \cdot g_D \cdot m_D \tag{5}$$

with a similar logic as for the heat wave crisis aspect, i.e. $N_D(t)$ corresponds to the number of drinking water nodes, g_D to the trigger rate for the drinking water related tasks and m_D to the prevention factor for drinking water disturbance.

The number of tasks to be sorted out in context of heavy rain were directly linked to the number of effected network nodes per time step, i.e., $n_R(t) = N_R(t)$. The tasks were attributed to the fire brigade and THW since they encompass topics like pumping, clearing of streets or emergency power supply. Forest fire missions $n_F(t)$ were also directly linked to the affected network nodes $N_F(t)$ shown in Fig. 4, i.e., $n_F(t) = N_F(t)$. They represent firefighting and evacuation deployments of the fire brigade, supported by THW. For those deployments, an interdependent workflow between the fire brigade and THW was implemented: after allocating its own required resources, the fire brigade initiates a THW support mission and can execute its task only once the THW has also provided all required resources. The duration of heavy rain and forest fire missions depended on the preparations states against those crisis aspects, i.e., $m_{HR,THW/FB}$ and $m_{FF,THW/FB}$.

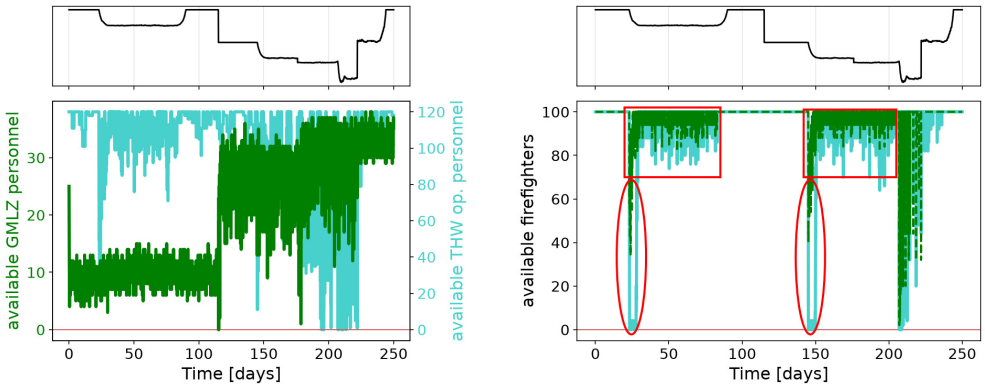
Tasks for the BBK are generated in proportion to the current level of network damage across all crisis aspects. Configurable probability distributions determine how these tasks are assigned to different personnel types depending on the affected crisis aspect. This approach assumes that local scenario severity can be approximated by the workload imposed on the supra-local BBK. While useful for modelling purposes, this remains a deliberate abstraction.

Besides the tasks evoked by the heat-drought crisis, the simulation also considered the baseline operation load of the different authorities, i.e., the usual business of the different organizations. For the ambulance services, those tasks encompassed the treatment of regular medical emergencies and the fire brigade needed to extinguish regularly appearing fires. For THW, it was assumed that specialist units are randomly deployed, unrelated to the heat-drought scenario and for BBK it was assumed that there is a basic workload for all different personnel types.

The exactly used parameters can be found in the Supplementary Information (SI). Based on all these definitions, single simulation trajectories can be constructed. Primary outputs of the simulation are time series of available resources and queued (unserviceable) mission requests per timestep. Results of the exemplary simulation of the heat drought crisis demonstrate differential capacity utilization across organizations and resource categories. For example, the BBK uses the possibility for auxiliary personnel requisition to successfully buffer peak demand during the heat wave and the phase with drinking water problems in the "Joint Reporting and Situation Center" (GMLZ), see Fig 5a. As another example, THW operational personnel exhibit compound overload in the later stage of the scenario arising from the simultaneous occurrence of the second wildfire phase, drinking water problems, and heavy rain events. To exemplarily illustrate the connection between the organizational setup, its preparation state, the severity of the crisis and the simulated authority performance, Fig. 5b shows the availability of firefighters of the fire brigade for two different simulations. Note that the baseline operational load of the fire brigade was suppressed to simplify the interpretation of the graphs, the same graph including routine tasks can be found in the Supplementary Information (SI). The first simulation, shown in green, assumed "good" preparedness for forest fires. The corresponding implementation scores are listed in Tab. 6 of the SI under "F. Scenario-driven operations – Fire brigade" and "Forest-fire and evacuation operation." Under this assumption, tasks could be completed relatively quickly. The second simulation, shown in cyan, assumed "poor" preparedness. Here, all related implementation scores were set to 1. As a result, forest-fire missions required significantly more time. In consequence, firefighters are significantly more occupied once the preparation state is "poor". Bottlenecks in the number of available firefighters even occur at the beginning of the forest fire phases. For the phase of heavy rains, on the other hand, there are no differences between both simulations, reflecting that the preparation state against this crisis aspect was similar.

4 Conclusion and Outlook

This study introduced a modular proof-of-concept framework for translating baseline load and crisis effects into time-dependent workload and resource demand for



(a) Simulation results THW and BBK.

(b) Comparison good vs. bad preparation.

Fig. 5: Exemplary results of authority process modeling. The simulation time step is one hour. At the top, the plots show the evolution of the heat-drought crisis for comparison. Note that the maximal numbers for the different personnel categories were set arbitrarily and do not reflect any confidential organizational information. a) THW personnel (cyan) and BBK personnel of the "Joint Reporting and Situation Center" (GMLZ, green) show different patterns due to different responsibilities during the heat-drought crisis. b) The number of available firefighters is shown, once with a "good" preparation state for forest fires (green) and once with a "poor" preparation state (cyan). Red boxes indicate the time intervals of the forest fires, red ellipses indicate the capacity shortages at the start of those time intervals for a bad preparation. Note that the baseline operational load of the fire brigade was suppressed to highlight the connection between resource occupation and effects of the heat-drought crisis.

public authorities and emergency response organizations. The framework's principal output is operational performance – not yet a fully validated scalar resilience index – represented by resource availability, queue length, waiting time, and unmet mission demand. The approach relies on a structured collection of an organization's resources, responsibilities, and direct vulnerabilities to the crisis under study. Its main outputs are trajectories of available resources and queued, i.e., unserviceable, mission requests over time. The framework is intended for use by diverse public authorities, guided by domain experts familiar with both the simulation methodology and the organizational structures of the applying agency. In the synthetic heat-drought case, the model reproduces expected bottleneck mechanisms and shows how preparedness assumptions influence resource occupation. The results demonstrate methodological feasibility but do not establish empirical resilience estimates for a specific authority. The main limitations of the study are the synthetic scenario, partial calibration of mission-trigger rates and preparedness effects, limited representation of inter-agency decision rules, and only limited external validation. Future work should compare simulated outputs with historical deployment data, conduct global sensitivity and uncertainty analyses,

formalize decision-relevant resilience metrics, and evaluate whether the model supports real planning decisions in participating organizations

When applying the approach to organizations, clear and functionally appropriate definitions of resources and tasks are essential for each organization. A major challenge here is that public organizations cannot easily be generalized, since each has its own duties, expertise, structures, and conventions. While emergency response organizations show significant standardization, notably, different fire brigades tend to share highly similar characteristics, the same does not hold for other types of authorities. Thus, while the categories of data to collect (routine and crisis-related duties, expected load under routine and crisis operations, preparation measures, and resources) are similar across organizations, the resulting information, and consequently the specific model implementation for a given authority, remains highly case-dependent. This makes it particularly challenging to capture interfaces properly. While modeling a fire brigade or municipal administration in isolation may be straightforward, since each understands its own structure, capturing the interaction between them tends to be more complicated, as there is typically no standardization beyond legal obligations.

Another challenge for practical application of the approach is posed by the relatively large number of parameters and concepts that need to be understood. To support practical use by agency representatives without programming expertise, a browser-based graphical user interface (GUI) was developed using the Python shiny package, see Fig. 2. The GUI allows users to configure simulation parameters via sliders and input fields and to inspect output plots interactively. The intended application workflow encompasses scenario identification, task and resource profiling, prevention status assessment, and iterative simulation of varying scenario severity. Still, the current version of the GUI requires further development and testing with practitioners. Another potential long-term pathway involves partial substitution of methodological guidance by an AI-assisted support system.

Besides the question of enabling a proper application of the simulation framework, additional further development is planned including the integration of XXX's (project anonymised for draft submission) second scenario, a hybrid crisis, improving the definition of baseline operational load missions, improving the modeling of inter-agency resource sharing and dependencies and the extension to additional organizations like municipalities or the police. Additional points of interest are the integration of human factors such as fatigue and demoralization, as well as the inclusion of volunteer and spontaneous helpers. In addition, the evaluation of the simulation results needs to be extended to simplify its interpretation. This might include the formal definition of scalar resilience metrics such as maximum mission waiting time or cumulative time during which a critical resource falls below a defined threshold. Additionally, Monte Carlo setups comprising 100 or more independent runs can be executed to investigate the influence of stochastic model elements on the model results. In case such a Monte Carlo setup is investigated, the results can be aggregated as means and standard deviations across all runs. Sliding-window smoothing can be useful here to suppress noise without loss of substantive information.

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