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A Multi-Agent System to Improve the Resilience of Critical Infrastructure in Cross-Border Disasters

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Abstract: The course of natural disasters is hard to forecast. Especially, these events do not stop at man-made borders between countries. In order to achieve a high resilience, it is important to overcome language and culture barriers and thereby to fasten the information and capacity exchange. Hence, a scenario-based simulation of cross-border communication and cooperation in crisis management yields a high potential to analyze different trajectories of a crisis and to find strategies for fast and robust reactions. Thereby, it can lead to a significant improvement of the resilience in a cross-border region. To this purpose, the paper outlines the scope for an agent-based simulation of cross-border cooperation in the case of a power blackout. For selected scenarios, the simulation illustrates the dynamic evolution of the crisis where the failure of critical infrastructure together with people behavior directly affect the coping capacity of the health system. Taking an event-based perspective, it is possible to identify the root cause or first order effects of cascading failures which makes it possible to propose appropriate preventive measures. A second type of analysis refers to the interoperability of authorities. It can be analyzed how communication and coordination among actors of different nationalities can be improved such that delays in information flows are minimized. The mentioned multi-agent system is developed as part of the INCA-project, a decision framework for improving cross-border area resilience. Apart therefrom, the project comprises behavioral studies, expert interviews and workshops, which lead to a deeper understanding of the character of a cross-border area. By finding a robust strategy for the optimal intervention to dampen cascading effects in critical infrastructure and to minimize delays in information flows, the project aims to strengthen the resilience of the border region.

Keywords: Borderland Resilience; Critical Infrastructure; Cross-border Cooperation; Multi-Agent System

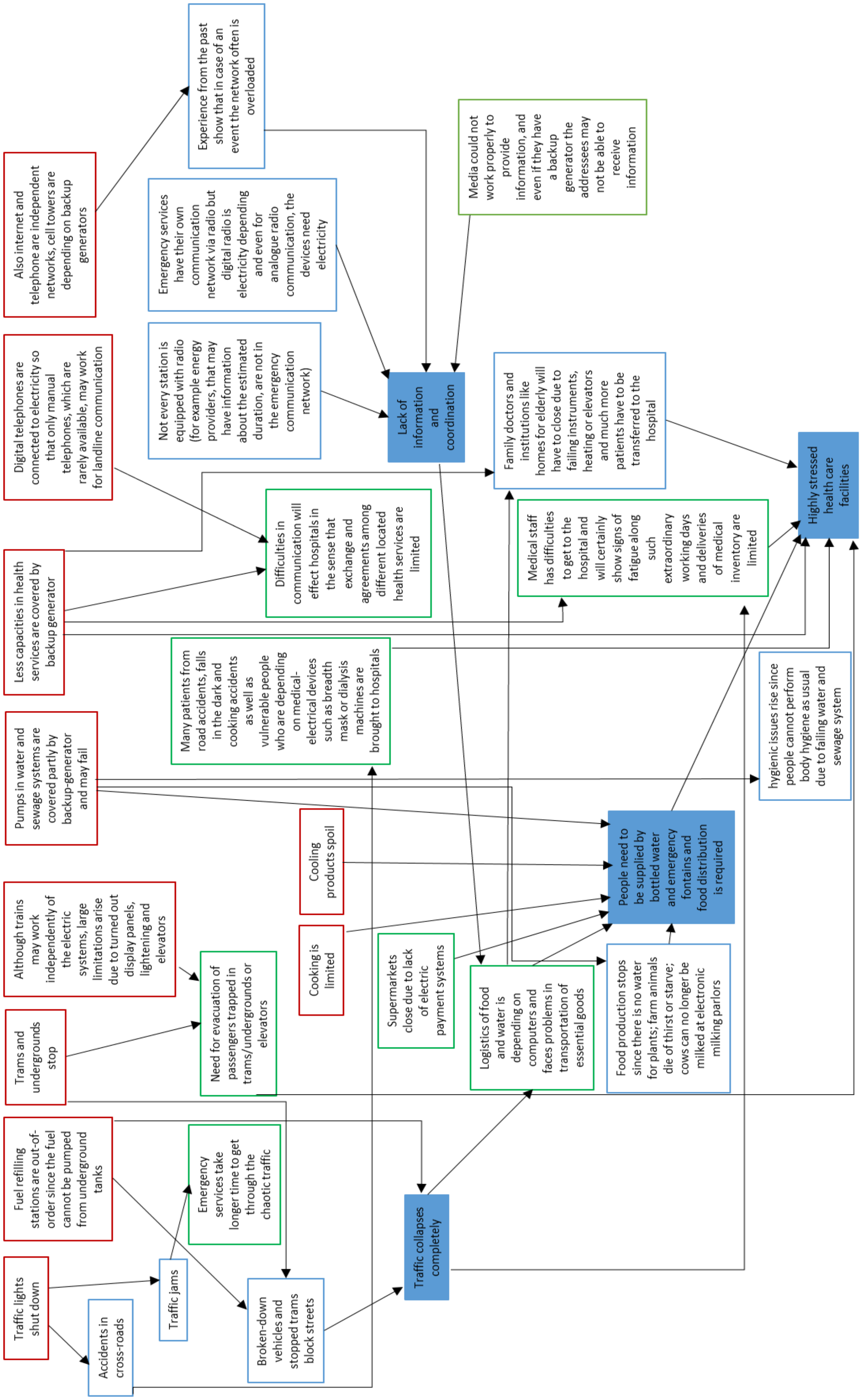
1. Introduction

Natural disasters have increased significantly in frequency and extent in recent years and especially, these events do not stop at man-made borders between countries. In addition, the world is becoming more interconnected, making it more susceptible to major disruptions. In particular, critical infrastructure failure or impairment would result in dramatic consequences having a large impact due to their major importance to the public sector (National Strategy for Critical Infrastructure Protection, Federal Republic of Germany 2009). A long-lasting power blackout might be an event with lower occurrence probability in Europe, but not an impossible event as seen in the power outages in Italy 2003 or in Germany 2006. If it happens, it is particularly disruptive since all areas of daily life are affected. Common cause, cascading and escalating failures will result and even worsen the situation since they affect all other parts of critical infrastructure within a short time period (Critical Infrastructure Interdependencies, Rinaldi et al. 2001). If a disaster occurs in a cross-border region, even more actors are involved and multiple organizations need to coordinate their procedures of response. Additionally, different languages and cultural backgrounds complicate the situation and may lead to failures. We detail the design of a multi-agent system to study these critical infrastructure failures and coordination difficulties in response. Such a model has the advantage that the identified problems can be simulated in different scenarios and robust solution suggestions can be derived at a relatively low cost. The purpose of the model is to derive general statements and identify factors of success about cross-border coordination issues in infrastructure failures that may apply in a similar way for different cross-border regions.

2. Critical infrastructure

Natural disasters have increased significantly in frequency and extent in recent years. Furthermore, today’s world is highly interconnected such that small disruptions in a system can escalate to large disruptions or even failures in the system or even cause cascading failures in other systems. First, we highlight in two examples how disruptions might lead to power blackouts to point out the relevance of the topic. As the focus of our study is on cross-border decision-making we selected two historic cases of power blackouts which impacted two neighboring countries: Both occurred in the year 2003, one in Italy due to disruptions in Switzerland and the other one in the border region of USA and Canada. In the first example, a domino effect of technical failures led ultimately to the separation of the Italian system from the rest of the European grid. The resulting 18 hours’ blackout affected 56,000,000 people (Power Blackout Risks, CRO Forum 2011). In the second example, “a combination of lack of maintenance, human error and equipment failures caused an outage” that affected a population of 50,000,000 for 4 days (Power Blackout Risks, CRO Forum 2011). Among others, there was a “failure to identify emergency conditions and communicate that status to neighboring systems” (Final Report on the August 14, 2003 Blackout in the United States and Canada, U.S.-Canada Power System Outage Task Force 2004).

Figure 1. (a) Cascading, escalation and common cause failures in interconnected critical infrastructure systems.



Traffic lights shut down
Accidents in cross-roads
Traffic jams
Fuel refilling stations are out-of-order since the fuel cannot be pumped from underground tanks
Emergency services take longer time to get through the chaotic traffic
Broken-down vehicles and stopped trams block streets
Traffic collapses completely
Trams and undergrounds stop
Although trains may work independently of the electric systems, large limitations arise due to turned out display panels, lightening and elevators
Need for evacuation of passengers trapped in trams/undergrounds or elevators
Cooking is limited
Cooling products spoil
Supermarkets close due to lack of electric payment systems
Logistics of food and water is depending on computers and faces problems in transportation of essential goods
Food production stops since there is no water for plants; farm animals die of thirst or starve; cows can no longer be milked at electronic milking parlors
People need to be supplied by bottled water and emergency fontains and food distribution is required
Pumps in water and sewage systems are covered partly by backup-generator and may fail
hygienic issues rise since people cannot perform body hygiene as usual due to failing water and sewage system
Many patients from road accidents, falls in the dark and cooking accidents as well as vulnerable people who are depending on medical-electrical devices such as breadth mask or dialysis machines are brought to hospitals
Less capacities in health services are covered by backup generator
Digital telephones are connected to electricity so that only manual telephones, which are rarely available, may work for landline communication
Difficulties in communication will effect hospitals in the sense that exchange and agreements among different located health services are limited
Medical staff has difficulties to get to the hospital and will certainly show signs of fatigue along such extraordinary working days and deliveries of medical inventory are limited
Family doctors and institutions like homes for elderly will have to close due to failing instruments, heating or elevators and much more patients have to be transferred to the hospital
Highly stressed health care facilities
Not every station is equipped with radio (for example energy providers, that may have information about the estimated duration, are not in the emergency communication network)
Lack of information and coordination
Emergency services have their own communication network via radio but digital radio is electricity depending and even for analogue radio communication, the devices need electricity
Also internet and telephone are independent networks, cell towers are depending on backup generators
Experience from the past show that in case of an event the network often is overloaded
Media could not work properly to provide information, and even if they have a backup generator the addressees may not be able to receive information

(b) Own representation, cf. Hiete et al. 2011, Lorenz 2010 (1)

As seen in the examples, major incidents can never be completely ruled out or avoided. In particular, the energy grid is closely linked across many national borders in Europe that are making it robust against frequency fluctuations in general. However, if disruptions occur, they affect a cross-border area more likely and can have a much greater impact than in separate systems. Hence, the scope of our research is to strengthen resilience of the affected community in case of a failure. We consider the health sector and the connected critical infrastructures having the highest impact on people's daily live as supply of food and water, traffic and transportation as well as information and telecommunication. The type of interconnectivity of the critical infrastructure failures are summarized in figure 1 by referring to the blackout in Germany in 2006 (Scenario-based impact analysis of a power outage on healthcare facilities in Germany, Hiete et al. 2011 and "Kritische Infrastrukturen aus Sicht der Bevölkerung", Lorenz 2010). Here, common cause failures are highlighted in red color, cascading failures are marked in blue and escalation failures got green color (cf. Rinaldi et al. 2001). As a natural disaster is hard to forecast and it is not completely known which of the mentioned critical infrastructure failures will occur, scenarios varying in time and extent of the failures are built. In urban areas, people are particularly affected since mobility is organized in a different way compared to rural areas: there is a higher use of trams and undergrounds, where people might be trapped in case of a power blackout. Additionally, there are more high-rise buildings with elevators or electric doors. In general, people living in urban areas have less storage of water and food due to smaller apartments and better availability (e.g. 24 opening hours of shops). Insurance claims after such an incident will be extreme, especially companies have high losses to be compensated.

3. Cross-border impact on communication and cooperation processes

Especially in the crisis response, many actors are active such that efficient coordination is required. In a cross-border context, even more actors are involved and cooperation among the countries is a key element for an efficient crisis recovery. Besides problems resulting from differences in language, organizational structures, standards of practice, regulations, etc. between the nations that need to be overcome, culture is another factor impacting the functioning of interoperability. Culture plays an important role for cross-border resilience as it has an impact on people's collective behavior (Challenges in Establishing Cross-Border Resilience, Adrot et al. 2018). According to Jacques, organizational culture is the "customary and traditional way of thinking and doing of things" (The Changing Culture of a Factory, Jacques 1952). Taking this as a starting point, scholars identified different cultural factors of variability (e.g., Cultures and Organizations: Software of the Mind, Hofstede et al. 2010, Riding the waves of culture, Trompenaars & Hampden-Turner 2012, The culture map. Decoding how people think, lead, and get things done across cultures, Meyer 2015).

In a crisis, there is no overall information available and the involved actors need to gain their set of information by communicating with others. However, as seen above, each message is interpreted in the context of the individual cultural background such that the personal attitude between sender and receiver of information is as much important as the knowledge about the other system to interpret the message in a right way and prevent misunderstandings. Additionally, one aspect in cross-cultural communication is trust in the received information, which is important in crisis management since increased trust prevents delays in information and fastens adequate actions.

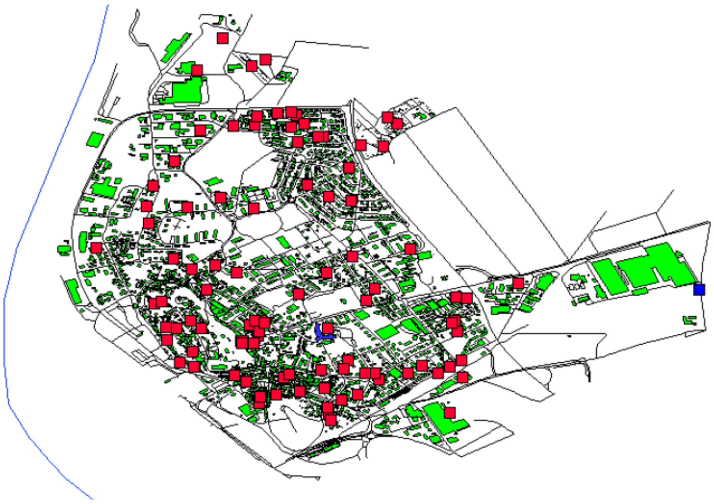
After we highlighted the important aspects in international crisis response to strengthen resilience, we will give insights on the realizations in a multi-agent system.

4. Agent-based modelling approach

Multi-agent systems are computational models, developed for the simulation of actions and interactions of autonomous agents in order to assess their behavioral impact on a particular system. There exist already various agent-based models which study disasters as the one by Joo et al. comparing various evacuation strategies for warehouses in the event of a fire (Agent-based simulation of affordance-based human behaviors in emergency evacuation, Joo et al. 2013) or the one by Crooks & Wise analyzing the Haiti earthquake of January 2010 by using crowdsourced GIS data (GIS and agent-based models for human assistance, Crooks & Wise 2013).
An "agent" is capable of carrying out flexible, autonomous actions in the artificial environment where it is located in order to meet its design objectives (Agent-Oriented Software Engineering, Jennings 1999). Hence, the approach is suitable to our purpose of modelling cross-border cooperation in the case of critical infrastructure failures for two reasons. First, the modeled environment can refer to any infrastructure system provided that the required data is available. Second, agent-based models are ideal tools if decentralized information transmission and the phenomenon of "emergence" play the central role in a dynamic decision-making context. It is straightforward that both aspects are highly relevant for rapidly evolving crisis situations where agents gain their set of information from their close environment and interoperability of organizations need to be improved to strengthen resilience. Our study aims to implement an appropriate communication procedure among several actors in crisis response and to measure the effect of personal attitude and trust in the received information in order to reduce misunderstandings and minimize delays in information flows. Therefore, we extend the models of communication from the literature by adding personal traits of the sender and the receiver of a message. In a network, we represent each agent by a node and connect two nodes by a weighted edge symbolizing the relationship of two agents (cf. Persistent parochialism: trust and exclusion in ethnic networks, Bowles & Gintis 2004). Furthermore, our communication model yields the possibility to equip each agent with a personal vector representing the "character" of the actor. Communication is simplified in a manner that the reliability of received information is higher the more similar the personal character traits of sender and receiver are. Differences can result in delayed information via misunderstandings and even lead to complete failure of communication. In order to quantify a "degree of similarity" in this context, the authors will apply the concept of "expected communication difficulty" defined by Bowles & Gintis (2004).

As mentioned above, the focus of this part is on an adequate provision of health services and essentials like food and water in the aftermath of a long-lasting power blackout. We are rather interested in the provision of resources than modeling the exact treatment of victims and procedures within a hospital. For our purpose, it is enough to model the time-depending capacities of a hospital in number of patients that can be treated and cared for. A natural environment of the agents is the road network of the affected region. Figure 2 shows a sample region. Here, the hospital is marked blue and one blue ambulance is placed left-hand side. The citizens are simulated as red squares moving in the streets. Vehicles can be implemented in the same way taking into consideration an additional variables of speed, available fuel in their tank or transported goods and passengers. Different road types as streets or highway may allow different speeds of the vehicles. Routing of ambulances and distribution routes for food and water supply due to closure of supermarkets as well as optimal positions for shelter can be calculated by considering blocked streets, which might be caused by stopped trams or accidents as a consequence of traffic light failures. Additionally, traffic jams can be simulated by limiting the capacities of the implemented roads, i.e. each section of the road can only be passed by a limited number of agents at a time. Based on the underlying dataset scenarios can be derived to find a robust routing strategy avoiding paths with high probability of failure.

Figure 2. (a) Sample region for transportation as critical infrastructure with underlying data of OpenStreetMaps.



(b) Own representation by using the Repast Simphony toolkit (2)

The figure shows the implementation of the road network; analogously one can implement the communication network or the energy grid in different layers. If one implements an appropriate connection between all the networks, the model will be able to simulate the interdependencies between the critical infrastructures, which is quite close to reality. By considering the energy grid in detail by assigning the frequency of the grid sections, the triggers of a power blackout could be analyzed and prevention measures could be deduced. The last mentioned aspects are interesting possible extensions, which are not the scope of the core research program of the INCA-project.

5. Summary and conclusions

The article outlined the design of a multi-agent system to strengthen resilience by studying the logistics of emergency supply and the underlying coordination in the aftermath of a cross-border power blackout. First, the relevance of the topic was highlighted by examples from the past. Afterwards, an overview of the health related critical infrastructure failures in case of a power blackout was presented with special considerations on urban areas. After discussing cultural impacts on cross-border cooperation, the realization of cross-border communication procedures in a multi-agent system was detailed. As a natural disaster may not be forecasted, a scenario-based approach is chosen to analyze different trajectories of a crisis and to find strategies for fast and robust reactions. The model faces a high level of abstraction since the strategic planning dimension to strengthen resilience is studied. The purpose of the model is to derive general statements and identify factors of success about cross-border coordination issues in infrastructure failures that may apply in a similar way to different cross-border regions. Nevertheless, each border region has its own specificities, e.g. there might be a cross-border culture (Adrot et al. 2018), such that the model needs to be complemented by cross-border trainings of the operation teams. The model has a very high degree of simplification in the first set-up. However, it is an ongoing work and the model will continuously be approached to the relevant properties of the real world.

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Conflict of Interest

State any potential conflicts of interest here or "The authors declare no conflict of interest"

No references for the short papers but hyperlinks within the text