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Understanding the impact of cascade effects of natural disasters on disaster relief operations

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ABSTRACT

This paper analyzes cascade effects of natural disasters and investigates their impact on relief operations with respect to critical infrastructure, in particular, the transport infrastructure, electricity and human health. Causal-Loop-Diagrams (CLDs) are generated in order to provide useful information for decision makers. CLDs clearly visualize cascade effects which enable one to identify non-linear critical feedback processes and to analyze the behavior of the considered system. In order to investigate if the identified behavior occurred in real-world cases, we apply the CLDs to concrete natural disaster events, the European flood of 2002 and the European heat wave of 2003. Independent of the type of disaster, it can be concluded that cascade effects negatively affect critical infrastructure. The impacts on disaster relief operations can be proven for the case of the flood of 2002. In case of the heat wave of 2003 some of the assumed interdependencies did not appear in that analysis. The analysis shows that cascade effects and interdependencies between the different sectors of critical infrastructure can be visualized by the presented CLDs and are of high importance in order to understand their impact on disaster relief operations.

1. Introduction

Natural disaster events constitute a risk to critical infrastructure [23]. The existence of interdependencies within the different sectors of the critical infrastructure is the reason for systemic failures [5]. These challenges and their amplification due to the cascading nature of disaster events affect decision makers across various types of relief operations. Cascade effects refer to “a sequence of events in which each produces the circumstances necessary for the initiation of the next” [1]. Due to the fact that climate change may increase the impact of natural disasters in the future [11], understanding of cascading influences and interdependencies is crucial to the effective management of relief operations. In order to deepen understanding and aid relief operations, we generate Causal-Loop-Diagrams (CLDs) to illustrate the impact of cascade effects on critical infrastructure, in particular, the transport infrastructure, electricity and human health, in the context of natural disasters. A literature review was conducted to identify the underlying systemic structure. Through the created CLDs, cascade effects are presented in a clear manner to facilitate a holistic view of cascades and interdependencies.

In order to investigate if the identified behavior occurs in the real world, we apply the developed CLDs to concrete disaster events. The European flood of 2002 and the European heat wave of 2003 are selected as case studies due to the fact that they are highly different in their characteristics. According to Tingsanchali [45], floods are one of the most significant disaster types worldwide. Floods cause high damages to property, while heat waves lead to a higher number of casualties. For example, floods alone accounted for an average annual loss of 3.8 billion USD under normalized values in Europe from 1970 to 2006 [2], while the total loss of human lives is estimated to 70,000 people during the European heat wave of 2003 [39]. Europe was struck again by a major flood and a heat wave in 2013, showing the importance of analyzing these types of events to enable more effective response operations in the future. We generated CLDs to visualize cascade effects and occurring interdependencies with focus on critical infrastructure. To investigate if the identified behavior, illustrated by the CLDs, occurs in real-world cases we applied the CLDs to the European flood of 2002 and the European heat wave of 2003.

The remainder of the paper is structured as follows: Section 2 outlines the necessity of systems thinking and provides a description of the System Dynamics (SD) approach with focus on CLDs. A description of the identified cascade effects on critical infrastructure is given and plotted in CLDs in Section 3. In Section 4, we analyze if the identified cascade effects of Section 3 occurred in the given case studies, the flood of 2002 and the heat wave of 2003. Section 5 concludes the findings and provides further possible research directions.

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2. The method of systems thinking

SD, first applied by [13], aims to show the behavior of systems characterized by complexity and interdependencies of the influencing variables. By establishing CLDs, it allows one to visualize the network of causes-and-effects that lies behind a system [28]. As model language, a simple symbolism is used. Arrows are drawn to describe cause-and-effect interactions. If this interaction is positive (negative), the arrows are supplemented by a "+" ("−") sign. CLDs can be either balancing or reinforcing. Reinforcing loops strengthen change, while balancing loops are self-correcting [44].

Systems thinking is a way of thinking and a language to describe and understand the power of interrelationships that form the behavior of the system [42]. This allows generating models to improve knowledge about the system's behavior [26]. The author points out that the world consists of an infinite number of cause-and-effect relationship chains. According to Vester [51], it is essential to step outside the system in order to reach a viewpoint that enables one to understand how the system behaves. For addressing complex issues, Vester [51] suggests using a cybernetic approach. This allows interconnected thinking. Bosch et al. [53] designed an approach for iterative learning processes. Based on a local and a global level, an Evolutionary Learning Laboratory (ELLab) and a Global Evolutionary Learning Laboratory (GELL) are presented and the authors conclude that the effectiveness of various organizations is strengthened through better understanding of interconnectivities and non-linear ways of thinking. These relationships and interconnectivities can be demonstrated by the CLD approach. For building CLDs, a high level of aggregation is required due to the objective of constructing a model for seeing the system from a wider view [26]. Helbing et al. [18] modeled cascading spreads of disasters due to causality networks. They discuss a semi-quantitative method based on causality chains. Peters et al. [31] investigate cascade effects and their complexity on a network based approach, illustrating the dynamics of disaster diffusion. Their model focuses on the time-dependent spreading of disasters in a quantitative way to identify the reliability of the network structures. In contrast we designed CLDs in order to investigate the influence of cascade effects on relief and to identify the system's behavior. The application of the CLDs to two real-world cases takes place in order to validate our CLDs. Laugé et al. [22] conduct expert surveys in order to identify and scale interdependencies between the sectors of critical infrastructure to discuss consequences of failures from a holistic point of view.

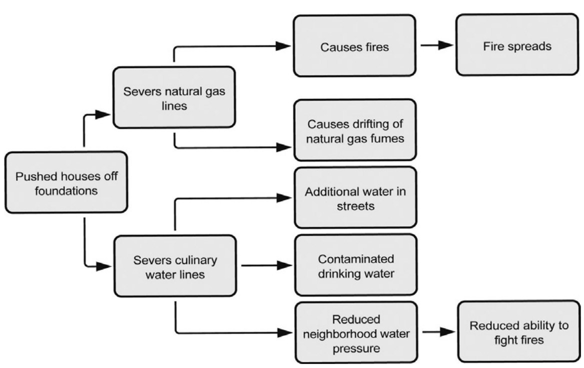

Fig. 1. Cascade effects [24].

The visual utility of CLDs is of great aid in the analysis of a system. In order to demonstrate this fact, we use the work of May [24] on cascade effects resulting from flash floods. The author uses hazard trees to illustrate the sequences of occurring cascades. An example of these hazard trees is shown in Fig. 1. It illustrates that if the flow impinges on structures, several consequences result, e.g., houses could be pushed off their foundations, which can lead to damaged gas and water lines, and if gas lines are severed, this may cause fires. An outline view of these causal sequences takes the form of a cascade tree. We created a CLD, shown in Fig. 2, to illustrate that visualizing the sequence of cascade effects and capturing interactions between these effects is possible. For example, the lack of water pressure reduces the possibility to fight fires, which influences their spread. Interdependencies between different cascade effects exist and can be shown with the method of CLD. It is possible to easily link additional variables into the diagram to visualize the occurring interconnections, e.g., if the drinking water is contaminated or gas fumes are drifting, more disaster management measures are required, and if more measures are conducted, fewer houses will be pushed off their foundations. This allows a holistic view of the studied disaster.

A limitation of CLDs is that they require a high level of abstraction. As a result, not all influencing variables are considered in CLDs. Due to this aggregation level, it is not possible to respect

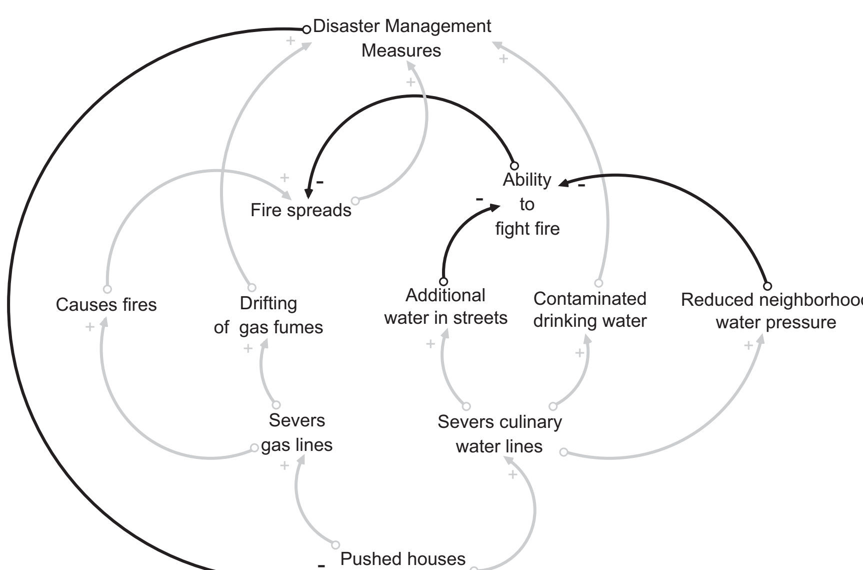

Fig. 2. Cascade effects as a CLD, based on [24].