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Cascades - Mapping the multi-disciplinary landscape in a post-pandemic world

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ABSTRACT

This paper introduces the Special Issue on *Cascading Effects in Disaster Risk Management*. It reviews the contributions and highlights their multi-disciplinary interpretations of cascades. It proceeds to discuss whether the on-going unfolding of the COVID-19 pandemic illustrates the cascades metaphor.

1. Understanding cascades

The cascading nature of disasters poses significant challenges to risk management emerging from the interconnectivity of natural, economic, and social systems that amplifies effects. Modern disasters increasingly tend to have domino effects: natural emergencies can rapidly develop into anthropogenic crises. The networked structure of the economy and society means that post-crisis equilibria are rarely stable. The Covid-19 pandemic is a case in point. This initially emerged as a public health issue that escalated into a pandemic creating an economic crisis, social disruption, and calls into question broader socio-economic trends, such as globalization, and the efficacy of supra-national structures such as the EU and the WHO. The integration of national economies and movement of people means that goods and services are increasingly mobile, and by extension, crises and disasters become more exportable. Cascades encompass a range of natural and human-induced hazards, including pandemics and anthropogenic emergencies such as financial fallouts.

The amplification of disaster outcomes that arises from the tight interconnectivity of natural, economic, and social systems is fertile ground for new exploration of theory, methods, and empirics of disaster risk science. In terms of theory, cascading disasters call for use of non-linear models, complex and adaptive systems to tackle the challenges of disasters with reciprocal and feedback loops. In terms of methods, cascading disasters demand approaches that distinguish between direct and indirect effects, first order and second order influences, identification threats and causality, along with capturing associative and fuzzy relationships. In terms of empirics, recent disasters have generated multiple opportunities for studying domino effects in a variety of interdisciplinary settings. These range from hazards engineering and planning through social and environmental sciences, public health, epidemiology and emergency medicine, and on to computational modelling and economics.

The cascading nature of disasters greatly complicates their analysis. For example, if an earthquake causes flooding, it is generally accepted that the cascading effect of these two disasters is a non-linear and exponential outcome far removed from the magnitude of the original shock [1]. This is because the sequential nature of the disaster (earthquake leads to flooding) adds a compound effect that is narrowly captured by the concurrence of both events at (essentially) the same time. Additionally, a multitude of other challenges exist when trying to capture the nature of cascades. These include incorporating recursivity as old events take on a new life becoming new events as they move forward in time [2], identifying the triggering or tipping point events that animate the cascades [3] and separating out cascades from multi-risk or multi-hazard events [4]. All of these challenges inject a measure of methodological ambiguity into the discussion of cascades and give rise to many competing conceptualizations.

This special issue aims to advance disaster risk management by showcasing a variety of multi-disciplinary approaches for describing and capturing the cascading effects in disaster science. Taken together, the compendium furthers the theoretical, methodological, and empirical grounding for capturing the cascade steeped in a rich and varied set of

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disciplinary moorings. They illustrate the use of a wide-ranging toolbox that includes both qualitative and quantitative approaches. The collection breaks new ground by illustrating how these different approaches can be harnessed to enhance practice in disaster risk management.

The contributions to this special issue originate from a scientific workshop on the topic of *Cascading Disasters: Theory, Methods, and Empirics* held at the Technion - Israel Institute of Technology, Haifa, in November 2018. This meeting was jointly sponsored by the Israeli National Knowledge and Research Center for Emergency Readiness, and the DIM2SEA research project at the Hebrew University of Jerusalem. It brought together leading experts from the fields of industrial management, physics, civil engineering, geography and environmental studies, transportation, urban planning, medicine and public health, public policy and management, and socio-economic modeling.

2. Interpreting cascades

While the interconnected nature of multiple natural hazards is not a new topic on the disaster management agenda (see for example [5]), the integration of physical and social systems poses significant challenges. Edward Lorenz's much acclaimed "butterfly effect" [6] essentially describes the cascading effects generated by random and non-linear actions in complex networks. The random events in a market in Wuhan, China have released a set of cascading consequences that have diffused across global networks.

Thus, cascades are inextricably interwoven with networks. Theoretically they should be predictable when a transmission break occurs in such networks. The paper by *Li* et al. investigates this claim. It emphasizes the interdependencies existing between networks which give rise to the so-called Networks of Networks (NON). This coupling of different systems only increases their vulnerability leading to a cascading escalation of failures from the initial power outage affecting an electricity grid to all of the networks that feed off it, such as water, transportation, energy and telecommunications. The many feedback loops between them amplify the cascade. Using the tools of statistical physics, they review the dynamics of cascading failures in inter-connected networks, the abrupt transitions imposed on them by exogenous shocks, and the percolation effects across networks given shocks of different critical values and networks of different sizes and typologies. The spatially embedded interdependent networks, such as the cascading effects of an earthquake on a power station, are a particularly interesting case. These locally-escalating shocks can cause substantially more damage than equivalent random shocks. Li et al. identify critical values of damage size radii for such shocks that are independent of the size of the network. These findings are particularly important for the protection of critical infrastructures and enabling networks of networks to function even with the collapse of a single system.

Ben Haim examines cascading failures in hierarchal networks from the perspective of info-gap theory. This draws from decision science and optimization to understand making choices under conditions of extreme uncertainty, for example predicting future returns on investments. Uncertainty exists with respect to the form of the modeled functional relationship and with respect to the parameter values that animate the relationship. In contrast to the Li et al. paper, the Ben Haim approach to cascades focuses on handling the uncertainty that makes these failures so damaging rather than on the generic attributes of cascading failures, such as network size, topology or behavior rules. The paper critiques conventional optimization techniques and presents an alternative for dealing with cascading failures in static networks grounded in testing the robustness of the decision making at each node in the hierarchy where the potential for cascading failure exists.

Menoni and Boni focus on data collection and analysis for cascading disaster management. They assess multiple incidents occurring across different scales, jurisdictions, and critical infrastructures, and address the lack of systematic collection of evidence essential for understanding how various risk factors, including hazards, exposure and vulnerabilities differentially contribute to diverse disaster events. The wrong dosage of the right action in the aftermath of an extreme event can amplify rather mitigate the overall impact. They posit that data collection systems need to change. Most data are fragmented across authorities in different jurisdictions and among private, public, and semi-public stakeholders. Significant coordination is needed to restructure the data in a way that common queries can be systematically addressed. In such a system key information regarding the phenomena that triggered the damage and its subsequent rounds of influence would be reported and in this way co-occurring or enchained hazards would be identified.

The paper by *Mizrahi* takes a management view of cascading disasters. As such, a cascade is conceptualized as a sequence of poorly managed crises with increasingly cumulative effects over time and space. Crisis situations are characterized by collective action. Using the tools of game theory, Mizrahi analyzes the dynamics of collective action and identifies the key parameters that promote different forms of such action in response to cascading disasters. The paper outlines four ideal types of cascading dynamics and presents two models (continuous time models and common knowledge models) to analyze the collective actions that emerge from different cascade prototypes. The damage arising from a cascading disaster can be regulated by mobilizing collective effort. For example, in the case of epidemics complete vaccination or alternatively complete contagion can result in full immunity. Capturing collective action (including the data referred to by Meroni and Boni) to understand cascades is key for disaster management.

Thomas, Jang, and Scandlyn offer a theoretically-grounded conceptual model of cascading disasters. Taking a people-centric lens of how social processes intensify disasters, the model illustrates how cascading disasters almost predictably give rise to socially inequitable disruptions and consequences. The domino and cumulative effects of cascading disasters reveal inequities throughout social systems manifesting in differential impacts and recovery opportunities across communities and subgroups of people. The model interrogates the tension between local communities and larger structural forces that produce social inequities at multiple levels, capturing how those inequities lead to cascading disasters.

Rey and Bar Gera investigate how road networks recover from disaster. Their approach uses an optimization method (bi-level programing) and numerical simulation. Cascade effects in a transportation context appear in the short, medium, and longer terms. Over the short term this could be manifested in congestion impacting lifeline services. Over the medium term, impacts are felt with respect to interoperability of the road network with other road networks or transportation mode networks such as rail or air. If roads are repaired but complementary networks are not, very little is gained. Over the long term, the state of road network recovery can impact supply chains in other sectors of the economy, as well as the demand for travel and mobility in other sectors. Thus, a reconstruction scheduling model that accounts for cascades is critical for network recovery.

Finally, the paper by *Felsenstein and Grinberger* examines cascading disasters through the prism of the labor market. They present a micro-economic analysis of the local labor market in the advent of a disaster and use agent-based simulation to animate some likely outcomes. The stylized approach to this exercise conceptualizes the disaster as a dramatic shock to capital stock. In turn, this has a cascading effect on labor reducing demand for workers and shrinking wages. In reality however, this may not transpire in a labor market context. The paper makes the case that cascades influence the local economy via altering local amenities for workers, residents and firms rather than through the impact on capital stock. Seen in this way, the cascade simply deepens the original negative shock to productivity by reducing local amenities. The earthquake that destroys capital stock can equally cause the collapse of the local healthcare system or generate an increase in crime. Both will have effects on local productivity and both are capital-altering. Similarly, the pandemic that locks down the population for fear of collapse of the public health system can release a set of cascading consequences for the economy as labor supply dries up.

3. Cascades in a post-pandemic world

The above multidisciplinary viewpoints beg the question as to how to interpret the COVID-19 pandemic from a cascading perspective. Given the duration of the publication process, some of the contributions in this special issue make direct reference to the pandemic (for example, the papers by Mizrahi and Thomas, Jang and Scandlyn) while others went into production prior to March 11, 2020 when the WHO recognized COVID-19 as a global pandemic.

The papers by Li et al. and Rey and Bar Gera couple cascades with disruptions in critical infrastructure and breaks in network connectivity. From such a perspective, we can imagine COVID-19 causing network failure for reasons both traditionally related to the collapse of essential lifelines such as health system distress and for reasons ostensibly far removed from the collapse of essential lifelines such as worker lockdown. Ironically, the COVID-19 crisis has not seen critical infrastructure collapse in those networks generally at risk in the case of natural hazard cascades such as airports, highways, dams and water defenses. In dense infrastructure networks, there is usually much slack and redundancy. If some parts of the network fall because of cascading effects, for example a tsunami that breaches a dam and floods a highway, there is invariably an alternative by-pass. However, cascading effects in the case of a pandemic leave little option for circumvention. Super-spreader events, persons, or areas have to be identified and isolated and cannot be evaded [7,8]. Under funded public health systems and healthcare that functions with just-in-time models of efficiency have little redundancy or surge capacity for preventing or controlling a pandemic. In the case of escalating COVID-19 effects, the ultimate weapon is forced isolation. Given the fact that a sustained lockdown of social and economic networks is not politically viable in most liberal democracies, the post-pandemic world faces an unprecedented situation whereby the only way to prevent cascading effects of the pandemic through networks is tantamount to dismantling the network.

An alternative approach for addressing cascades and exemplified in the paper by Thomas et al. is to take vulnerable populations as a starting point and to tackle the escalating (cascading) legacy of inequalities that intensify in the wake of a disaster. For example, low income families living and working in high exposure occupations compound the likelihood of contagion. These front-line populations often work in jobs such as essential services characterized by high contact patterns, low wages, and no possibilities for remote working. Cascading effects here are rooted in social and economic networks. Worker exposure is firstly physical and subsequently economic as places of work shut down or workers become exposed to the pandemic and are forced to lockdown with the loss of income that this implies.

The Mizrahi paper, associates cascades with a sequence of poorly-managed crises that have cumulative effects and are mitigated by collective action. Using this framework, viewing COVID-19 as a cascading phenomenon has less to do with an escalating collapse (of the health system or the economy) and more to do with the response to this threat. The probability of contagion is mediated as collective action is mobilized. Quigley et al. [9] bring empirical evidence to this theoretical construct. They simulate the cascading effects through a multi-hazard event whereby a natural hazard occurs concurrently with COVID-19. In such instances disaster relief measures may exacerbate COVID-19 exposure and issues of collective action become paramount.

Meroni and Boni's focus on need (and lack thereof) for comprehensive data which would enable data-driven decision-making, rings strong with the experiences of some countries with COVID management. The lack of such data management has led to an inability to put in place the necessary real-time monitoring systems which would enable informed decisions [10]. For Ben Haim, the challenge of COVID-19 lies in the extreme uncertainty that it generates. While the containment of SARS, Ebola and MERS can be considered some kind of historical precedent, the current threat to public health underscores the interconnectedness of global mobility and supply chain networks that did not exist in the past. Hitherto it has not been possible to adequately express the magnitude of this threat in terms of probabilities, thereby compounding uncertainty. The challenge is to design a command network that adequately mitigates cascading failures associated with COVID-19. For example, adequately granular lockdown measures are likely to limit contagion and protect the collapse of the health system, but cascade the economy into upheaval. Increased economic disparities will in turn lead to social unrest and loss of political legitimacy.

Alternatively, the Felsenstein and Grinberger paper looks neither at the direct damage, such as infrastructure disruption nor at the cumulative response, but rather at the amenity-reducing potential of the disaster. If COVID-19 is mainly a shock to labor supply, the disutility effects to workers from lack of local services and associated neighborhood decline is the relevant point of reference for understanding the pandemic rather than the cumulative effects of the pandemic on productivity as firms and workers go into lockdown.

So just how well does the COVID-19 pandemic conform to a cascading event? In the first instance, if cascades are simply a sequence of mishandled crises, many countries may have managed to extricate themselves from their first wave 'corona crises' after two to three months but are now struggling to cope with subsequent waves. The time horizon is crucial here and we still do not know what the correct frame of reference should be. In the case of flagship cascading events such as the Sendai-Fukushima disaster of 2011 after-effects could only be effectively assessed over the long term (10-plus years). The current crisis is still not out of the short-term (6–9 months) phase. The perpetuating feeling of emergency is probably driven by its cascade-like nature. While modern medical advances and societal emphasis on saving lives is likely to mean lower death rates than previous historical pandemics, the cascading effects into economic networks may mean disproportionately higher economic costs than in the past.

The indirect and induced impacts of COVID-19 are somewhat different to knock-on effects of cascades. Cascades are generally described through impacts on built and engineered systems, for example when flooding bursts a dam that leads to electric outage that contaminates the water system. In contrast, the COVID-19 pandemic leads to inter-sectoral cascading, for example from the health sector to the economy, to domestic and international politics. Similarly, cascades tend to cause domino effects in sectors far removed from the initial event. In a parallel fashion COVID-19 emerges from an initial contagion and then extends to the economic and social system causing long-term disruptions.

In terms of the economy-wide shock resulting from cascades, COVID-19 has led to near total economic shutdowns in various countries. In economic terms, the coronavirus has induced a shock to labor on the supply side along with both a reduction of consumption and a limited increase in production in certain sectors (food, hospital supplies etc.) on the demand side. The potency of the COVID-19 shock, however, may lie in the 'stagnation trap' that it can induce [11]. Under this regime pessimistic growth expectations can lead to persistent slumps from which recovery is difficult. In contrast, cascades grounded in the physical destruction of capital stock have induced short-term localized downturns from which local economies tend to build back better [12].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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