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Insights from the COVID-19 pandemic for systemic risk assessment and management

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Abstract. The COVID-19 pandemic has activated hundreds of interdependent long-lasting risks across all sectors of society. Zoonotic diseases are on the rise, fuelled by climatic change, by encroachment and destruction of habitats, and by unsustainable practices. Risk assessment and management must be greatly improved to prevent even worse consequences than COVID-19 if the next pandemic is caused by an agent with higher infectiousness and lethality. Insights from a project on systemic pandemic risk management reveal that the interdependency of risks creates cascading effects mediated by millions of vicious cycles which must be addressed to gain control over a pandemic. We propose a method for systemic, cross-sectoral risk assessment that detects the myriad of causal influences resulting from the risks, allowing to identify and mitigate the most potent risks, i.e., those participating in the highest numbers of vicious loops.

Keywords: Systemic risk, Cascading effects, Vicious cycles, Risk system analysis, Risk mitigation.

1 Introduction

1.1 Have we learnt enough from COVID-19 to manage new pandemic waves better?

At the time of writing this work, the COVID-19 pandemic continues to be a global problem nearly two years after the World Health Organization (WHO) activated its Incident Management Support Team to ensure coordination of activities and response across the three levels of WHO (Headquarters, Regional, Country) for public health emergencies

[1]. The COVID-19 pandemic has affected many countries in a roller-coaster pattern, often with increasing heights for the 2nd, 3rd, 4th or even the 5th pandemic wave.
Norway and Denmark were among the best performers in the world, with low numbers of COVID-19 cases per million and low lethality (ratio deaths/cases). But then, the 14th December 2021, Denmark had 1193 COVID cases per million and Norway had 888, although the share of people that have been fully vaccinated in both countries is higher than 70 percent and the percentage of people vaccinated at least once is about 80 percent [2]. The graphs for both countries (Figure 1) show that their last COVID-19 wave even surpasses the highest peaks in the UK (872 cases per million) and in the USA (756 cases per million), which both happened in January 2021.

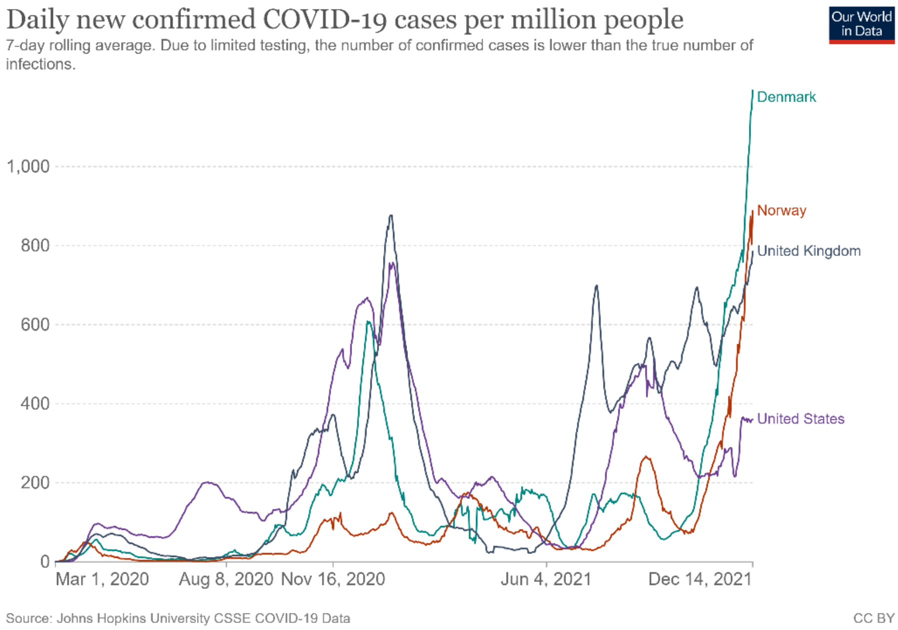

Figure 1 COVID-19 statistics of daily cases per million people for selected countries. (c) Our World In Data https://ourworldindata.org

The fact that COVID-19 is still a major problem nearly two years after it became a global problem should cause concern. The United Nations Environment Programme alerts that diseases transmitted from animals to humans (zoonoses) are on the rise [3, p7]. Never have so many opportunities existed for pathogens to pass from wild and domestic animals to people. More than 20 new human zoonotic pathogens have been detected since 1990 and over 60 per cent of all known infectious diseases in humans are zoonotic [4, p38].

The share of people that have been fully vaccinated in many counties in the Third World is below 10 percent by mid December 2021 [2]. In many cases the share is below 2 percent. Unsatisfactory hygienic conditions combined with high population densities in poor countries favour the evolution of aggressive virus variants that in our globalized world can cross continents in a few days. We may experience new pandemic waves with virus variants that are more contagious, that have higher mortality and that existing vaccines do not provide adequate protection against.

Risk assessment and management is crucial for disaster preparedness and response [5]. We contend that the nearly universal failure to control COVID-19 may be due to the inadequate current practices of risk assessment and management of pandemics.

The Global Assessment Report on Disaster Risk Reduction 2019 from the United Nations Office for Disaster Risk Reduction (UNDRR) is a powerful message that systemic risk assessment and management is indispensable to achieve the goals of the Sendai Framework [6]. The awareness of systemic risk is the recognition that the interactions between risks create a network, or system, of associated risks and outcomes, where the outcomes of risks are risks themselves, and where the resulting consequences can be complex. Risks are a system where a single risk can cause a plethora of other risks, and, very importantly, cause vicious cycles of risks. Vicious cycle is a short name for a chain of events that reinforce themselves through a feedback loop.

Applied to risks, vicious cycles are the mechanisms that allow small risks to grow into major problems, as in this quote from the Global Assessment Report on Disaster Risk Reduction 2019: “Systemic risks might be easy to mitigate early on. However, failure or even intentional ignorance to capture the role of underlying drivers of systemic risk will allow small risks to grow into major problems, increasing the opportunity costs of failed interventions and missed opportunities.” [6, p71] Since disasters do not follow scripts, it is unavoidable that underlying drivers of systemic risk will emerge during the response to disasters. In other words, systemic risk management is indispensable during disaster response.

The Global Assessment Report on Disaster Risk Reduction 2019 advocates stochastic risk management models. In section “4.1 The risk systemicity approach” we delineate a different approach that has been successfully applied to systemic risk assessment of large engineering projects since the 1990s. We have adopted and extended this method to pandemics.

Pandemics, and other major disasters have disruptive cross-sectorial effects. A recent call in the risk management literature, in 2016, recognises the immaturity of risk assessment with respect to complexity: *“…substantial research and development to obtain adequate modelling and analysis methods – beyond the ‘traditional’ ones – to ‘handle’ different types of systems… which are complex systems and often inter-dependent*” [7, p10].

In the context of COVID-19, Amaratunga et al. [8] contend that “*current policies that are designed to address conventional risks are unable to capture and deal with the complexity and interconnectedness of systemic risks. Hence, a policy mechanism that facilitates ‘systemic risk governance’ is much called for.*” Solarz and Waliszewski [9] argue for understanding the holistic nature of the COVID-19 pandemic, and they suggest that “*in the long run, it will be possible to monitor the pandemic via an integrated, holistic system of systemic risk management.*” However, neither Amaratunga et al. nor Solarz et al. have developed methods or policies for systemic (holistic) risk assessment and governance.

A recent article applies systemic risk and response management in the Republic of Korea. The study explored the official database of the Korea Centers for Disease

Control and Prevention and then identified the disaster risks and countermeasures from the government press briefings and news media in the same period. The study proved three lessons-learned to enhance pandemic response management: 1) Respond rapidly, even when lacking information and knowledge about the new type of risk. 2) Establish a multi-sectoral response. 3) The government should prioritise transparency [10].

To the best of our knowledge, so far only one country, Norway, has performed a full evaluation of all relevant aspects of the national management of the COVID-19 pandemic. The Norwegian government appointed the 24th April 2020 an interdisciplinary committee of experts that delivered 14th April 2021 a report to this effect. The Corona Committee Report lists seventeen main findings [11]. Main finding no. 1 concludes that overall, the authorities have handled the pandemic well (When the report was delivered, Norway had among the European countries the lowest mortality from the pandemic and was among the least affected economically). Not quite consistent with the first main finding, the second main finding criticizes the government for insufficient preparedness, even though the Norwegian Directorate for Civil Protection had evaluated a major pandemic as the most probable and most serious national crisis.

The third main finding further weakens the message of the first finding: "*In its emergency preparedness efforts, the Government has paid little attention to how risk in one sector is affected by risks in other sectors. A crisis preparedness system in which each sector evaluates its own risks and vulnerabilities, will fail if no one takes responsibility for evaluating the sum of the consequences for society at large. There is a need for a cross-sectoral system that can accommodate the interaction of risks across all sectors. This is a lesson applicable to preparedness in general.*"

Surprisingly, the Norwegian Corona Committee does not refer to the Global Assessment Report on Disaster Risk Reduction 2019 [6]. This omission makes the Corona Committee Report's less compelling and may explain why the message of the third finding has not yet triggered much interest so far among the Norwegian authorities. Also, the Norwegian Corona Committee does not recognize that systemic risk management requires more that considering the systemic aspects for preparedness. Systemic risk management is indispensable for mitigating the high number of vicious cycles that escalate the pandemic risks (cf. p11).

The wording "evaluating the sum of the consequences" in the third main finding of the Norwegian Corona Committee could be perceived as adding up consequences identified in one sector 1 with those identified in other sectors. But joint consideration of all relevant sectors together increases the system size, and the number of consequences does not often increase linearly as a sum, but exponentially. And so is the case for major pandemics, cf. p11.

During the same period as the Norwegian Corona Committee conducted its evaluation, a Norwegian funded project on systemic pandemic risk management with international participation had started in parallel with the committee's evaluation. The project has developed a cross-sectoral system for systemic risk assessment and management that captures how the risks in the various sectors interact with each other with respect to health care. The project's methods can be adapted to disaster preparedness and response in general when complex interactions between risks are apparent, i.e., beyond pandemics [12].

A pandemic is a complex dynamic system. The risks act through vicious cycles. Vicious cycles are mostly interconnected, which drive complex, compounded effects [12]. This is the domain of "dynamic complexity" that is resistant against interventions [14, p96-97].

To the best of our knowledge no country has designed its COVID-19 response based on systemic risk assessment and systemic risk response. Hence, the question posed as this section's heading, "Have we learnt enough from COVID-19 to manage new pandemic waves better?", must be probably answered with a 'no' with respect to potential new COVID-19 waves, and 'not yet' with respect to future major pandemics.

1.2 The aim of this paper and how it is organized

In this paper, we discuss the key characteristics that a systemic risk assessment and management method must satisfy to conduct risk and vulnerability assessments with full consideration of the systemic inter-dependencies of a major pandemic, and to develop strategies for preparedness and responses to a major pandemic like COVID-19. COVID-19 has reminded us that a major pandemic can have long duration and that it can have several waves. Further, that one must be prepared for the unexpected during response. The Global Assessment Report on Disaster Risk Reduction 2019 emphasizes that systemic risks are emergent, and not necessarily obvious … until the disaster occurs, and that unanticipated risks emerge [6, p38]. Our approach is in accord with this request: "The Sendai Framework impels a move away from an obsession with prediction and control towards an ability to embrace multiplicity, ambiguity and uncertainty." [6, p, 43].

We organise this paper as follows. In Section 2 "Characteristics of a major pandemic in the globalization era", we summarise key aspects that are relevant for a systemic approach. In section 3 "Risks in the light of systemic interdependencies", we review how risk must be approached and defined to allow for a systemic risk assessment. In section 4 "Order of magnitude of pandemic cascading effects", we first summarise our method. Thereafter we discuss the meaning of cascading effects in the context of a major pandemic and the order of magnitude of cascading effects occurring in a major pandemic such as COVID-19. In section 5 "Discussion" we point to future research and developments, and we summarise our findings in the light of the Global Assessment Report on Disaster Risk Reduction 2019.

2 Characteristics of a major pandemic in the globalization era

COVID-19 is in terms of number of cases, deaths, and global impact the largest pandemic disaster since the Spanish Flu 1918-1920.

A recent publication [15] presents strong evidence that the challenges of the COVID-19 pandemic are unique, owing to the characteristics of the cascading effects, the long duration of the pandemic and the need to prioritize risk mitigation in a hierarchical manner, which altogether make the character of the COVID-19 pandemic very different from other disasters. Indeed, hierarchical prioritization must follow from attention to the relative significance of risk within the context of the whole system of risks. The authors of reference [15] also point out that is no clear distinction between the impact and response phases in the COVID-19 pandemic. Casualties continued to mount even as response activities were implemented. Indeed, the roller-coaster pattern implies that impact, response, and recovery attempts overlap. We add that these phases often do not occur simultaneously, even in neighbouring countries.

Infectious diseases are the origin of pandemics, and the occurrence and propagation of pandemics find numerous direct and indirect channels for exponential propagation.

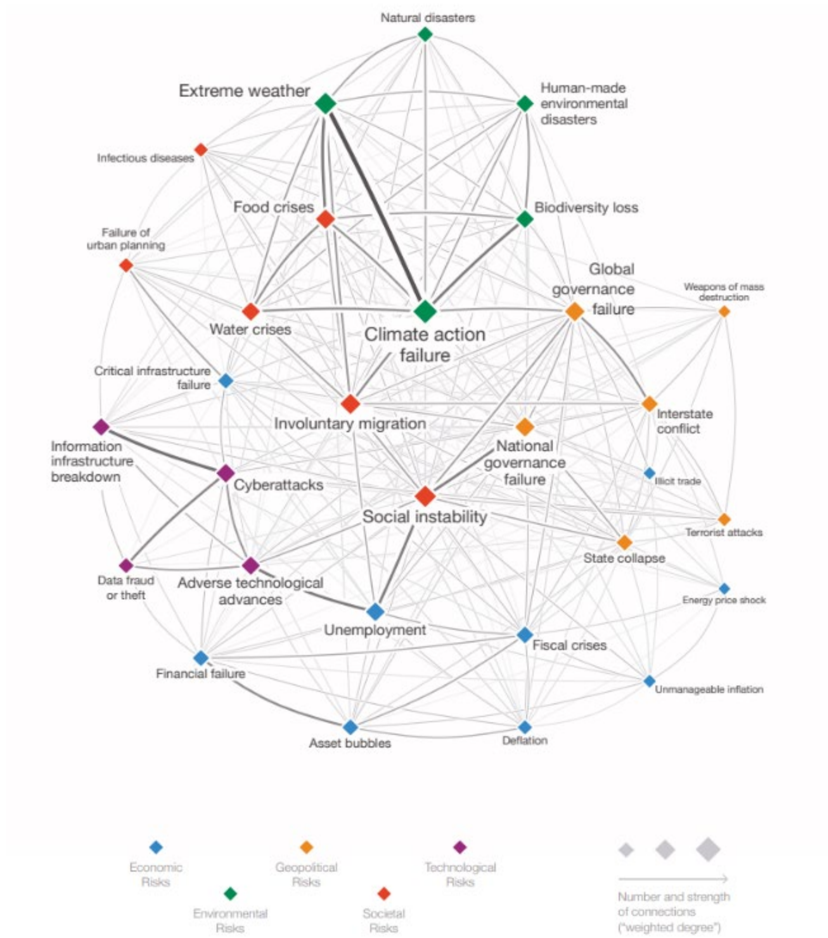

Figure 2 The Global Risks Interconnections map. The Global Risks Report 2020 (c) World Economic Forum

Figure 2 illustrates one view of the global interconnections, which bundle numerous cause-effect influences coupling environmental, societal, geopolitical, technological, and economic risks. These influences are the origin of the increase in zoonoses, and with that the risk of major pandemics. The drivers of zoonoses are unsustainable patterns of consumption and production causing climate change, habitat loss and fragmentation, loss of biodiversity, pollution, and poor waste management [4, p38]. But then the characteristics of COVID-19, and arguably of major pandemics to come, are consequences of the interconnections and interdependencies in the era of globalization. The large number of cascading effects, particularly of vicious cycles that drive exponentiation; the long duration of the pandemic; the emergence of new and more aggressive virus variants in part responsible for new waves with even higher case incidence: they all relate to the flood of interdependent risks enabled by the interconnections.

Numerous factors outside of the health system impacted on the management of the COVID-19 pandemic, e.g., infodemics, mass gatherings, travels, logistics and even criminal behaviour, …, and vice versa: the pandemic itself impacted on numerous outside factors which had causative effects on the pandemic.

Vicious cycles must be detected, understood, and responded to with measures that are anchored in proper understanding of the systemic interdependencies and the resulting dynamic complexity [14]. Quoting Senge [16], dynamic complexity is characterised by *"…cause and effect are subtle…the effects over time of interventions are not obvious. Conventional forecasting, planning and analysis methods are not equipped to deal with dynamic complexity.*"

The next section discusses the concept of risk in the context of systemic interdependencies.

3 Risks in the light of systemic interdependencies

3.1 Adequate risk definition in the presence of dynamic complexity

Risk is typically understood as an adverse circumstance and the chance (probability) of its occurrence. The Oxford English Dictionary defines risk as *"(Exposure) to the possibility of loss, injury, or other adverse or unwelcome circumstance; a chance of something bad happening.*" [17] The Oxford Dictionary of Economics defines risk as "*A form of uncertainty where, while the actual outcome of an action is not known, probabilities can be assigned to each of the possible outcomes.*" [18] The Dictionary of the Social Sciences defines risk as "*Generally, the chances of malign events or uncertainty of outcome. Risk may or may not be quantifiable in terms of specific likelihoods of outcomes, but its most common use implies that the underlying probabilities of various outcomes are known. These probabilities may either be objectively specified, as in the case of a lottery, or may reflect an individual's private subjective beliefs.*" [19]

In practice, risk occurs in systems, and systems can be complex. There is general awareness that complexity makes it difficult to model a system and predict its behaviour, i.e., to compute probabilities for risk assessment [20-25]. There is less awareness that there are different kinds of complexity, and that the complexity type has crucial importance for risk assessment and management.

A recent work [25] examines complexity and discusses its relation to risk. The authors consider as the key issue how risk can be assessed based on the knowledge of the system elements and the assumptions about these elements. Their approach is still anchored in the classical triplet definition of risk in terms of events/scenarios (s), probabilities (p) and consequences (c), i.e. (s,p,c) [26]. The perspective of the authors of reference [25] on complexity is of the knowledge at the system level being poor, even if one has strong knowledge at the sub-system level. In other words, it is not possible to model the system behaviour in this way of thinking about risk. They argue accordingly that the risk assessment has strong limitations, hampering risk management.

The perspective in reference [25] is from complex engineering systems. But most engineering *systems* do not have dynamic complexity that is resistant to interventions. Exceptions are large engineering *projects*, which do exhibit dynamic complexity characterized by numerous interdependencies and dynamics across sectors and disciplines. As consequence, disruptions of large engineering projects (considerable delays and cost overruns) are ubiquitous [27-29].

The complexity of the engineering systems as analysed in reference [25] is *numerosity*, i.e., large number of components and activities. In other words, they exhibit "detail complexity" rather than "dynamic complexity". Pandemics (and many other disaster types), but also large engineering projects, have more than just a high number of parts. They are characterised by a high number of interdependencies that are dynamic, i.e., change over time, and that to a large degree cannot be described by known relations (by laws of Nature or using correlations). Interdependencies in both large engineering projects and pandemics are often non-linear and act with significant time delays [13, 14].

3.2 Quantitative analysis of qualitative models of systemic risk

The dynamic complexity of major pandemics implies that assessing most present risks in terms of probabilities is a futile task. A major pandemic triggers many time-dependent risks (adverse circumstances) within and across societal sectors. The risks are interdependent, i.e., the dynamics of any risk influences the dynamics of other risks. In our Systemic Pandemic Risk Management project experts identified in round numbers 220 hundred risks across society. The interdependencies between risks count in round numbers 600 or more. Most of such influences defy quantitative description, owing to insufficient knowledge.

Consider ascertaining the probability of new virus variant to occur, its infectiousness and its lethality (which likely would be time dependent as well). The behaviour over time of direct and indirect pandemic risks is strongly influenced by the agent's infectiousness and its consequences in terms of case incidence and death case rate.

Consider the quantitative risk assessment of infodemic and the impact of different messages in social media; the invention of conspiracy theories that would influence citizens' behaviours (trust in the authorities; disruptive activities; propensity of vaccination, etc).

Even if it was possible to obtain the required insights, it would not happen in near real time. Near real time insight would be indispensable to achieve an agile response to the pandemic, based on fast update and analysis of the risk model.

A reasonably complete model of a pandemic for mitigation would be impossible to design and simulate in near real time, because of its sheer size and complexity, with its difficulties compounded by the need to act agile against a problem with new and emergent features.

In contrast, qualitative descriptions, based on experience and general observation, are possible. Models can be constructed that reflect the experience and wisdom of those who have sought to manage at least parts of the system. Bringing together these views begins to develop a holistic view.

The behaviour over time of direct and indirect pandemic risks is strongly influenced by the agent's infectiousness and its consequences in terms of case incidence and death case rate. Infectious agents evolve over time. We do know that in many cases it is beneficial for an infectious agent to become less virulent. It can then spread without causing too much damage to the host, thus increasing the probability of being transmitted. But it has happened before, the most famous case shaping the second wave of the Spanish Flu 2018-2020, that the infectious agent evolved to much higher infectiousness and lethality [30]. This evolution of the Spanish Flu virus has been explained by practices in the Western front of World War I, where individuals immobilized by illness were transported repeatedly from one cluster of susceptible hosts to another, in trenches, tents, hospitals, and trains. Such practices aided more virulent variants to infect and kill people without paying the price of reduced transmission [31].

For COVID-19 it has been argued that different social practices in Sweden and Norway may explain the significant difference of case mortality between these otherwise similar neighbour countries. When reference [32] was published 19th November 2020, Sweden, which had not enacted strict containment measures, had more than three times as many deaths per 100 cases as Norway. At the time of writing this article, Sweden, which in the meantime had enacted stricter containment rules, has a case fatality ratio of 1,22%, still more than three times as many deaths per 100 cases as Norway, whose case fatality ratio is 0,36% (source: Johns Hopkins Coronavirus Center https://coronavirus.jhu.edu/map.html, retrieved 14th December 2021).

Traditional risks assessment methods cannot cope with interdependent risks and the dynamic complexity of a pandemic. Most pandemic risks cannot be computed. Instead, risk must be considered as "a phenomenon that has the potential to deliver substantial harm, whether or not the probability of this harm eventuating is estimable" [33, p10], or whether the behaviour over time of this harm can be computed or estimated from its causes (which are mostly other risks).

Because of the different meanings that may be given to the nature of causation – intensity, strength, probability etc – the judgments about the causal relations will always be disputed. However, an overriding consideration is the practical constraints on providing sensible quantification of so many risks and their relationships.

The method discussed in the next section has quantitative flavour added to qualitatively representing risks in maps that include vast numbers of causal loops. By identifying, through an analysis of the structure of the risk system, the most potent risks and the most potent causal relations, and ranging them hierarchically according to degree of potency, portfolios of strategies can be designed to mitigate those potent risks and causal influences.

Ultimately risk mitigation depends on the judgments of policymakers, and the role of modelling is to assist the policymakers about the validity of the risk system and analysis of it, thus enabling them to improve their decision making.

4 Order of magnitude of pandemic cascading effects

4.1 The risk systemicity approach

The fundament and point of departure of our project on systemic pandemic risk management are methods developed through decades of research on strategic management and systemic risk assessment and mitigation for engineering projects. Among the numerous references we mention [12, 34, 35]. Recently, the risk systemicity approach was extended to societal resilience [36]. The research on strategic management and systemic risk assessment and mitigation employed tools known as Group Explorer and Decision Explorer [37] that have recently inspired the internet-based tool *strategyfinder*™.

A recent paper [12] has extensively described the risk systemicity approach for pandemics and the results obtained using *strategyfinder* in risk workshops with carefully selected experts on health care risks and in the various sectors that interact with each other with respect to health care.

Therefore, in this paper it should suffice to summarize the key features of the risk systemicity approach.

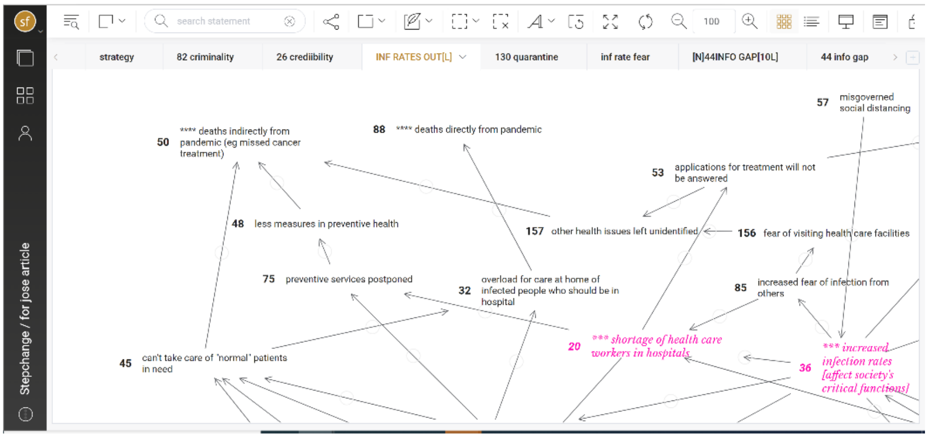

Figure 3 An enlarged screenshot of the canvas of strategyfinder™ depicting a view of the pandemic model developed for the Systemic Pandemic Risk Management project. See the main text for details.

The risk systemicity approach uses a special collaborative software to elicit and collect wisdom, experience, and knowledge from a carefully selected interdisciplinary expert team in a structured way. This software – *strategyfinder*™ – allows the experts to 'meet' via the internet and work on a causal map of the interconnected risks. A facilitator works with the group to help ensure that the different individual perspectives are structured to reveal significant causal chains of argument that allow for further reflection, extension, and debate amongst group members.

Each participant (expert) is able to add material to the map in a manner that means as changes and additions are made to the map all participants can see these changes. The participants add links between the views representing causal influences, which often lead to discovering feedback loops (vicious and virtuous cycles, and balancing/controlling feedback loops).

Figure 3 shows part of a view of the pandemic risk model. Views are created by a facilitator who also has the rights to export the risks from the complete map of interconnected risks (which, of course, are found in a view itself) to the selected view. Views showing model sections depict selected scenarios of the complete model. The view shown on Figure 3 focuses on risks influencing risk #88 “deaths directly from pandemic” and risk #50 “deaths indirectly from pandemic (e.g. missed cancer treatment)”. Risks are numbered automatically by *strategyfinder* as they appear on the canvas. The numbers are otherwise unimportant (i.e., unrelated to the relevance of the risk). Arrows express cause-effects. E.g., risk #45 “can’t take care of ‘normal’ patients in need” affects (increases) the risk #50 “deaths indirectly from pandemic (e.g. missed cancer treatment)”.

The view shown on Figure 3 was developed by the facilitator after the workshop with experts. The facilitator added information (such asterisks and colours) that is relevant for workshops to occur later (such as quality assurance of the model, development of mitigating strategies).

The system of risks presented in a causal map format then allows participants to i) explore and validate a map of the system of risks, and ii) develop impactful strategies that are also practical. The *strategyfinder* software has powerful tools for analysing the risk map, to detect feedback loops, in particular the most potent feedback loops and find the most central parts of the risk system, to rate strategies and explore the different views of group members about impact and practicality, and so guide the participants during this strategy development process towards realistic actions and goals.

The extension and adaptation of the risk systemicity approach to pandemics meets new challenges related to the large number of risks and the richness of interdependencies among the risks. Our pandemic risk model obtained in the workshops with experts has, in round numbers, 220 risks factors, with interconnections in the order of 600, yielding in round numbers 5 million of interconnected vicious cycles, most of them highly interconnected with other vicious cycles. So many vicious cycles in the model can be seen as characterizing the nature of a pandemic and the difficulties in managing one. It follows that the management of such a complex challenge cannot be met with conventional strategies addressing isolated risks, even if the strategy targets ten, twenty or even thirty identified risks. Using the *strategyfinder* analysis tools it is possible to find those risks that if mitigated would be likely to have the biggest impact in terms of reducing the long-term impact of infections and both indirect and direct deaths. It is these risks that become the focus of strategy development. To ensure best strategy coverage, portfolios of effective and practical strategies targeting multiple risk factors in highly compounded vicious risks networks are developed.

4.2 Cascading effects as vicious cycles

The previous considerations have implications for the concept of cascading effects in major pandemics (and probably in other major disasters). The term "cascading effects" (sometimes expressed as "cascade effects") appears frequently in the disaster literature, but it is also often used in other domains (ecology, finances, forensics, history, medicine, and some others). Curiously, the term "cascading effects" is rarely precisely defined. It is taken for granted in much of the literature. Even in reference works such as Oxford Dictionary of Ecology (*Cascade effect: A sequence of events in which each produces the circumstances necessary for the initiation of the next*) [38] or the Handbook of Transitions to Energy and Climate Security *("cascading disasters" or "cascading consequences" where multiple disasters happen either simultaneously or in close proximity to one other*) [39] the definitions lack a metric for cascading effects.

Taking the concept of cascading effect for granted, the literature tends to (sometimes) illustrate the concept with sentences like e.g., "*cascading effects, which tend to create extreme events: the overload of one component of the system challenges other components, which therefore causes a propagation of problems through the system. … They tend to occur when the interdependencies in the system exceed a critical strength*" [40], and then proceed to model and compute the impacts of the tacitly defined cascading effects in terms of proxies such as the level of criticality of crowd density [40], the spread of impacts [41], or the fraction of the functional entities [42].

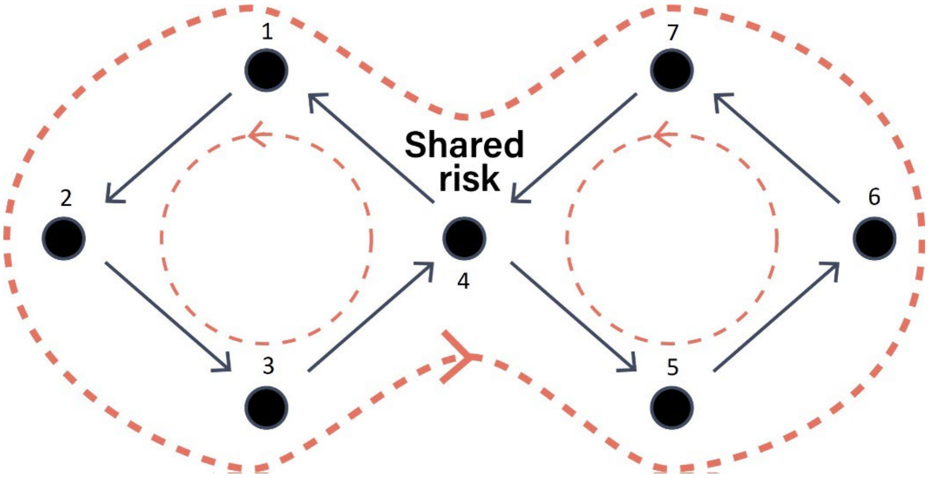

Figure 4 Example showing two single vicious cycles and one nested vicious cycle

Consider the example shown on Figure 4. It shows seven risks labelled 1…7, forming two single vicious loops and one nested vicious loop where risk 4 is passed through twice. Each causal link (arrow) can cause a cascading effect if activated. For example, if risk 1, say "insufficient PPE to protect health staff attending infectious patients", is active then it influences risk 2 (increase of health staff infected in hospitals). The vicious cycle on the l.h.s. of the figure could have these two additional risks "3: "diminishing the availability of health care staff" and "4: higher number of infected people in the general populations", which – owing to the increased need of health care for a higher number of infected persons – would exacerbate risk 1. Each risk increases the next risk in the vicious cycle and the negative consequences get reinforced. In this example all the cascading effects occur within the same sector (the health care sector). One has inner-sector cascading effects. But if one risk or more risks would relate to a difference sector one would have inter-sector cascading effects. Indeed, in many instances the l.h.s. may be a vicious cycle in one sector and the r.h.s. in another, and through risk 4 they interact to create the nested inter-sector vicious cycle.

The usual definitions of cascading effects tend to only mention the influence from one effect (risk) to another effect ("*the overload of one component of the system challenges other components*" [40]). But the real issue is the chain of effects going round and round in the vicious cycle. It is the reinforcing of the negative consequences that creates systemic disruption and exponentiation.

Now consider again Figure 4. Does the nested vicious cycle 1→2→3→4→5→6→7→4→1 have additional impact beyond the impacts caused by the single vicious cycles 4→1→2→3→4 and 4→5→6→7→4?

Indeed it does, and nested vicious cycles must therefore be counted in addition to the single vicious cycles to fully estimate the impacts of cascading effects and to find the most potent risks and potent causality.

Think of risk 3 as flood of misleading information (risk occurring in the information and telecommunication sector), risk 4 as diminishing trust in politicians (risk occurring in the government sector), risk 5 as decreasing citizen willingness to be vaccinated, and risk 7 as increasing infections in the population, ultimately increasing risk 4 (diminishing trust to politicians), etc. This shows that compounded inter-sector cascading effects between the three mentioned sectors requires adding up the individual cascading effects traversing the nested vicious loop 1→2→3→4→5→6→7→4→1.

As mentioned on p8 the systemic pandemic risk model obtained in the workshops with experts has, in round numbers, 220 risks factors, yielding over 5 million of vicious cycles, most of them highly nested. The *strategyfinder* software counts the vicious cycles using the algorithm of reference [43]. Since the huge number of vicious cycles is likely to challenge the reader's intuition, we provide a mathematical expression to count the number of vicious cycles, single and nested in a "n-leaves-clover". (Figure 4 displays a 2-leaves-clover of vicious cycles.) We choose the "n-leaves-clover" example because the number of vicious cycles in it can be easily found using the binomial theorem. The total number of vicious cycles in a n-leaves-clover model is $\binom{n}{0} + \binom{n}{1} + \binom{n}{2} + \cdots \binom{n}{n-1} + \binom{n}{n} - 1 = 2^n - 1$, of which *n* are single and $2^n - n - 1$ are nested.

Thus, one gets an exponential increase in vicious cycles depending on the number of leaves (single vicious cycles). If there are, say, 20, vicious cycles sharing one common element both the total number of vicious cycles and the total number of nested vicious cycles surpasses one million.

In our pandemic risk systemicity model there are many vicious cycles sharing one common risk, and also quite many vicious cycles sharing two or even more common risks. Thus, while possibly surprising and counterintuitive, we can trust the algorithms that count more than 5 million vicious cycles, most of them highly nested, in our risk systemicity model.

With such huge number of vicious cycles driving the dynamics of the pandemics one suspects it is the joint contribution of many vicious cycles that account for the complex dynamics of a pandemic.

Here is it where the quantitative analysis of the risk system as a directed graph enters. A risk having many incoming causal arrows is exposed to potential cascading effects from many different risks (each causal arrow in having the potential to cause a cascading effect in the receiving risk). Many outgoing causal arrows may imply that the risk in question has many paths to effectuate cascading effects (each causal arrow out being a potential source to pass a cascading affect).

Shortage of Health Care Workers in Hospitals

Agreed Strategies, their Purpose, and Implementation Teams

Establish high-level infection protection (PPE) for healthcare and emergency workers
In order to: Directly avoid shortage of Health Care Workers in Hospitals, and Control local outbreaks in hospitals, and so avoid having exhausted health care workers and so reduce possibility of low productivity of working health care staff because o shortage of staff
Implementation Team: Chief physician at short-term nursing home, Hospital contingency planner

Priority of vaccination for health care workers
In order to: Directly avoid shortage of Health Care Workers in Hospitals, and Avoid local outbreaks of virus in nursing homes, and in hospitals Avoid delays in ordinary medical education
Implementation Team: Crisis manager Kristiansand Municipality, Physician specialist in public health

Limit visits and staff exchange
In order to: Avoid local outbreaks of virus in nursing homes, and in hospitals
Implementation Team: Chief physician at short-term nursing home, Crisis manager Kristiansand Municipality

Not allow student health care workers to be in different locations
In order to: Avoid local outbreaks of virus in nursing homes, and so Avoid care home residents being hospitalized and shortage of care home staff
Implementation Team: University of Agder, Faculty for health and sport sciences

Effective communication and cooperation between hospital and municipality
In order to: Avoid local outbreaks of virus in nursing homes, and so Avoid care home residents being hospitalized and shortage of care home staff
Implementation Team: Physician specialist in public health

Avoid transportation by bus for health care workers
In order to: Avoid local outbreaks of virus in nursing homes, and so Avoid care home residents being hospitalized and shortage of care home staff
Implementation Team: Crisis manager Kristiansand Municipality

Arrange core hospital staff in cohorts

Figure 5 Portfolios of strategies address each key risk scenario to provide enough points of attack in case that some of the strategies fail to achieve desired effect. The picture shows such portfolios for the key risk "shortage of health care workers in hospital".

The most potent risks are those that if mitigated will have the most significant impact on the risk system. Satisfactory mitigation implies the risk can be deleted from the risk system and so the structure of the risk system changes. When the risk system contains nested vicious cycles then the most potent risk will be that which if mitigated (deleted) minimizes the number of remaining vicious cycles. Thus, the most potent risk is that which creates a significant cascading effect (where a cascade implies escalating risks through vicious cycles).

Such quantitative analysis of a qualitative risk system can be used to devise portfolios of strategies to mitigate the pandemics. As described in [12] the analysis for the strategy development workshops involves three steps:

i) find all the vicious cycles,
ii) find the risks that appear in the most vicious cycles, and
iii) find which causal links, if deleted, would reduce the maximum number of vicious cycles.

Finding the most potent risks and most potent causal links between risks then means that strategies are developed i) to mitigate the most potent risk, and ii) to break the most potent link. This requires a portfolio of strategies, on the basis that some will fail. When either or both mitigation strategies have been developed then these risks or causal links are 'deleted' from the risks system and the next most potent risks and causal links found, and the strategy development process continued.

To this effect, the facilitator/analyst uses the sequence of maps developed by the group to compose a document on the agreed portfolio of strategies (Figure 5 shows the first page of the document). For each portfolio, the rationale of the strategy is explained in terms of its causal implications.

5 Discussion

"*The pandemic has reminded us, in the starkest way possible, of the price we pay for weaknesses in health systems, social protection and public services.*" [4, p38]

Whereas the risk systemicity approach has been successfully been applied in practice within industrial settings, the project on systemic pandemic risks management is at the stage of proof of concept. The challenge is its adoption in hospitals, major organisations, and government agencies for civil protection and disaster assistance. The adoption depends on the perception that risk systemicity is needed, but also in tight collaboration between scientists and practitioners. The approach must be used on a multi-organisational basis to ensure multi-disciplinary/trans-disciplinary expertise and policy-makers.

For pandemics and major disasters, the risk systemicity approach is still at the stage of an invention. The distance from invention to innovation (wide adoption in practice) can be large, and achieving the innovation stage often takes much time [44].

To facilitate the adoption of the risk systemicity approach our project on systemic pandemic risk management is developing support for automated risk scenario identification, automated analysis of impacts for prioritizing and generation of policy options writing scenarios.

The use of computer software is critical. As shown, risk systems related to pandemics and disasters are likely to have millions of vicious cycles, and these need to be identified. Although *strategyfinder* has appropriate algorithms for their identification, and for many other useful analyses of complex networks, the computational effort means that it is not currently possible to undertake these analyses quickly (within a few seconds) when used through internet browsers. A facilitator needs to be able to undertake analyses in real-time when working with a group of policy makers. The analysis for potency needs be possible as the group work on possible strategies – 'what happens if' analyses need to be reported to the group 'instantly'. Analyses such as 'closeness', 'betweenness' and 'connectedness' are also important contributors to the process of understanding the nature of a risk system.

These analyses are available in current versions of *strategyfinder* but need to be embedded in appropriate facilitation processes of the sort that are being developed and tested.

The UN Secretary-General stated April 2, 2020 "*We simply cannot return to where we were before COVID-19 struck, with societies unnecessarily vulnerable to crisis. We need to build a better world.*" [45].

The UNDRR's Global Assessment Report on Disaster Risk Reduction 2019 [6] recognizes that systemic risk assessment and management of disasters is a *sine qua non*. However, the report advocates stochastic risk management models, ignoring other approaches. The sheer number of the emergent risks that must be addressed in near real time for proper response to a major pandemic do exclude stochastic models of pandemic risks from practical consideration for pandemic response, at least for the time being. In contrast, our risk systemicity approach can be used in near real time by capturing the wisdom of appropriately selected interdisciplinary teams. Such teams can be reconfigured to accommodate for expertise to capture emerging risks. Risks are phenomena that have the potential to deliver substantial harm, whether or not the probability of this harm eventuating is estimable. Since the risks participate in vicious cycles, the risks will be reinforced and ultimately cause harm. Hence, our approach targets the most potent risks and the most potent causal links – those that if mitigated will have the most significant impact on the risk system.

Systemic risks are ubiquitous in humankind's Gran Challenges. Quoting again UNDRR's "Global Assessment Report on Disaster Risk Reduction 2019": "*the systemic risks … are embedded in the complex networks of an increasingly interconnected world. The behaviour of these networks defines quality of life and will shape the dynamic interactions among the Sendai Framework, the 2030 Agenda, the Paris Agreement, New Urban Agenda and the Agenda for Humanity. Ultimately, the behaviour of these networks determines exposure and vulnerability at all scales.*"

For the need to improve approaches toward systemic risks and dynamic (systemic) complexity watch the TEDx talk "Can technology help against technology?" [46].

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