Journal of Environmental Informatics Letters 7(2) 64-68 (2022)

Journal of Environmental Informatics Letters

www.iseis.org/jeil

Extending Simulation Decomposition Analysis into Systemic Risk Planning for Domino-Like Cascading Effects in Environmental Systems

M. Kozlova[1] and J.S. Yeomans[2 *]

[1] *School of Business and Management, LUT University, Yliopistonkatu 34, Lappeenranta 53850, Finland*
[2] *OMIS Area, Schulich School of Business, York University, 4700 Keele Street Toronto, ON M3J 1P3, Canada*

Received 6 April 2022; revised 2 May 2022; accepted 16 May 2021; published online 21 June 2022

ABSTRACT. In interconnected environmental systems, the innocuous failure of one component can sometimes trigger a subsequent domino-like effect resulting in a cascading collapse of the entire system. Risk analysis in "real world" contexts frequently requires the need to simultaneously contrast numerous uncertain factors and difficult-to-capture dimensions. Monte Carlo simulation modelling has often been employed to integrate uncertain inputs and to construct probability distributions of the resulting outputs. Visual analytics and data visualization can be used to support the processing, analyzing, and communicating of the influence of multi-variable uncertainties on the decision-making process. In this paper, the novel Simulation Decomposition (SimDec) analytical technique is extended into complex assessments of cascading risk analysis and used to quantitatively examine situations involving potentially catastrophic, domino-like collapses of an entire system. SimDec analysis proves to be beneficial due to its ability to reveal interdependencies in complex models, its ease of decision-maker perception, its visualizable analytic capabilities, and its significantly lower computational burdens. The case example visually demonstrates that when a system collapse is a low-probability/high-impact event, more expensive, reactive policies minimize the overall value loss under conditions of system survival, while more proactive policies enable better loss prevention under system survival. However, proactive approaches significantly decrease the likelihoods and magnitudes of losses for scenarios resulting from the collapse of the system. Such findings would not have been revealed without the visualization provided by SimDec.

Keywords: cascading risk, domino effect, environmental risk management, monte carlo simulation, simulation decomposition, visual analytics

1. Introduction

Within the overall framework of an interconnected global network, a seemingly innocuous failure of certain elements can instigate a subsequent cascading effect resulting in the collapse of entire systems (Cozzani et al., 2005). Such domino-like breakdowns have been observed in climate systems (Lawrence et al., 2020), financial sectors (Silva et al., 2017), power systems (Guo et al., 2017), information security (Guariniello et al., 2014), supply chains (Yang et al., 2021), disease progression (Permal, 2021), and many other such environments. Recent examples of major cascading phenomena include the continuing COVID pandemic (Malden and Stephens, 2020), the major power system blackout in Texas (Busby et al., 2021), and the breaching of the Evergreen cargo ship in the Suez Canal interrupting the entire global logistics systems (Knowler, 2021).

There are numerous environmental illustrations of significant cascading destabilizations that possess a significant potential for collapsing entire systems in this domino-like manner. For instance, if even a single species were to become extinct as a result of climate change, pollution, habitat loss, or any other natural and/or man-made factors, the resulting domino effect could provoke a massive impact to the entire global ecosystem (UNEP, 2022). Watts (2018) warned of the domino-like cascade effects of warming seas, melting sea ice, shifting currents, and dying forests that would invoke a global, "hothouse" state beyond which any human efforts to reduce emissions would be rendered futile. Similarly, Turner (2021) comments that as climate change endures, the impacts on ocean currents and ice sheets could mutually destabilize each other, invoking domino-like consequences that would severely impact half the global population. Cho et al. (2021) concluded that numerous environmental "domino effects" were already observable in the existing global warming data. As such cascading effects generally belong to the "black swan" category of events characterized by high impact and low probability, where the balance between proactively committing to counter-measures rather than acting reactively remains delicate.

Whilst it can be acknowledged that cascading effects do occur, there appears to be a relative dearth of exploratory analytical approaches in existence than can be straightforwardly used to assess their potential impacts in environmental settings. Domino effects have been examined previously for numerous process and chemical industries settings (Kadri and Chatelet, 2013; Wu et al., 2015; Mukhim et al., 2017; Swuste et al., 2019).

* Corresponding author. Tel.: 416-736-5074; fax: 416-736-5687.
E-mail address: syeomans@yorku.ca (J.S. Yeomans).

ISSN: 2663-6859 print/2663-6867 online
 doi:10.3808/jeil.202200079

The predominant approaches applied within these studies for assessing such things as the time, location, and causes of cascading accidents include quantitative risk assessment (QRA), Bayesian networks, Monte Carlo simulation, game theory, and probit analysis (Kadri and Chatelet, 2013; Wu et al., 2015; Mukhim et al., 2017; Swuste et al., 2019).

Recently an exploratory data analysis approach referred to as Simulation Decomposition (SimDec) has been introduced that extends Monte Carlo analysis by enhancing the explanatory power of the cause-effect relationships between multi-variable combinations of inputs on the simulated outputs aspects (Kozlova and Yeomans, 2019). SimDec operates by pre-classifying some of the uncertain input variables into states, clustering the various combinations of these different states into partitions, and then collecting simulated outputs attributable to each multi-variable input partition. Since the contribution of the subdivided partitions on the overall output is easily portrayed visually, SimDec can reveal previously unidentified connections between the multi-variable combinations of inputs on the outputs. A SimDec approach is generalizable to any Monte Carlo model with negligible additional computational overhead and, hence, can be readily used for environmental analyses, such as climate, hydrology, harvest risk assessment, and potential biological removal that employ simulation models. As with domino-like industrial processes, cascading environmental situations involve multi-dimensional problems possessing considerable uncertainty and Monte Carlo approaches can be employed to assess these uncertain aspects (Kozlova and Yeomans, 2019). Consequently, this research note illustrates how the SimDec exploratory analytical approach can be easily appended into the assessment process of cascading systemic risk models for facilitating decision-making within domino-like environmental applications.

SimDec, in essence, is an extension of Monte Carlo simulation that maps user-specified, multi-variable combinations of input variables onto resulting distributions of output variables (Kozlova and Yeomans, 2020). This visual analytics approach enables the consequences of combinations of different initial states to be made straightforwardly visible to decision-makers (Kozlova and Yeomans, 2020). As the initial states represent different risks or different measures, SimDec readily produces actionable insights that support decision-making. It is these visual analytics proficiencies that contribute substantial benefits to SimDec's practical decision-support capabilities. The SimDec approach has previously been applied to several environmental systems including CO_2-emission analysis (Deviatkin et al., 2021), carbon capture and storage investment incentives (Kozlova and Yeomans, 2019), water pollution from agricultural fertilizer run-off (Raul et al., 2022), aviation electrification projections (Kozlova et al., 2022), and renewable energy investment strategies (Kozlova and Yeomans, 2020). An open access prototype of SimDec software can be accessed via Kozlova and Yeomans (2020).

Monte Carlo simulation is a well-established technique for assessing systemic risk (Lehar, 2005; Huang et al., 2009; Teplý and Klinger, 2015). Furthermore, the more complex and/or nonlinear the underlying models are, the more comprehensive the SimDec insights tend to be. Therefore, given the fact that SimDec analysis provides a relatively straightforward extension to Monte Carlo methods, the complexity of underlying models does not impede its adoption. Thus, the goal of this note is to show how the existing decomposition concept can be extended to the more complex cascading risk assessments involving potentially catastrophic, domino-like collapses of an entire environmental system.

2. The Simulation Decomposition Approach

SimDec is a novel, analytical technique that builds upon Monte Carlo simulation by uncovering inherent causalities and hidden interactions in the underlying system (Kozlova and Yeomans, 2020). To accomplish this task, the SimDec algorithm clusters the output distribution from an entire simulation by partitioning certain input variables into states, constructing an exhaustive list of multi-variable combinations (partitions) of these states, and then mapping the resulting input combinations onto the output distribution (Kozlova and Yeomans, 2019; Deviatkin et al., 2021). As a consequence of the algorithm, one can observe the overall output distribution, as in the classical Monte Carlo simulation, together with the simultaneous projections of the various partitions onto this distribution (Kozlova and Yeomans, 2020). The algorithm circumvents the necessity of running multiple simulations by tracking the values of inputs variables alongside the output variable during a single simulation run and then utilizing them for construction of the partitions according to the user-specified states of input variables. Thus, the computational costs for performing the algorithm are negligible (Kozlova and Yeomans, 2020). The partitions are displayed with different colours during the visual analytics stage. In particular, the states of the most influential variables are assigned different colours, while all further partitions are colour-coded as gradations of the main colour to preserve visual consistency and to facilitate human perception (Kozlova and Yeomans, 2020). By displaying partitions comprised of multivariable groups as segments of the output variable, SimDec is able to visually reveal various nonlinearities and interactions of variables within the model, which frequently leads to an uncovering of previously concealed relationships (Kozlova and Yeomans, 2020).

The SimDec algorithm can be summarized in the six steps (detailed explanations can be found in: Kozlova and Yeomans, 2019; Deviatkin et al., 2021; Kozlova et al., 2022):

Step 1) Select key input variables for the decomposition from the set of all randomized variables in the model.

Step 2) Define relevant states for each of the key input variables (e.g., pessimistic, most-likely, optimistic).

Step 3) Establish numeric boundaries for each identified state. For each variable, the resulting boundary ranges of the states must be mutually exclusive and collectively exhaustive.

Step 4) Create all possible combinations of the states of key input variables. Each group corresponds to a multivariable partition (e.g., a 2-variable partition might be: X_1 pessimistic and X_2 most-likely).

Step 5) Record values of the output and input variables while running the simulation and map every simulation run to the corresponding partition based on the partition association created in Step 4.

Step 6) Construct the output probability distribution and colour-code it in accordance with the partitions.

3. Modeling Systemic Risk with a Domino-Like Cascading Effect

This section demonstrates the application of SimDec to a stylized example of system risk containing a cascading effect, together with possible mitigation strategies. While based upon an actual environmental planning application, the specific case study materials, themselves, are confidential, so the details have been generalized in order to maintain confidentiality.

In the example, the system is exposed to a single risk. The impact from the risk can be realized to different degrees and the corresponding effects are measured by the resulting financial impact on the system. Three distinct levels of risk impact are identified — low, medium, and severe. At a certain threshold, the damage, coupled with an external random event, causes a cascading effect and the whole system collapses.

There are three different mitigation policies are considered in order to tackle the risk consequences.

1) Reactive Policy I is a business-as-usual practice operated by the system under normal conditions.
2) Reactive Policy II requires a more expensive set of remedial measures.
3) The Proactive Policy assumes the incurrence of some costs in advance, irrespective of the actual risk realization, in order to anticipate which required resources are needed to tackle the risk and to increase the minimum threshold of system collapse.

Each policy has its specific costs, affects financial flows of the system by correcting the impact of the realized risk, and has its own uncertainty in terms of its efficiency of engagement. The total value loss due to the risk realization is calculated, simulated for all the related uncertainties, and its overall distribution is shown in Figure 1 and its legend is provided in Table 1. In the figure, system survival is characterized by the rightmost portion of the distribution, while system collapse appears as the tail in the extreme, leftmost portion — shown within the dashed box.

Using SimDec, the overall value loss is subsequently decomposed by the mitigation policy type and risk realization impact. The decomposition colour scheme employed is displayed in Figure 1. The universe of possible decisions (i.e., which policy to employ) is simulated in a single instance (i.e., the original simulation run) and, accordingly, the effects of all three policies can be visualized simultaneously within the original, overall, single histogram by observing the colour patterns.

It should be further noted that, for this example, the distribution should not be considered in a strict probability theory framework sense, but instead treated as an exploratory analysis using a frequency distribution of the possible outcomes. Since the frequency numbers displayed on the y-axis are largely dependent on the choice of simulation runs (ultimately, the number of data points generated), and do not contribute any additional meaning to the picture, the axis is not displayed. The model is implemented in Excel, and the Monte Carlo simulation and SimDec analysis are both run via the open access VBA code provided in Kozlova and Yeomans (2020).

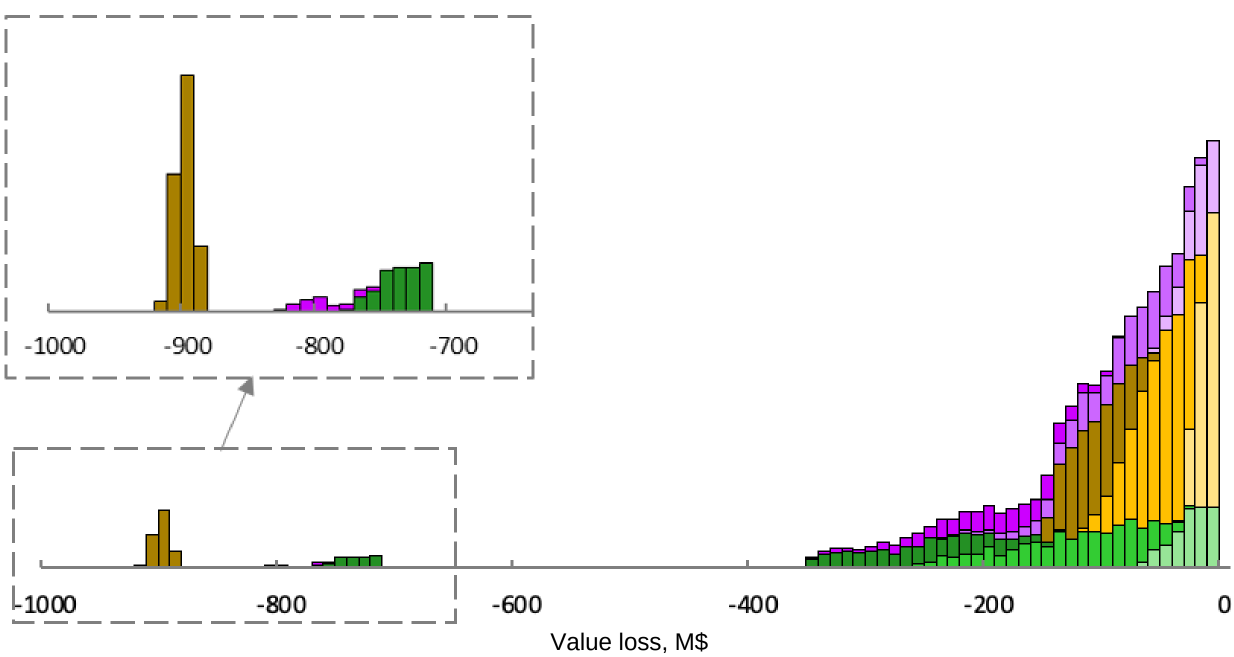

Figure 1. Simulation Decomposition of a hypothetical systemic risk.

Table 1. Legend for Figure 1

Colour	Partition	Strategy	Risk realization
	sc1	Reactive Policy I	low
	sc2		medium
	sc3		severe
	sc4	Reactive Policy II	low
	sc5		medium
	sc6		severe
	sc7	Proactive Policy	low
	sc8		medium
	sc9		severe

Multiple conclusions can be drawn from examining the resulting graphical representation of the system.

1. The system collapse is, indeed, a low-probability/high-impact event. It is represented by the area of the very small tail of the distribution on the left-hand-side of the figure. (See, also, the magnified box).
2. Reactive Policy II, although being more expensive, minimizes the overall value loss in the event of system survival. It can be readily observed that the yellow partition does not exceed 200 monetary units of loss, while the green partition (Reactive Policy 1) stretches down to −350.
3. The Proactive Policy occupies the middle ground in terms of its loss prevention capabilities in the event of system survival. However, it significantly decreases the likelihood of a situation resulting in the collapse of the system.
4. The respective likelihoods of system collapse under each of the three mitigation strategies can be visually approximated by examining the relative area sizes of the colour patterns in the leftmost tail of the distribution. Collapse under the Proactive Policy (dark purple) is much less likely to occur than under either of the other policies. Collapse under Reactive Policy II (dark brown) is considerably more likely than under Reactive Policy I (dark green).
5. Under conditions of system collapse, Reactive Policy II is considerably more expensive than for the other policies and the likelihood of incurring these expenses is substantially higher. Furthermore, although the costs of the Proactive Policy exceed those of Reactive Policy I, the likelihood that these losses are incurred is much lower.

The final decision on policy selection could be ascertained by employing a frequency weighted value loss for each partition (since the frequency of every policy type occurrence is equal in the simulation, such a measure is directly comparable for the different policy types).

Even with all the detail, this case study represents a fairly simplified approach, because it looks only at a single risk and the policy choices are assumed to be mutually exclusive. In reality, multiple risks and policies can interact with each other. Obviously, domino-like events can consist of a primary event, followed by a secondary event, a third event, a fourth event, and so on, with each event leading to different levels of damage — namely, primary effects, secondary effects, tertiary effects, etc. For example, employing a Proactive Policy for one risk may strengthen the system's position against another risk, or, on the contrary, expose the system to another risk to a greater extent. Rarely are such complex models implemented, since most analytics toolkits can seldom make sense of such complexities. However, SimDec is readily able to capture and display the interplay of different risks and policies, which can then be used to efficiently inform decision-making. Irrespective of the overall complexity of the application, as long as a Monte Carlo model can be constructed that captures the cascading issues for the problem being studied, SimDec can be readily employed to evaluate its various output effects either separately or collectively according to the analytical predilections of the decision-maker.

Finally, it has been well-established that the majority of risk management professionals continue to employ qualitative approaches in their risk assessing practices rather than deploying more quantitative analytical methods (Hubbard, 2020). One of the most popular techniques is a colourful risk matrix that assigns each risk to a position in a two-dimensional space dictated by the likelihood and impact of the risk. Because of its visual analytics nature, SimDec could serve to smooth the transition from this qualitative risk matrix approach to more rigorous quantitative uncertainty modeling due to preserving familiar colours of different risk groups. However, SimDec contributes considerably more analytical value when applied to complex models containing numerous nonlinearities and interdependences. Through these lenses, improved systemic risk modeling with its network-like structures and cascading effects would benefit the most from the application of SimDec.

4. Conclusions

In this paper, it has been shown how the novel SimDec analytical technique can be extended into complex assessments of cascading risk analysis and used to quantitatively evaluate situations involving potentially catastrophic, domino-like collapses of entire environmental systems. SimDec can be used to balance the interplay of the uncertain and the actionable in a risk analysis case with cascading effects. The case example facilitated a visual analytical representation of system risk. Specifically, the example visually demonstrated that while the system collapse is indeed a low-probability/high-impact event, the Reactive Policy II, while being more expensive, minimizes the overall value loss in the event of system survival. This observation would not have been uncovered without the visual exposition supplied by SimDec. Furthermore, the Proactive Policy provides a "middle ground" in terms of loss prevention in the event of system survival. However, the Proactive Policy significantly decreases the likelihood and magnitudes of losses in the situation resulting from the collapse of the system. Such factors would not have been revealed — or would not be readily apparent — without the support provided by the SimDec visualization process. Decision-makers could subsequently draw final conclusions by employing a frequency weighted value loss for each policy. Consequently, based upon the outcomes illustrated by the example, one can strongly advocate for the usage of SimDec for the analysis of cascading systemic risks, due to its ability to evaluate complex models while revealing interdependencies, its ease of decision-maker perception, its visualizable analytic capabilities, and its significantly lower computational burdens.

Acknowledgments. The authors would like to thank the editor and two anonymous referees for providing numerous helpful suggestions that lead to a substantially improved paper. This research was supported in part by grant OGP0155871 from the Natural Sciences and Engineering Research Council and by funding from Business Finland, grant # 6713/31/2021.

References

Busby, J.W., Baker, K., Bazilian, M.D., Gilbert, A.Q., Grubert, E., Rai, V., Rhodes, J.D., Shidore, S., Smith, C.A. and Webber, M.E. (2021). Cascading risks: understanding the 2021 winter blackout in texas. *Energy Research and Social Science*, 77, 102106. https://doi.org/10.1016/j.erss.2021.102106

Cho, J., Han, G., Lee, C.J., Lee, S.H. and Yoo, A.Y. (2021). Evidence and prediction regarding the continuous global warming: a severe domino effect. *American Journal of Environmental Science and Engineering*, 5(4), 76-86. https://doi.org/10.11648/j.ajese.20210504.11

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G. and Zanelli, S. (2005). The assessment of risk caused by domino effect in quantitative area risk analysis. *Journal of Hazardous Materials*, 127(1-3), 14-30. https://doi.org/10.1016/j.jhazmat.2005.07.003

Deviatkin, I., Kozlova, M. and Yeomans, J.S. (2021). Simulation decomposition for environmental sustainability: enhanced decision-making in carbon footprint analysis. *Socioeconomic Planning Sciences*, 75(1), 100837. https://doi.org/10.1016/j.seps.2020.100837

Guo, H.D., Zheng, C.Y., Iu, H.H.C. and Fernando, T. (2017). A critical review of cascading failure analysis and modeling of power system. *Renewable and Sustainable Energy Reviews*, 80, 9-22. https://doi.org/10.1016/j.rser.2017.05.206

Guariniello, C. and DeLaurentis, D. (2014). Communications, information, and cyber security in systems-of-systems: assessing the impact of attacks through interdependency analysis. *Procedia Computer Science*, 28, 720-727. https://doi.org/10.1016/j.procs.2014.03.086

Huang, X., Zhou, H. and Zhu, H.B. (2009). A framework for assessing the systemic risk of major financial institutions. *Journal of Banking and Finance*, 33(11), 2036-2049. https://doi.org/10.1016/j.jbankfin.2009.05.017

Hubbard, D.W. (2020). *The failure of risk management: why it's broken and how to fix it*. John Wiley and Sons. ISBN: 9781119522034

Kadri, F. and Chatelet, E. (2013). Domino effect analysis and assessment of industrial sites: a review of methodologies and software tools. *International Journal of Computers and Distributed Systems*, 2(3), 1-10.

JOC. Suez disruption ripples to be felt for months: carriers. https://www.joc.com/maritime-news/suez-disruptionripples-be-felt-months-carriers_20210327.html (accessed April 4, 2022).

Kozlova, M. and Yeomans, J.S. (2019). Multi-variable simulation decomposition in environmental planning: an application to carbon capture and storage. *Journal of Environmental Informatics Letters*, 1(1), 20-26. https://doi.org/10.3808/jeil.201900003

Kozlova, M. and Yeomans, J.S. (2020). Monte carlo enhancement via simulation decomposition: a "must-have" inclusion for many disciplines. *INFORMS Transactions on Education*, 22(3), 147-159. https://doi.org/10.1287/ited.2019.0240

Kozlova, M. and Yeomans, J.S. (2020) Visual analytics in environmental decision-making: a comparison of overlay charts versus simulation decomposition. *Journal of Environmental Informatics Letters*, 4(2), 93-100. https://doi.org/10.3808/jeil.202000047

Kozlova, M., Nykänen, T. and Yeomans, J.S. (2022). Technical advances in aviation electrification: enhancing strategic r&d investment analysis through simulation decomposition. *Sustainability*, 14 (1), 414. https://doi.org/10.3390/su14010414

Lawrence, J., Blackett, P. and Cradock-Henry, N.A. (2020). Cascading climate change impacts and implications. *Climate Risk Management*, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lehar, A. (2005). Measuring systemic risk: a risk management approach. *Journal of Banking and Finance*, 29(10), 2577-2603. https://doi.org/10.1016/j.jbankfin.2004.09.007

Malden, K. and Stephens, S. (2020). Cascading economic impacts of the covid-19 outbreak in China. *U.S.-China Economic and Security Review Commission*, 1-24. https://purl.fdlp.gov/GPO/gpo1544-82

Mukhim, T.A., Tauseef, S.M. and Abbasi, S.A. (2017). Domino effect in chemical process industries triggered by overpressure – formulation of equipment-specific probits. *Process Safety and Environmental Protection*, 106, 263-273. https://doi.org/10.1016/j.psep.2017.01.004

Permal, S. (2021). Cascading effect of COVID-19: de-globalisation and its impact on global governance. *Australian Journal of Maritime and Ocean Affairs*, 1-9. https://doi.org/10.1080/18366503.2021.1962080

Raul, V., Liu, Y.C., Leifsson, L. and Kaleita, A. (2022). Effects of weather on iowa nitrogen export estimated by simulation-based decomposition. *Sustainability*, 14(3), 1060. https://doi.org/10.3390/su14031060

Silva, T.C., da Silva, M.A. and Tabak, B.M. (2017). Systemic risk in financial systems: a feedback approach. *Journal of Economic Behavior and Organization*, 144, 97-120. https://doi.org/10.1016/j.jebo.2017.09.013

Swuste, P., van Nunen, K., Reniersa, G. and Khakzadaa, N. (2019). Domino effects in chemical factories and clusters: an historical perspective and discussion. *Process Safety and Environmental Protection*, 124, 18-30. https://doi.org/10.1016/j.psep.2019.01.015

Teplý, P. and Klinger, T. (2015). Monte carlo simulations: a case study of systemic risk modelling. *In The Second International Conference on Electrical, Electronics, Computer Engineering and their Applications (EECEA2015)*, Manila, Philippines, 43-50. ISBN: 978-1-9491968-07-9 ©2015 SDIWC

Ben Turner. *Climate 'tipping points' could push us past the point-of-no-return after less than 2 degrees of warming*. https://www.livescience.com/climate-domino-effects-close.html (accessed April 4, 2022).

UNEP. The domino effect – biodiversity loss and why it matters? https://www.unep.org/interactive/domino-effect-biodiversity-loss-why-it-matters (accessed April 4, 2022).

The Guardian. Domino-effect of climate events could move earth into a 'hothouse' state. https://www.theguardian.com/environment/2018/aug/06/domino-effect-of-climate-events-could-push-earth-into-a-hothouse-state (accessed April 4, 2022).

Wu, J., Yang, H. and Cheng, Y. (2015). Domino effect analysis, assessment and prevention in process industries. *Journal of Systems Science and Information*, 3(6), 481-498. https://doi.org/10.1515/JSSI-2015-0481

Yang, Q., Scoglio, C.M. and Gruenbacher, D.M. (2021). Robustness of supply chain networks against underload cascading failures. *Physica A: Statistical Mechanics and its Applications*, 563, 125466. https://doi.org/10.1016/j.physa.2020.125466