

Reliability of expert estimates of cascading failures in Critical Infrastructure

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ABSTRACT

Owing to the complexity of Critical Infrastructures and the richness of issues to analyze, numerous approaches are used to model the behavior of CIs. Organizations having homeland security as mission often conduct desktop-based simulations using judgmental assessment of CI interdependencies and cascading failures. Expert estimates concern direct effects between the originally disrupted CI sector and other sectors. To better understand the magnitude of aggregate cascading effects, we developed a system dynamics model that uses expert estimates of cascading failures to compare the aggregate effect of cascading failures with the primary direct cascading failures. We find that the aggregate effect of compounded cascading failures becomes significantly greater than the primary cascading failures the longer the duration of the original disruption becomes. Our conceptually simple system dynamics model could be used to improve desktop-based exercises, since it illustrates consequences that go beyond judgmental assessment.

Keywords

Critical Infrastructure, Cascading failures, Expert assessment, Desktop exercise, Tabletop exercise, Modeling and simulation, Dynamic complexity

INTRODUCTION

Critical Infrastructures (CIs) are essential resources for the performance of society, including its economy and its security, understood as safety of citizens and security of society's assets. They are slightly differently defined in different countries. However, there is general agreement that CIs include government, telecommunication based on ICT (information and communication technology); financial sector; energy supply; water supply; transportation systems; health sector; and security services (first responders, police, military).

CIs are interconnected and, hence, interdependent (see e.g., Macaulay, 2008). As consequence, the performance of any CI influences the performance of other CIs and depends on the other CIs performance. The behavior over time of CIs is extremely complex. There are two kinds of complexity: *detail complexity* and *dynamic complexity*. Detail complexity is related to the system size (number of components and functions of each CI). Beyond detail complexity, the system of CIs is *dynamically complex* (Sterman, 2000, p21-23). Dynamic complexity is characterized by a set of criteria, which all are satisfied by any system of CIs. The system's behavior is time-dependent and changing ("dynamic"); the system is tightly coupled and, hence, governed by feedback effects; the relations between the CI components are mostly nonlinear; managerial interventions are typically resource intensive and costly, thus precluding taking other interventions and determining the future course ("path dependence"); the complexity of the interconnected CIs challenges the human ability to understand them, often resulting in counterintuitive system behavior, inviting interventions that fail or even worsen the situation ("policy resistance"); feedback in the system typically shows up time-delayed, which can lead to long-run responses that are very different from the short-run outcomes, to the extent that solutions that work in the short run may become harmful in the long run.

Detail complexity can be overcome by breaking the problem in subproblems that are easier to solve ("divide and conquer"). The dynamic complexity of systems cannot be mastered by breaking the system in smaller systems, since the complexity arises through the interconnections and interdependencies across any imagined boundary

between subsystems.

In the event of a disruption occurring in some CI, the interdependencies among CIs pave the way for secondary disruptions in other CIs, called cascading effects (Franchina, Carbonelli, Gratta, Crisci and Perucchini, 2011) or cascading failures (Katina and Keating, 2015). The literature has identified several types of interdependencies (see ref. Ouyang, 2014, Table 1 and examples E1-E10, on p45-46)

Owing to the extreme complexity of the CI system, many different approaches, targeting different purposes, exist for analyzing cascading effects. No single approach does full justice to the problem's complexity. To the best of our knowledge, the most recent extensive review of modeling and simulation of interdependent CIs was performed by Ouyang (2014). A useful model is designed for a purpose, viz. answering specific questions, hence the model simplifies the description of reality to preserve what is relevant for the model's purpose, excluding what is irrelevant. Ouyang's review covers six modeling categories for different purposes, viz. empirical approaches, agent-based approaches, system dynamics-based approaches, economic theory-based approaches, network-based approaches, and miscellaneous modeling approaches.

One modeling category is not included among Ouyang's review, viz., desktop-based expert assessment of CI interdependencies and cascading failures, most certainly because peer-reviewed publications of such activities are missing. A desktop exercise (a.k.a. tabletop exercise) is conducted with participants sitting around a table, addressing a fictional scenario. Desktop exercises concerning risk assessment in CIs are also model-based, since they are synthesis of the mental models of practitioners representing each of the CIs as well as the mental models of people with cross-cutting expertise on CIs. The distance from the synthesized mental model for risk assessment to conducting a simulation (i.e., figuring out the consequences of the model) is short. It is in principle possible to extend the modeling exercise to figure out the consequences. Another, more powerful option, is the one we follow in this paper: using the expert estimates in a system dynamics simulation model.

Desktop-based expert assessment of CI interdependencies and cascading failures are typically performed by organizations having homeland security as mission. Hence, such assessments are important. But then, the research question arises: To what extent can expert practitioner assessments account for the aggregate impact of the cascading failures upon a disruption affecting a critical infrastructure? Indeed, since CIs are interdependent, a disruption affecting a given CI will propagate along multiple feedback loops, causing primary, secondary, tertiary, etc. cascading failures (kind of "ripple effect"). Is this ripple effects moderate, in the sense that it gets quickly damped and the contribution of the primary cascading failures dominate? Or can the aggregate contribution of higher order cascading failures make the ripple effect quite considerable, especially if the duration (or the intensity) of the original disruption is large?

To address the research question, we provide the necessary background information in section "Details of the assessment in the Norwegian desktop exercise"; in section "Expert assessment of cascading failures" we review recent work (Laugé, 2014, Laugé, Hernantes and Sarriegi, 2015) that will allow us develop a quantitative simulation model to answer the research question; in section "System Dynamics model" we explain the key equations of the simulation model and the validation process (the full description of the model is given in the appendix). In section "Assessment of the reliability of expert estimates" we present the simulation results; they provide evidence that expert estimates of cascading failures become less accurate when the length of the disruption triggering the cascading failures increases. In the final section, we provide an interpretation of our findings; in addition, we discuss the robustness of our findings, given the limitations of our study.

DETAILS OF THE ASSESSMENT IN THE NORWEGIAN DESKTOP EXERCISE

In this section, we review the findings of the expert assessment of cascading failures in a risk analysis of a cyber-attack on the Norwegian telecommunication CI sector (DSB, 2015). The corresponding desktop exercise was coordinated by the Norwegian Directorate of Civil Protection (abbreviated DSB, from the initials in the Norwegian name). The risk analysis of a cyber-attack was part of the "National Risk Analysis 2014", considering disasters that may affect the Norwegian society.

Two one-day seminars were conducted. Seminar 1, done in Oslo 12th June 2014, assembled 30 expert participants representing the following CI sectors: energy supply; transportation systems; emergency/security services; water supply; financial sector; health sector; and telecommunication sector. The scenario of seminar 1 was a cyber-attack causing complete disruption lasting 5 days of the ICT CI's transport network in Norway. The leading question posed at seminar 1 was: How will the critical functions in *your own CI sector* be affected by the disruption in the telecommunication sector.

The experts representing a given CI were asked to describe how the disruption in the telecommunication critical infrastructure would impact the performance of their own CI. The detailed answers were afterward mapped to a qualitative scale of values [small, medium, large] for the impact. Thus, the desktop exercise elicited expert

assessments of *primary* cascading failures based on judgmental methods. Note that no quantitative forecasting methods were used, i.e., no time series data were produced. No doubt because of the duration of the event (one day), less effort was dedicated for how the cascading failures further propagated to other CIs and which were the secondary, tertiary, etc. impacts. In fact, the report does not provide qualitative estimates, small/medium/large impact, for propagation of the primary cascading failures to induce secondary cascading failures, and further down to tertiary, quaternary, etc. cascading failures.

Leaving out the detailed description of the cascading failures, the overall assessment was that a cyber-attack causing complete disruption of the ICT CI's transport network for 5 days in Norway would have:

- high impact on the security CI sector;
- high impact on the financial CI sector;
- high impact on railways and airline traffic, and moderate impact on other transport CIs;
- low impact on the water supply CI sector;
- low impact on the energy supply CI sector; but then secondary cascading failures from minor disruptions on energy infrastructure would increase significantly the disruption of ICT CI;
- moderate impact on the health CI sector.

Seminar 2, conducted 1st September 2014, addressed other consequences of the hypothetical cyber-attack (how it would affect citizens; its influence on societal indicators; losses accrued). Seminar 2 is out of scope for our study.

It is not possible to answer our research question with data from the report by the Norwegian Directorate of Civil Protection (DSB, 2015): 1) the expert assessment did not go beyond assessment of the impact of primary cascading failures; and 2) no further and deeper desktop exercise was conducted that would provide a benchmark to determine the degree to which the impact assessments of the experts are off the mark.

Thus, we ask if there are studies providing estimates of cascading failures across all CI sectors? That is, we ask for estimates of cascading failures considering all possible values of j and k , how a disruption in a sector j (CI_j) affects other CI sector k (CI_k).

EXPERT ASSESSMENT OF CASCADING FAILURES

Fortunately, a Ph.D. research project conducted by Ana Laugé, with a Ph.D. thesis available electronically (Laugé, 2014) and a journal publication (Laugé, Hernantes and Sarriegi, 2015), provides the data we are looking for.

Laugé conducted a survey with CI managers to obtain estimates on a Likert scale for cascading impacts caused by disruptions of different durations in a CI_j , where the index j , running from 1 to 11, refers to the following CI sectors: Energy supply; ICT; Water supply; Food; Health; Financial; Order & Safety; Civil Administration; Transport; Chemical & Nuclear; and Space & Research, respectively. She obtained estimates for the cascading impacts on CI_k , where the index k run through all values between 1 and 11 (of course, excluding $j=k$). Laugé asked the experts to provide estimates of direct dependencies between any two CIs in case the disruption period was less than two hours, less than six hours, less than 12 hours, less than 24 hours, more than 24 hours and more than one week. She computed averages of the provided estimates, resulting in tables for each of the cases. As example, see Figure 1, adapted from ref. (Laugé, 2014), p175.

Now, as in the case of the Norwegian desktop exercise, the experts participating in Laugé's survey provided estimates for how much a total disruption in CI sector j (CI_j) impacted another CI sector k (CI_k). But as opposed to the Norwegian case, where only one value of j was considered (viz. the telecommunications Critical Infrastructure), in Laugé's case she obtained an 11x11 matrix describing all possible impacts on other CIs coming from any disrupted CI. Note that the expert estimates tacitly include expert knowledge about response measures in the affected CI sectors. In other words, notwithstanding that the net impact of the cascading failures is an assessment of failures, we must trust that the experts' knowledge included expertise about preparedness, mitigation and response capability in *their home CI*.

Using Laugé's data, it becomes then possible to use a system dynamics model embedding the cascading failures estimates from Laugé's Ph.D. thesis (Laugé, 2014) to compare how reliable the expert estimates are. The trick is to compare two simulation outcomes, viz. the outcome considering the unrestricted propagation of the cascading failures vs the outcome that only accounts for the primary cascading failures.

Effect on Failed CI	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy	-	4.1	3.7	4.6	4.6	4.3	5	3	4	5	3
ICT	4.3	-	2.7	4.1	4	4.3	4.3	2.8	4.2	5	2.7
Water	3.2	2.4	-	4	3.4	0.7	3.7	2.8	2	3.7	1.7
Food	2.5	1.6	1	-	3.4	0	3.7	1.2	0.6	1.3	1.7
Health	1.8	1.6	0.7	2.2	-	0.3	4.3	2.8	0.8	1	1.3
Financial	2.7	1.4	1.3	3.1	1.8	-	1.7	0.3	1.4	2	1
Order & Safety	3.2	1.7	1.7	2.9	2.4	4	-	2.8	1.8	1.3	1.3
Civil Admin.	1.8	2.1	0.7	1.8	2.8	1.3	1.3	-	1.8	1.7	1.7
Transport	2.8	2.3	2	4.3	3.2	2.7	3.7	2.6	-	1.7	2
Chemical & Nuclear	2.7	1.6	2.3	1.9	1.6	0	3.3	1.4	0.8	-	0.3
Space & Research	0.8	1.6	0.3	0.4	0	0	0.7	0.6	0.6	0	-

Figure 1. Table showing impacts on a CI if other CIs are down for more than 24 hours © Ana Laugé

SYSTEM DYNAMICS MODEL

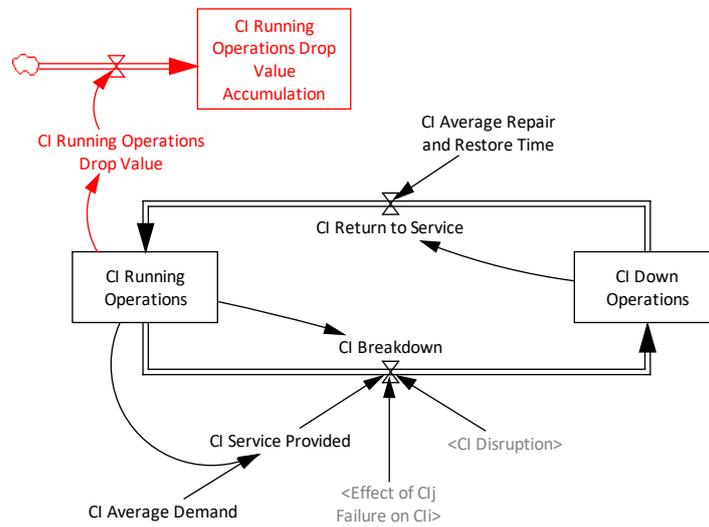


Figure 2: CI System Dynamics Structure (with vector variables – see main text)

The system dynamics model used to produce the results of this research is an extended version of the model published in Abdelgawad, Farstad and Gonzalez (2019), which was inspired by the model built by Canzani (2016). As depicted in Figure 2 (system dynamics structure in black color), in our model every CI has a CI_i Running Operations level which contains all this CI's functioning operations divided by its all operations capacity of this CI, i.e. the fraction of the functional operations. A disruption depletes the running operations through the CI_i Breakdown rate, and increases the value of the CI_i Down Operations level, which contains the non-functional operations fraction of all operations of this CI. A recovery process will restore the operations back to CI_i Running Operations through the CI_i Return to Service rate. Our model utilized the Vensim DSS subscripts to vectorize the same system dynamics structure/equations to be used for all above mentioned 11 CIs

included in Laugé's research (that is, the index i assumes values $1 \dots 11$, labeling eleven CI sectors).

In the following, we provide a description of the key equations and parameters along with the validation of our model (see also Abdelgawad, Farstad and Gonzalez, 2019, p631-634). In the appendix, we provide a full description of the model, including documentation of parameters and equations.

Both CI_i *Running Operations* and CI_i *Down Operations* levels are respectively defined as:

$$CI_i \text{ Running Operations} = \int_0^t (CI_i \text{ Return to Service} - CI_i \text{ Breakdown}) \cdot dt + 100 \quad (1)$$

and:

$$CI_i \text{ Down Operations} = \int_0^t (CI_i \text{ Breakdown} - CI_i \text{ Return to Service}) \cdot dt \quad (2)$$

It should be noted that at the beginning of the simulation ($t = 0$) CI_i *Running Operations* = 100 while CI_i *Down Operations* = 0, and this is why 100 was added to the former integration.

Furthermore, CI_i *Breakdown*¹ and CI_i *Return to Service* rates are respectively defined as:

$$CI_i \text{ Breakdown} = CI_i \text{ Disruption} + CI_i \text{ Running Operations} \cdot \sum_{j \in J} \left(\text{Effect of } CI_j \text{ Failure on } CI_i \cdot \frac{1 - CI_i \text{ Service Provided}}{|J|} \right) \quad (3)$$

Where $|J|$ represents the cardinality (sum of all elements in a set representing the CIs considered), J is an ordered 11-tuple defined as $J = (\text{Energy}, \text{ICT}, \text{Water}, \dots, \text{Space \& Research})$, and:

$$CI_i \text{ Return to Service} = \frac{CI_i \text{ Down Operations}}{CI_i \text{ Average Repair and Restore Time}} \quad (4)$$

The CI_i *Return to Service* rate moves the failed operations accumulated inside CI_i *Down Operations* level back to CI_i *Running Operations* level over an average period of time that is equal to the average total time required to restore and repair these failed operations.

In the model, the CI_i *Service Provided* is defined as a piecewise function:

$$CI_i \text{ Service Provided} = \begin{cases} 1, & CI_i \text{ Running Operations} \geq CI_i \text{ Average Demand} \\ \frac{CI_i \text{ Running Operations}}{CI_i \text{ Average Demand}}, & CI_i \text{ Running Operations} < CI_i \text{ Average Demand} \end{cases} \quad (5)$$

he CI_i *Average Demand* was arbitrarily assumed to be 95% of this CI's full capacity required to supply the demand of its dependent CIs.

Laugé's research presented the effects of all failed CIs on all other CI in different tables. Each of these tables represents a different disruption duration, which means that the effect of certain failed CI on another CI changes over time as far as the failure continues. The successive effects of one failed CI on another were extracted from Laugé's tables and were pushed in a separate vector for each pair of CIs using time (disruption durations) as its index. Figure 3 shows Laugé's successive tables as well as marking the effects for the ICT Energy pair. These vectors of each pair of CIs were included in the model as time-based graphical functions to account for these over-time changes or dynamics. These graphical functions were included in the model through *Effect of CI_j Failure on CI_i Data*. The graphical function of the effect of CI_2 failure on the CI_1 is shown in Figure 4 as an example ($i=1$ denotes Energy, while $j=2$ denotes ICT).

¹ In the model, a more complex equation for CI_i *Breakdown* was used for technical reasons. However, the simplified version showed in the paper will act similarly in general.

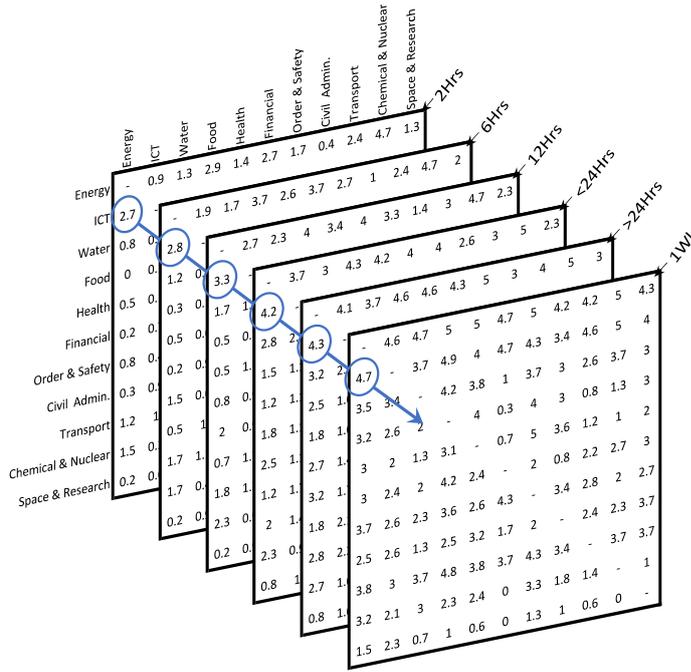


Figure 3. CI Interdependencies for Different Durations (Abdelgawad, Farstad and Gonzalez, 2019)

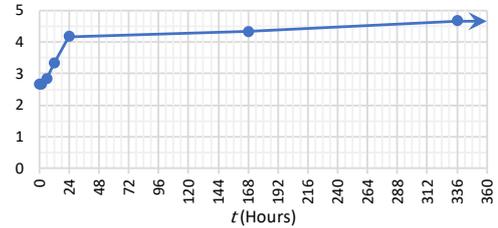


Figure 4. Effect of CI₂ Failure on CI₁ over Time (Disruption Durations) [i=1 denotes Energy, while j=2 denotes ICT] (Abdelgawad, Farstad and Gonzalez, 2019)

In the model, a disruption occurring to any of the CIs is produced in the CI Disruption structure shown in Figure 6 (structure in black color). The CI_i Disruption is defined as:

$$CI_i \text{ Disruption} = CI_i \text{ Disruption Magnitude} \cdot \Pi_{t_d, (t_d + \Delta T)}(t) \tag{6}$$

$\Pi_{t_d, (t_d + \Delta T)}(t)$ is a Boxcar function (Weisstein), where: t denotes the time or the simulation time in the case of the model, t_d denotes the beginning of the disruption or the CI_i Disruption Time in the model, and ΔT denotes the CI_i Disruption Duration. In piecewise notation, $\Pi_{t_d, (t_d + \Delta T)}(t)$ can be defined as (Figure 5 shows its graphical representation):

$$\Pi_{t_d, (t_d + \Delta T)}(t) = \begin{cases} 0, & t < t_d \\ 1, & t_d \leq t < (t_d + \Delta T) \\ 0, & t \geq (t_d + \Delta T) \end{cases}$$

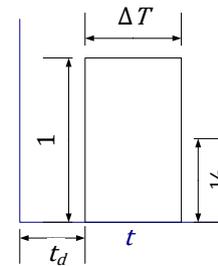


Figure 5. Boxcar function graph

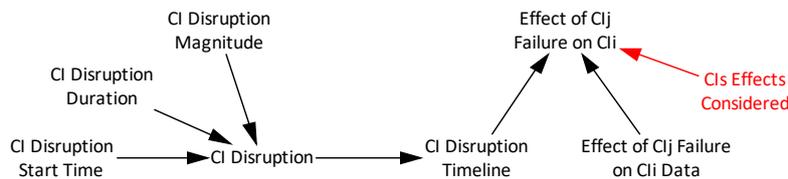


Figure 6. CI Disruption Structure

The beginning of a disruption through CI_i Disruption triggers the above mentioned time-based graphical functions that account for the dynamics recognized via Laugé’s interdependencies tables. In the model, the beginning of a disruption starts a new timeline different from the simulation timeline. This new timeline (generated inside CI_i Disruption Timeline) continues as long as the disruption remains and stops otherwise. Figure 7 shows the original timeline of the model (i.e. simulation time) and another disruption timeline for a CI disruption that

starts at hour 48 and ends 24 hours later.

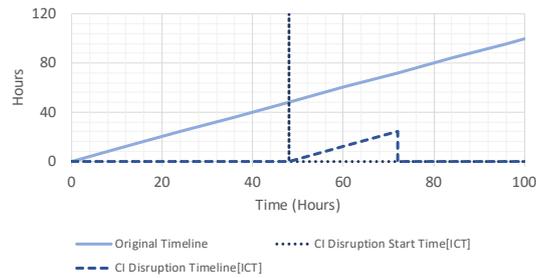


Figure 7. Generated Disruption Timeline

MODEL TESTING AND VALIDATION

To detect any issues in our model as well as increase trust in our model, we have used all the applicable tests introduced by Forrester and Senge (1996) and recommended by Sterman (2000). Our model inherited the same boundaries and basic structure of Canzani's model (Canzani, 2016), which although a simple model, includes all necessary components to study a CI disruption effect at this level of aggregation, making it possible for the model to pass the boundary adequacy test (Sterman, 2000, Forrester and Senge, 1996, Barlas, 1996) After including the fixes introduced in Abdelgawad, Farstad and Gonzalez (2019), the model is more consistent with the relevant descriptive knowledge of the system enabling it to pass the structure assessment (Sterman, 2000, Barlas, 1996).

Other than a few arbitrarily chosen values which were included in the model, all other parameters were retrieved from Laugé's survey. Accordingly, the parameters are consistent with relevant descriptive and numerical knowledge of the system (Sterman, 2000, Forrester and Senge, 1996, Barlas, 1996). Unit check of Vensim DSS (Ventana Systems, 2009) assured the model dimensional consistency (Sterman, 2000, Forrester and Senge, 1996, Barlas, 1996). Moreover, the model was tested for integration errors (Sterman, 2000), and the combination of Euler's method and time step of 0.125 was found suitable.

The model's robustness has been tested with successful results under extreme conditions (Sterman, 2000, Forrester and Senge, 1996, Barlas, 1996). To further test the model's robustness under assumed uncertainties in parameters and initial values, sensitivity analysis (Sterman, 2000, Forrester and Senge, 1996) was applied to the model using. There is no information about the probability distribution of the parameters, accordingly, we have assumed Uniform probability distribution for all parameters. We did not have any benchmark for the numerical changes in the model variables due to the change in any of the tested parameters to test our results against. However, in all sensitivity tests we have conducted, we have not spotted any change in the modes of behavior, consequently, no policy implications change due to the change in the values of the parameters. Therefore, the results were found acceptable.

ASSESSMENT OF THE RELIABILITY OF EXPERT ESTIMATES

To find the difference between the case in which the cascading failures among the CIs are taken into consideration and in which they are not, we have made some changes to the system dynamics model used in Abdelgawad, Farstad and Gonzalez (2019). The first change was adding a new variable *CI_j Effect Considered*, shown in Figure 6 (in red color). This variable is an eleven elements binary vector. Every element corresponds to a CI sector, *CI_i*. This vector controls which CI interdependencies to be taken into consideration during the simulation, i.e. it controls which elements of *Effect of CI_j Failure on CI_i Data* that would be included in *Effect of CI_j Failure on CI_i*.

For example, in the case of considering only the direct effects caused by the failure of ICT CI on all other CIs, and not considering the propagated cascading failures of all other CIs, elements of the vector *CI_i Effect Considered* would be all zeros except the second element (denotes the ICT CI) which would be one. i.e. *CI_j Effect Considered* = [0 1 0 ... 1]. In such a case, the value of *Effect of CI_j Failure on CI_i* would be expressed as follows:

$$\text{Effect of } CI_1 \text{ Failure on } CI_i = 0 \cdot \text{Effect of } CI_1 \text{ Failure on } CI_i \text{ Data}$$

$$\text{Effect of } CI_2 \text{ Failure on } CI_i = 1 \cdot \text{Effect of } CI_2 \text{ Failure on } CI_i \text{ Data}$$

$$\text{Effect of } CI_3 \text{ Failure on } CI_i = 0 \cdot \text{Effect of } CI_3 \text{ Failure on } CI_i \text{ Data}$$

⋮

Effect of CI_{11} Failure on $CI_i = 0 \cdot$ Effect of CI_{11} Failure on CI_i Data

In matrix form:

Effect of CI_j Failure on $CI_i = [0 \ 1 \ 0 \ \dots \ 1] \cdot$ Effect of CI_j Failure on CI_i Data

In this equation, only direct effects of a failed ICT CI on all other CIs are taken into consideration, however, the cascading failures from the affected CIs will not be propagated. On the other hand, in the normal case in which all cascading failures are considered, elements of the vector CI_j Effect Considered will be all ones. Accordingly, the Effect of CI_j Failure on CI_i would be:

Effect of CI_j Failure on $CI_i = [1 \ 1 \ \dots \ 1] \cdot$ Effect of CI_j Failure on CI_i Data

Using this new vector CI_j Effect Considered, we were able to simulate the model with the higher order cascading failures OFF and ON. To clarify the difference between the two cases, we will present the detailed results of two different simulation cases, one that excludes the higher order cascading failures (denoted by: cascading OFF) and another that includes the cascading failures (cascading ON). In both cases the model was injected with a disruption in the ICT CI that started after 48 hours from the beginning of the simulation with the a magnitude of ten (which is the highest disruption magnitude defined by Canzani (2016)), and ended after 24 hours. The left graph in Figure 8 shows the Running Operations behavior over time for all CIs in case the higher order cascading failures are not included, while the right graph shows the same Running Operations in case that all the cascading failures are included.

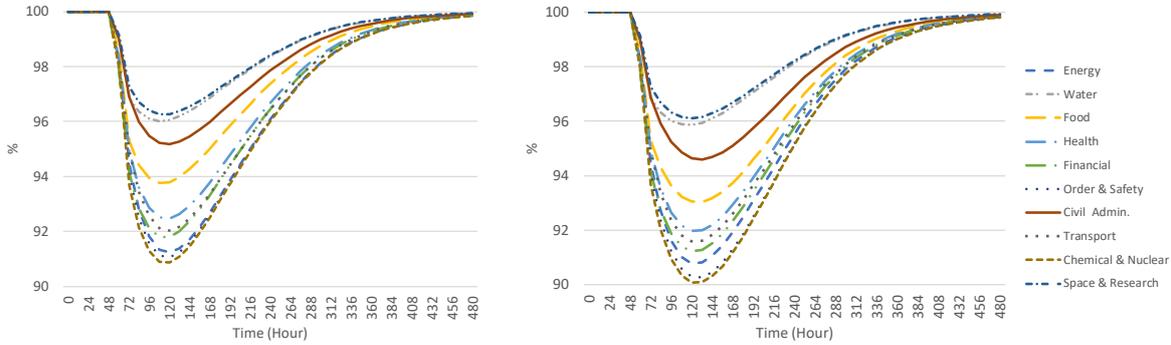


Figure 8. Running Operations (Left: Cascading OFF | Right: Cascading ON)

Figure 9 shows the Service Provided by all CIs in both simulations mentioned above, higher order cascading failures are not included in the left graph, while included in the right graph.

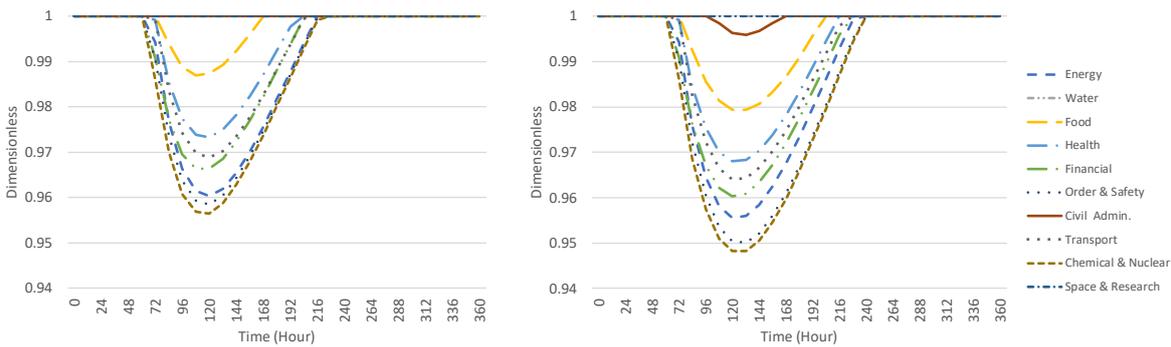


Figure 9. Services Provided (Left: Cascading OFF | Right: Cascading ON)

Differences between the two simulation cases can be visually identified through Figure 8 and Figure 9. Nonetheless, to quantitatively assess the difference between them, our second addition to the model (shown in red color in Figure 2) calculates CI_i Running Operations Drop Value, which is defined as:

$$CI_i \text{ Running Operations Drop Value} = 100 - CI_i \text{ Running Operations}$$

Then the new structure calculates the area under the curve of CI_i Running Operations Drop Value as well. The area under the curve is the accumulation or the integration of the CI_i Running Operations Drop Value over

time, i.e.:

$$CI_i \text{ Running Operations Drop Value Accumulation} = \int_0^t CI_i \text{ Running Operations Drop Value} \cdot dt$$

At the beginning of the simulation $CI_i \text{ Running Operations Drop Value Accumulation} = 0$ by design. Figure 10 shows the $CI_i \text{ Running Operations Drop Value Accumulation}$ of all CIs in both cases, cascading failure are excluded in the left graph, and included in the right graph.

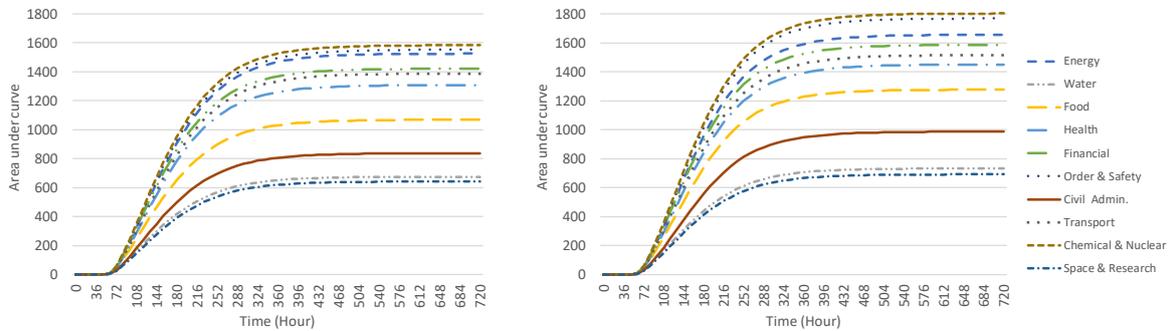


Figure 10. Area under the Curve (Left: Cascading OFF | Right: Cascading ON)

To compare the difference between the two areas under the curve per CI of both cascading ON and OFF simulations, we used the following equation:

$$\Delta = \frac{\text{Area under Curve}_{\text{Cascading ON}} - \text{Area under Curve}_{\text{Cascading OFF}}}{\text{Area under Curve}_{\text{Cascading OFF}}}$$

For a more comprehensive set of results, we have conducted another five experiments. In each experiment, we have changed the disruption period and kept everything else as it was. The disruption periods we have used matched Laugé disruption durations, i.e. two hours, six hours, 12 hours, 24 hours, 168 hours, and 336 hours. Table 1 shows the identified differences Δ per CI as resulted from these different ICT CI disruption durations. Figure 11 shows the same results in a graph.

Table 1. The Identified Differences Δ Resulted from Different ICT CI Disruption Durations as Defined by Laugé

ICT CI Disruption Duration						
	2 Hours	6 Hours	12 Hours	24 Hours	168 Hours	336 Hours
Δ per CI						
Energy	0 %	0 %	4.37 %	8.62 %	23.47 %	23.69 %
Water	0 %	0 %	5.01 %	8.39 %	15.72 %	13.72 %
Food	0 %	0 %	10.49 %	19.43 %	42.73 %	39.55 %
Health	0 %	0 %	5.38 %	10.86 %	31.03 %	32.31 %
Financial	0 %	0 %	6.38 %	11.69 %	27.03 %	26.25 %
Order & Safety	0 %	0 %	6.82 %	13.87 %	39.06 %	40.62 %
Civil Admin.	0 %	0 %	9 %	17.78 %	43.74 %	40.22 %
Transport	0 %	0 %	4.90 %	9.33 %	23.13 %	22.08 %
Chemical & Nuclear	0 %	0 %	7.33 %	13.91 %	34.37 %	34.38 %
Space & Research	0 %	0 %	4.05 %	7.55 %	18.46 %	15.91 %

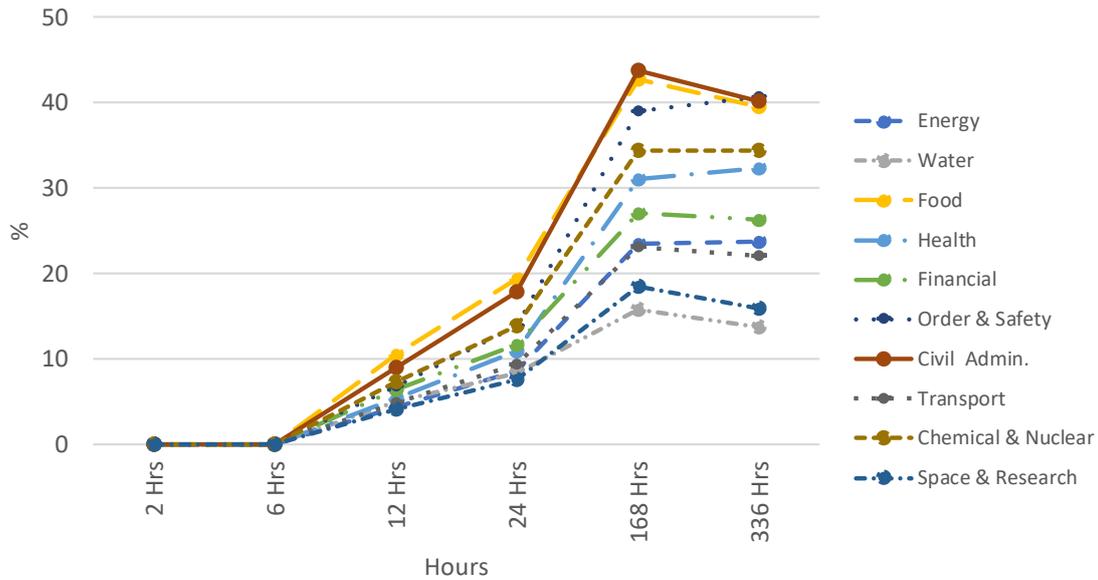


Figure 11. Behavior of the Identified Differences Δ Resulted from Different ICT CI Disruption Durations as Defined by Laugé

CONCLUSION

Desktop simulation exercises have been often employed to engage first-responders in relevant scenarios related to emergency management, with emergency understood as generic term for crisis and disaster situations (Smith, Dowel and Ortega-Lafuente, 1999). Most often, the purpose of emergency management desktop exercises is to train the different role-players in situations where they would have to act together. The literature distinguishes between two main categories of desktop simulation exercises: scenario planning and scenario-based planning (Van Niekerk, Coetzee, Botha, Murphree Michael, Fourie, Le Roux, Wentink, Kruger, Shoroma, Genade, Meyer and Annandale, 2014).

Our point of departure was a desktop modeling exercise targeting expert assessment of *primary* cascading failures, specifically, the immediate consequences upon other CI sectors triggered by a disruption in the telecommunication CI sector (the disruption being a complete breakdown of five days duration of the telecommunication CI sector owing to a sophisticated cyber-attack). We asked the questions: 1) Is the aggregate impact of the cascading failures moderate, in the sense that this “ripple effect” is quickly damped and the contribution of the primary cascading failures dominate? Or can the aggregate contribution of higher order cascading failures make the ripple effect quite considerable, especially for large values of the duration (or the intensity) of the original disruption?

To answer the question, we developed a system dynamics simulation model using estimates of primary cascading effects obtained by Laugé (Laugé, 2014, Laugé, Hernantes and Sarriegi, 2015). The simulation results show, indeed, that the ripple effect becomes more and more significant the longer the duration of the original disruption.

For an explanation, we point the reader’s attention to the richness of feedback loops in a CI system. The system dynamics model in Figure 2, describing a system of 11 interdependent CI sectors has a huge number of feedback loops (a total of 308,152 loops, in fact). The “simplicity” of the model structure is deceptive, because the choice of vector variables that makes the model diagram compact hides the pathways of propagation of cascading failures along the model’s feedback loops.

Owing to the huge number of feedback loops, the original disruption finds many pathways to propagate to other CI sectors and cause failures (primary cascading failures). In turn, the primary cascading failures can propagate along the many pathways to cause secondary cascading failures, etc. Intuitively, one expects damping of the failures, the higher the order of the cascading failures is. Intuitively also, one expects that the damping effect becomes less and less pronounced the longer the duration of the original disruption is. Accordingly, our simulation results should not be surprising.

Surprising results or not, our research question needed to be posed and addressed. Ultimately, the question relates to the human ability to intuitively deal with complexity. Here, the issue is the ability of human minds, even if they are expert ones, to intuitively assess the contribution of a huge number of pathways to the ripple effect. In the

light of our results, since the desktop assessment (DSB, 2015) concerned a total disruption of the telecommunication CI sector of five days duration some doubts arise as to the ability of the experts to account for the aggregate effects of cascading failures in the scenario. It is hard to expect that the experts' assessment is anchored in mental aggregation and computation of cascading failures up to higher orders.

How robust are our results? We admit that the data set from Laugé refers to assessment of cascading failures in Spanish Critical Infrastructure while our research question emerged in the context of Norwegian Critical Infrastructure. Hence, we cannot claim that the quantitative results of our simulation must be accurate renderings of the situation in Norway (or for that matter in other countries). Also, we have restricted our simulation to a plausible set of parameters for repair and restores times. But we would expect the validity of the qualitative finding of more significant ripple effect, the longer the duration of the original disruption.

Owing to the practical relevance of assessment of cascading failures and the fact that here the interests of practitioners and researchers meet, we hope to trigger the interest of these communities to elicit and test relevant data.

Once our results are confirmed by other researchers and with more solid data, we believe that the proposed system dynamics model could be a valuable addition to desktop exercises. Its diagram structure (Figure 2) is quite compact and, in a sense, simple and intuitive. Its worth for practitioners would be anchored in the model's ability to extend human assessment of primary cascading failures to include higher order cascading failures (i.e., the totality of the ripple effect).

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APPENDIX

In this appendix, we present a full description of our model. The description was generated based on the model’s Vensim file using SDM-DOC (the .NET version) (Argonne National Laboratory, 2014), described in (Martinez-Moyano, 2012). Some manual editing and cleaning were conducted. The following table contains the variables’ counts, symbols, types, and abbreviations used in the description below.

L: Level (6/66)*	F: Flow (6)	A: Auxiliary (17)	C: Constant (18)	T: Lookup (1/11)**	D: Data (1)	[sub] Sub: Subscripts (2)
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* (state variables/total stocks).

** (lookup variables/lookup tables).

Type	Variable Name and Description
#1 C 	CI Average Demand (Dimensionless) CI Average Demand [CIi] = 95 Description: <i>An assumption is made that all CI perform on average at 95 percent of full capacity at any given time to supply their demand to each other.</i> Present in 1 view: <ul style="list-style-type: none"> All CIs Used by: <ul style="list-style-type: none"> CI Service Provided
#2 C 	CI Average Demand ICT (Dimensionless) CI Average Demand ICT [CIi] = 95 Description: <i>Like CI Average Demand.</i> Present in 1 view: <ul style="list-style-type: none"> Only ICT Used by: <ul style="list-style-type: none"> CI Service Provided ICT
#3 C 	CI Average Repair and Restore Time (Hours) CI Average Repair and Restore Time [CIi] = 72 Description: <i>The sum of the total average repair and restore time variables from Canzani’s model.</i> Present in 1 view: <ul style="list-style-type: none"> All CIs Used by: <ul style="list-style-type: none"> CI Return to Service
#4 C 	CI Average Repair and Restore Time ICT (Hours) CI Average Repair and Restore Time ICT [CIi] = 72 Description: <i>Like CI Average Repair and Restore Time.</i> Present in 1 view: <ul style="list-style-type: none"> Only ICT Used by: <ul style="list-style-type: none"> CI Return to Service ICT
#5 F,A 	CI Breakdown (Dimensionless/Hour) CI Breakdown [CIi] = MIN (CI Running Operations[CIi]/ Fastest Draining Time ,CI Disruption[CIi]+ Unit Normalization* CI Running Operations[CIi] / 100 * ZIDZ (((Effect of CIj Failure on CIi[CIi,Energy] * (1 - CI Service Provided[Energy])) + (Effect of CIj Failure on CIi[CIi,ICT] * (1 - CI Service Provided[ICT])) + (Effect of CIj Failure on CIi[CIi,Water] * (1 - CI Service Provided[Water])) + (Effect of CIj Failure on CIi[CIi,Food] * (1 - CI Service

Type	Variable Name and Description
	<p> $\text{Provided[Food]}) + (\text{Effect of CIj Failure on CIi[CIi,Health]} * (1 - \text{CI Service Provided[Health]}) + (\text{Effect of CIj Failure on CIi[CIi,Financial]} * (1 - \text{CI Service Provided[Financial]}) + (\text{Effect of CIj Failure on CIi[CIi,Public and legal order and safety]} * (1 - \text{CI Service Provided[Public and legal order and safety]}) + (\text{Effect of CIj Failure on CIi[CIi,Civil administration]} * (1 - \text{CI Service Provided[Civil administration]}) + (\text{Effect of CIj Failure on CIi[CIi,Transport]} * (1 - \text{CI Service Provided[Transport]}) + (\text{Effect of CIj Failure on CIi[CIi,Chemical and nuclear industry]} * (1 - \text{CI Service Provided[Chemical and nuclear industry]}) + (\text{Effect of CIj Failure on CIi[CIi,Space and research]} * (1 - \text{CI Service Provided[Space and research]})) , \text{Max Effect of CIj Failure on CIi})$ </p> <p>Description: <i>The breakdown rate from running operations to down operations with and added specific disruption, to simulate multiple disruption-scenarios. The rate emulates cascading effects from the other CI's. The If then else clause prevents the level from reaching a negative value. The equation uses the respective e(ij) values from the subscript array.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Down Operations CI Running Operations
<p>#6 F,A WAB →</p>	<p>CI Breakdown ICT (Dimensionless/Hour)</p> <p> $\text{CI Breakdown ICT [CIi]} = \text{MIN} (\text{CI Running Operations ICT[CIi]} / \text{Fastest Draining Time ICT ,CI Disruption[CIi]} + \text{Unit Normalization} * \text{CI Running Operations ICT[CIi]} / 100 * \text{ZIDZ} ((\text{Effect of CIj Failure on CIi ICT[CIi,Energy]} * (1 - \text{CI Service Provided ICT[Energy]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,ICT]} * (1 - \text{CI Service Provided ICT[ICT]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Water]} * (1 - \text{CI Service Provided ICT[Water]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Food]} * (1 - \text{CI Service Provided ICT[Food]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Health]} * (1 - \text{CI Service Provided ICT[Health]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Financial]} * (1 - \text{CI Service Provided ICT[Financial]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Public and legal order and safety]} * (1 - \text{CI Service Provided ICT[Public and legal order and safety]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Civil administration]} * (1 - \text{CI Service Provided ICT[Civil administration]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Transport]} * (1 - \text{CI Service Provided ICT[Transport]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Chemical and nuclear industry]} * (1 - \text{CI Service Provided ICT[Chemical and nuclear industry]}) + (\text{Effect of CIj Failure on CIi ICT[CIi,Space and research]} * (1 - \text{CI Service Provided ICT[Space and research]}))) , \text{Max Effect of CIj Failure on CIi ICT}))$ </p> <p>Description: <i>Like CI Breakdown.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Down Operations ICT CI Running Operations ICT
<p>#7 A WAB</p>	<p>CI Disruption (Dimensionless/Hour)</p> <p> $\text{CI Disruption [CIi]} = \text{PULSE TRAIN} (\text{CI Disruption Start Time[CIi]} , \text{CI Disruption Duration[CIi]} , \text{Time between CI Disruption Durations[CIi]} , \text{CI Disruption Durations Final Time[CIi]}) * \text{CI Disruption Magnitude[CIi]}$ </p> <p>Description: <i>The disruptive function d(t), implemented by using the PULSE function to simulate disruptive behaviour at a point in time t with a duration T, multiplied by the Disruption magnitude.</i></p> <p>Present in 2 views:</p> <ul style="list-style-type: none"> All CIs Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown CI Breakdown ICT CI Disruption Timeline CI Disruption Timeline Trigger Delayed CI Disruption
<p>#8 C</p>	<p>CI Disruption Duration (Hours)</p> <p> $\text{CI Disruption Duration [CIi]} = 0, 336, 0, 0, 0, 0, 0, 0, 0, 0, 0$ </p>

Type	Variable Name and Description
WAB	<p>Description: <i>The duration of the disruption.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Disruption
#9 C WAB	<p>CI Disruption Durations Final Time (Hours)</p> <p>CI Disruption Durations Final Time [Ci] = 720, 720, 720, 720, 720, 720, 720, 720, 720, 720, 720</p> <p>Description: <i>to limit the number of disruptions, this ends the disruption train.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Disruption
#10 C WAB	<p>CI Disruption Magnitude (Dimensionless/Hour)</p> <p>CI Disruption Magnitude [Ci] = 0, 10, 0, 0, 0, 0, 0, 0, 0, 0, 0</p> <p>Description: <i>The dimensionless magnitude of the disruption, ranging from 0 (no disruption), to 10 (complete breakdown).</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Disruption
#11 C WAB	<p>CI Disruption Start Time (Hours)</p> <p>CI Disruption Start Time [Ci] = 0, 48, 0, 0, 0, 0, 0, 0, 0, 0, 0</p> <p>Description: <i>The time during the simulation in which the disruption occurs.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Disruption
#12 A WAB	<p>CI Disruption Timeline (Hours)</p> <p>CI Disruption Timeline [Ci] = IF THEN ELSE (CI Disruption[Ci]> 0,Time- CI Disruption Timeline Trigger[Ci] ,0)</p> <p>Present in 2 views:</p> <ul style="list-style-type: none"> All CIs Only ICT <p>Used by:</p> <ul style="list-style-type: none"> Effect of Cij Failure on Ci Effect of Cij Failure on Ci ICT
#13 A WAB	<p>CI Disruption Timeline Trigger (Hours)</p> <p>CI Disruption Timeline Trigger [Ci] = SAMPLE IF TRUE((CI Disruption[Ci]- Delayed CI Disruption[Ci])<> 0,Time ,0)</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Disruption Timeline
#14 L WAB	<p>CI Down Operations (Dimensionless)</p> <p>CI Down Operations [Ci] = \int CI Breakdown[Ci]- CI Return to Service[Ci] dt + [0]</p> <p>Description: <i>The down-phase, where the Energy CI has a lack of output in production. Dependent on the rate, disruption and cascading factors.The assumption is made that at t=0 the level is empty.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Return to Service
#15	<p>CI Down Operations ICT (Dimensionless)</p>

Type	Variable Name and Description
L 	<p>CI Down Operations ICT [CIi] = \int CI Breakdown ICT[CIi]- CI Return to Service ICT[CIi] dt + [0]</p> <p>Description: Like CI Down Operations.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • Only ICT <p>Used by:</p> <ul style="list-style-type: none"> • CI Return to Service ICT
#16 F,A 	<p>CI Return to Service (Dimensionless/Hour)</p> <p>CI Return to Service [CIi] = CI Down Operations[CIi]/ CI Average Repair and Restore Time[CIi]</p> <p>Description: The rate at which the Energy CI returns to full service.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by:</p> <ul style="list-style-type: none"> • CI Down Operations • CI Running Operations
#17 F,A 	<p>CI Return to Service ICT (Dimensionless/Hour)</p> <p>CI Return to Service ICT [CIi] = CI Down Operations ICT[CIi]/ CI Average Repair and Restore Time ICT[CIi]</p> <p>Description: Like CI Return to Service.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • Only ICT <p>Used by:</p> <ul style="list-style-type: none"> • CI Down Operations ICT • CI Running Operations ICT
#18 L 	<p>CI Running Operations (Dimensionless)</p> <p>CI Running Operations [CIi] = \int CI Return to Service[CIi]- CI Breakdown[CIi] dt + [100]</p> <p>Description: Running operations represents the day-to-day functions of the Energy CI. It is assumed that the CI operates at 100% capacity at time t=0.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by:</p> <ul style="list-style-type: none"> • CI Breakdown • CI Running Operations Drop Value • CI Service Provided
#19 F,A 	<p>CI Running Operations Drop Value (Dimensionless)</p> <p>CI Running Operations Drop Value [CIi] = 100-CI Running Operations[CIi]</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by:</p> <ul style="list-style-type: none"> • CI Running Operations Drop Value Accumulation
#20 L 	<p>CI Running Operations Drop Value Accumulation Area under Curve ICT (Hours)</p> <p>CI Running Operations Drop Value Accumulation Area under Curve ICT [CIi] = \int CI Running Operations Drop Value ICT[CIi] dt + [0]</p> <p>Present in 2 views:</p> <ul style="list-style-type: none"> • All CIs • Only ICT <p>Used by:</p> <ul style="list-style-type: none"> • Comparison Results
#21 L	<p>CI Running Operations Drop Value Accumulation (Hours)</p>

Type	Variable Name and Description
	<p>CI Running Operations Drop Value Accumulation [CIi] = \int CI Running Operations Drop Value[CIi] dt + [0]</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> Comparison Results
#22 F,A  	<p>CI Running Operations Drop Value ICT (Dimensionless)</p> <p>CI Running Operations Drop Value ICT [CIi] = 100-CI Running Operations ICT[CIi]</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Running Operations Drop Value Accumulation Area under Curve ICT
#23 L 	<p>CI Running Operations ICT (Dimensionless)</p> <p>CI Running Operations ICT [CIi] = \int CI Return to Service ICT[CIi]- CI Breakdown ICT[CIi] dt + [100]</p> <p>Description: Like CI Running Operations.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown ICT CI Running Operations Drop Value ICT CI Service Provided ICT
#24 A 	<p>CI Service Provided (Dimensionless)</p> <p>CI Service Provided [CIi] = IF THEN ELSE (CI Running Operations[CIi]>= CI Average Demand[CIi] ,1,CI Running Operations[CIi]/ CI Average Demand[CIi])</p> <p>Description: The control variable which assesses over time the service provided by the Energy CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown
#25 A 	<p>CI Service Provided ICT (Dimensionless)</p> <p>CI Service Provided ICT [CIi] = IF THEN ELSE (CI Running Operations ICT[CIi]>= CI Average Demand ICT[CIi] ,1,CI Running Operations ICT[CIi]/ CI Average Demand ICT[CIi])</p> <p>Description: Like CI Service Provided.</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown ICT
#26 Sub [sub]	<p>CIi</p> <p>: Energy, ICT, Water, Food, Health, Financial, Public and legal order and safety, Civil administration, Transport, Chemical and nuclear industry, Space and research</p> <p>Present in 2 views:</p> <ul style="list-style-type: none"> All CIs Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown CI Breakdown ICT CI Disruption CI Disruption Timeline CI Disruption Timeline Trigger

Type	Variable Name and Description
	<ul style="list-style-type: none"> • CI Down Operations • CI Down Operations ICT • CI Return to Service • CI Return to Service ICT • CI Running Operations • CI Running Operations Drop Value • CI Running Operations Drop Value Accumulation Area under Curve ICT • CI Running Operations Drop Value Accumulation • CI Running Operations Drop Value ICT • CI Running Operations ICT • CI Service Provided • CI Service Provided ICT • CI_j • Comparison Results • Delayed CI Disruption • Effect of CI_j Failure on CI_i • Effect of CI_j Failure on CI_i ICT
#27 Sub [_{sub}]	<p>CI_j : Energy, ICT, Water, Food, Health, Financial, Public and legal order and safety, Civil administration, Transport, Chemical and nuclear industry, Space and research</p> <p>Present in 2 views:</p> <ul style="list-style-type: none"> • All CIs • Only ICT <p>Used by:</p> <ul style="list-style-type: none"> • Effect of CI_j Failure on CI_i • Effect of CI_j Failure on CI_i ICT
#28 C WAB	<p>CIs Effects Considered (Dimensionless) CIs Effects Considered [CI_j] = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1</p> <p>Description: <i>The slected CIs to consider their Failure Effects on other CIs.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by:</p> <ul style="list-style-type: none"> • Effect of CI_j Failure on CI_i
#29 C WAB	<p>CIs Effects Considered ICT (Dimensionless) CIs Effects Considered ICT [CI_j] = 0, 1, 0, 0, 0, 0, 0, 0, 0, 0</p> <p>Description: <i>Like CIs Effects Considered.</i></p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • Only ICT <p>Used by:</p> <ul style="list-style-type: none"> • Effect of CI_j Failure on CI_i ICT
#30 A WAB	<p>Comparison Results (Dimensionless) Comparison Results [CI_i] = 100*ZIDZ((CI Running Operations Drop Value Accumulation[CI_i]-CI Running Operations Drop Value Accumulation Area under Curve ICT[CI_i]),CI Running Operations Drop Value Accumulation Area under Curve ICT[CI_i])</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by: This is a supplementary variable.</p>
#31 DE	<p>Delayed CI Disruption (Dimensionless/Hour) Delayed CI Disruption [CI_i] = DELAY FIXED (CI Disruption[CI_i] ,TIME STEP ,0)</p> <p>Present in 1 view:</p> <ul style="list-style-type: none"> • All CIs <p>Used by:</p> <ul style="list-style-type: none"> • CI Disruption Timeline Trigger

Type	Variable Name and Description
#32 A WAB	<p>Effect of CIj Failure on Cfi (Dimensionless) Effect of CIj Failure on Cfi [Cfi,CIj] = CIs Effects Considered[CIj]*Effect of CIj Failure on Cfi Data[Cfi,CIj] (CI Disruption Timeline[CIj]* Unit Normalization) Description: <i>The effect each CI has on the other based on the PhD thesis of Ana Lauge.</i> Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown
#33 T,D,A WAB x	<p>Effect of CIj Failure on Cfi Data Effect of CIj Failure on Cfi Data [Cfi,Energy] = GET XLS LOOKUPS('data_sheet_all.xlsx','Energy','a','b3') Effect of CIj Failure on Cfi Data [Cfi,ICT] = GET XLS LOOKUPS('data_sheet_all.xlsx','ICT','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Water] = GET XLS LOOKUPS('data_sheet_all.xlsx','Water','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Food] = GET XLS LOOKUPS('data_sheet_all.xlsx','Food','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Health] = GET XLS LOOKUPS('data_sheet_all.xlsx','Health','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Financial] = GET XLS LOOKUPS('data_sheet_all.xlsx','Financial','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Public and legal order and safety] = GET XLS LOOKUPS('data_sheet_all.xlsx','Public & legal order & safety','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Civil administration] = GET XLS LOOKUPS('data_sheet_all.xlsx','Civil administration','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Transport] = GET XLS LOOKUPS('data_sheet_all.xlsx','Transport','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Chemical and nuclear industry] = GET XLS LOOKUPS('data_sheet_all.xlsx','Chemical and nuclear industry','a','b3') Effect of CIj Failure on Cfi Data [Cfi,Space and research] = GET XLS LOOKUPS('data_sheet_all.xlsx','Space and research','a','b3') Present in 2 views:</p> <ul style="list-style-type: none"> All CIs Only ICT <p>Used by:</p> <ul style="list-style-type: none"> Effect of CIj Failure on Cfi Effect of CIj Failure on Cfi ICT
#34 A WAB	<p>Effect of CIj Failure on Cfi ICT (Dimensionless) Effect of CIj Failure on Cfi ICT [Cfi,CIj] = CIs Effects Considered ICT[CIj]*Effect of CIj Failure on Cfi Data[Cfi,CIj] (CI Disruption Timeline[CIj]* Unit Normalization) Description: <i>Like Effect of CIj Failure on.</i> Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown ICT
#35 A WAB	<p>Fastest Draining Time (Hours) = TIME STEP Present in 1 view:</p> <ul style="list-style-type: none"> All CIs <p>Used by:</p> <ul style="list-style-type: none"> CI Breakdown
#36 A WAB	<p>Fastest Draining Time ICT (Hours) = TIME STEP Present in 1 view:</p> <ul style="list-style-type: none"> Only ICT <p>Used by:</p>

Type	Variable Name and Description
	<ul style="list-style-type: none"> CI Breakdown ICT
#37 C WAB	FINAL TIME (Hour) = 1440 Not Present In Any View
#38 C WAB	INITIAL TIME (Hour) = 0 Not Present In Any View Used by: <ul style="list-style-type: none"> Time
#39 C WAB	Max Effect of CI_j Failure on CI_i (Dimensionless) = 5 Description: <i>Normalize all $e(ij)$ by dividing each by the max possible value, which is 5.</i> Present in 1 view: <ul style="list-style-type: none"> All CIs Used by: <ul style="list-style-type: none"> CI Breakdown
#40 C WAB	Max Effect of CI_j Failure on CI_i ICT (Dimensionless) = 5 Present in 1 view: <ul style="list-style-type: none"> Only ICT Used by: <ul style="list-style-type: none"> CI Breakdown ICT
#41 C WAB	SAVEPER (Hour) = 12 Description: <i>The frequency with which output is stored.</i> Not Present In Any View
#42 C WAB	Time between CI Disruption Durations (Hours) Time between CI Disruption Durations [CI _i] = 720, 720, 720, 720, 720, 720, 720, 720, 720, 720, 720 Description: <i>to generate a several disruptions, the value of this variable needs to be less than the final time of the model.</i> Present in 1 view: <ul style="list-style-type: none"> All CIs Used by: <ul style="list-style-type: none"> CI Disruption
#43 C WAB	TIME STEP (Hour) = 0.125 Present in 2 views: <ul style="list-style-type: none"> All CIs Only ICT Used by: <ul style="list-style-type: none"> Delayed CI Disruption Fastest Draining Time Fastest Draining Time ICT
#44 C WAB	Unit Normalization (Dimensionless/Hour) = 1 Description: <i>The normalizing factor which ensures the units for the $e(ij)$-factors are coherently Dimensionless/Hour.</i> Present in 2 views: <ul style="list-style-type: none"> All CIs Only ICT Used by: <ul style="list-style-type: none"> CI Breakdown

Type	Variable Name and Description
	<ul style="list-style-type: none">• CI Breakdown ICT• Effect of CIj Failure on C_{li}• Effect of CIj Failure on C_{li} ICT