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Simulations of networked critical infrastructures

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Abstract

Critical infrastructure (CI) refers to assets that are essential for the functioning of a society and economy, such as telecommunication/ICT; energy generation, transmission and distribution; financial sector; etc. CIs are tightly coupled, creating a complex system where failures propagate from a disrupted CI to other CIs, aggravating and prolonging the societal impact through cascading effects. This thesis extends a system dynamic model by Eliza Canzani describing how a failed critical infrastructure that cannot deliver products and services impacts other critical infrastructures, and how a critical infrastructure is affected when another critical infrastructure fails. The model is simply enough to influence mental models of crisis managers. It provides a high-level view of the dynamics of disruptive events in CIs, facilitating understanding scenarios of disruptions and forecasting cascading effects, hopefully aiding strategic planning for protection of CIs.

Key words: Critical infrastructures, interdependencies, system dynamics modelling, epidemics modelling.

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Abbreviations

CI: Critical infrastructure
ICT: Information and communications technology
SCADA: Supervisory control and data acquisition

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Foreword

This work is the culmination of a five-year study in the field of computer engineering at the University of Agder. The thesis was written by me, Tor-Edin Farstad (toredf13@student.uia.no) and is submitted as my Master Thesis in the ICT Master programme. It has been a fantastic journey that is now coming to an end and I am immensely grateful for the knowledge gained and the people that have helped me along the way.

I want to acknowledge and thank my supervisor, Professor Jose Julio Gonzalez for introducing me to this field of study and to Canzani's work, for suggesting the research topic and for supervision of this thesis. I also would like to thank Dr. Ahmed Abdeltawab Abdelgawad for insight in model testing and structure, and Elisa Canzani for the research she has done, which has provided the basis for this thesis. Finally, I want to thank my spouse, Miia Farstad for her input in the thesis.

Tor-Edin Farstad

1 Introduction

The overall aim of the thesis is to develop a system dynamics model that simulates the cascading effects in critical infrastructures (CI) when a disruption in any CI occurs. For example, from the Information and communications technology **(**ICT) perspective it is of importance to maintain an ICT -infrastructure that is secure and durable in the event of a disruption; this is also applicable to other CI that are dependent on ICT for their daily operations. On the other hand, the ICT-infrastructure can be affected if, e.g., the energy CI is disrupted. All CIs are interdependent. The proposed thesis model will be used to simulate various scenarios where a disruption to one or more CI affects interdependent CIs through cascading effects.

The starting hypothesis is that the model proposed by (Canzani, 2016) is not appropriate to represent the disrupting cascade-effects in critical infrastructures. Her work as a graduate student of the Universität der Bundeswehr München proposes a different and interesting approach to CI behaviour and is a valuable contribution which has led to this thesis. However, an in-depth study of Canzani's model shows that it is not ideal to use to simulate cascading effects after disruptions to CI. Her adaptation of an epidemics model (SIRS) to simulate the cascading effects of disruptions is not appropriate because a central element in any epidemic is missing when a CI is disrupted: the transmission of infections, does not occur when critical infrastructures are disrupted, whether directly or through cascading effects. The parameters that express the effects CI have on each other that are considered down for a certain amount of time, are also misinterpreted. Furthermore, Canzani's model has not been tested following best practice in system dynamics and, thus, it has not documented credibility.

Based on these weaknesses, the following problem statements have been developed:

1. Can Canzani's model be improved to represent critical infrastructure behaviour?
2. Will the data from the thesis survey provide significantly differing results from the survey data used in Canzani's scenarios?

To test the hypothesis and answer the problem statements, the thesis work was divided into four sub-goals. The first goal was to replicate the model created by Canzani and to be able to produce the same results. Replication is a crucial part of scientific research (Jasny et al. 2011) but replication studies in social and management sciences were rarely done (Sterman, 2000) and probably they are still rare. The first step to achieve an accurate replication was a literature study of how system dynamics operate within the confined space of critical infrastructure. Replicating Canzani's model required using the same mathematical equations and parameters, making the literature study of vital importance. The second step was to analyse Canzani's model and assess how well it reflects system dynamic behaviour. During the assessment, the aim was to discover how it could be improved or changed to more accurately reflect the behaviour in critical infrastructures, according to how system dynamics operate. This lead to the second goal, which was to create the thesis model that could run the same and new simulations, which would answer the problem statements and establish the hypothesis as right or wrong. The third goal was to create a survey which would be distributed to leading experts in critical infrastructures in Norway to assess the service provided by critical infrastructures in the event of cascading disruptions over time. These results would then be used in simulating disruption scenarios in Norway using the thesis model. Lastly the fourth goal was to create a worst-case scenario where disruption causing maximum destruction across all networked CI could be simulated with the thesis model.

The motivation for researching this topic and achieving these goals stems from a desire to understand how systems dynamics modelling works and how the models behave during disruptive events. Because ICT is a wide field of study and important to society as an integral part in numerous aspects, it is a topic which can be evaluated from many different perspectives. Prior to the thesis work, the perspective has been the details about how various ICT devices and infrastructure operate. This increased the understanding of individual units and devices work but has not shown how they all behave together as a system where interdependencies are present. To model these interdependencies of CI using system dynamics modelling required a deeper understanding of mathematics and learning how to use modelling tools, such as Vensim DSS. This thesis presents a new approach and a valuable learning opportunity in system dynamics and modelling. The thesis work as such is considered a new area of study and work, which generated the motivation to further explore it.

1.1 Model development

The thesis model was developed using Vensim DSS modelling software (Ventana Systems, 2016) in iterative stages, based upon the model created by Canzani (2016). The review of Canzani's methods and model was used as starting point for designing and developing the thesis model. The thesis model structure was evaluated during each iterative stage and compared with results from previous iterations. Furthermore, it was sent to the thesis supervisor for feedback.

1.2 Thesis limitations

In replicating Canzani's model, the greatest limitation was the lack of access to her model. The reproduced thesis model is therefore based on the description, article graphics and the simulation results only. This limits the evaluation and ability to compare the results with exactness and creates a dimension of uncertainty. The thesis model had limited peer review during the creation process. An increased number of peer reviews could potentially have yielded a more accurate model. Another limitation is that the thesis survey sent to experts gave very few responses from the recipients, causing the simulated scenarios to not be a realistic representation for Norway's critical infrastructures.

1.3 Thesis structure

Chapter one of this thesis presents the topic, its background, the introduction of the study and how the thesis is built to support the hypothesis and problem statements. Chapter two presents the theory behind the main elements and the concepts related to the model and the topic of study. Chapter three describes the methods used in to evaluate Canzani's model, the development of the thesis model, survey and worst-case scenario. Chapter four consists of the thesis model in detail. Chapter five features the various testing done with the thesis model. Chapter six contains the results from the simulated scenarios. Chapter seven is a discussion of the results and whether the problem statements have been answered and the hypotheses confirmed or disproven. Chapter eight is a summary of the thesis work and it also entails possible future work available. Chapter nine is a reference section, containing a list of references used throughout the thesis. Following these are the appendices.

2 Theory

2.1 System dynamics

The system dynamics concept was developed by Jay Forrester (1961) to describe why an employment cycle was unstable in a company he worked for. By developing system dynamics, he was able to explain the underlying cause of the instability. This sparked the development of system dynamics and since then been further developed by many scholars, such as the works of John Sterman (2000) and Forrester himself (et al. 1968) which attempt to further explain and develop system dynamics and provides a deep explanation on how to apply them to a variety of modern-day scenarios. Sterman’s book, *Business Dynamics* (2000), is the most recent applicable book due to its comprehensiveness of system dynamics and has been referenced frequently by various disciplines of study, such as a study and simulation of US infrastructure interdependencies (Hyeung-Sik J. Min et al. 2007).

System dynamics can be overall described as a system of nonlinear differential equations which attempt to explain a systems behaviour. The four main elements are feedback, stocks and flows and time delays. The usage of stock-and-flow diagrams and feedback loops are the central elements used in the methodology of system dynamics. The stock and flow diagrams refer to stocks or levels which are accumulations in the system and flows which are effectively rates entering or leaving the stocks. In a Vensim model file, these each have their own graphical representation as shown in figure 1.

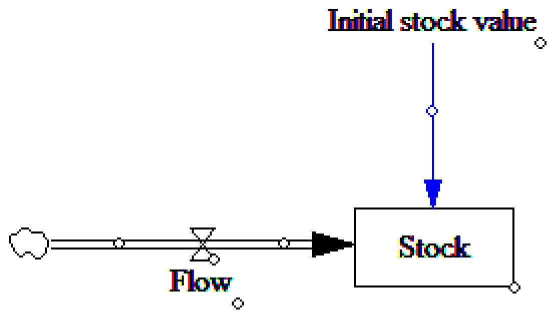

Figure 1. The stock (box) represents a level that is affected by some flow(arrow) and an initial stock value variable. The flow could be either outgoing or inbound, depending on if the stock is increasing or decreasing its level. In this case it is inbound.

Each stock is mathematically represented with differential equations. The flows, either in or out are factors that influence the equations. The same applies to any other variable or constant that affects the flow or stock. In Figure 1, the Stock can be mathematically represented as $\frac{d}{dt} Stock = Initial\ stock\ value + Flow$. Modelling system behaviour requires some prior knowledge to how the system works, to identify the key structures, i.e. stocks and flows. The importance of them appears most clearly when seen in a continuous view. As much as discrete timed events are possible to simulate, the continuous view looks for underlying dynamic patterns (System Dynamics Society , 2018). Topics that can be evaluated with system dynamics modelling can be human behaviour in a dynamic environment, such as an attempt at modelling human behaviour in airline queues (Canzani et al. 2014). or modelling accumulated debris in Low-Earth Orbit. (Drmola et. al 2018). Important studies that have used system dynamics modelling and techniques are environmental case studies, (Beall et al. 2009), project management modelling (Ford, et al 2007), group model building (Andersen et al. 2007) and modelling improvement processes (Repenning et al. 2001). These studies show that system dynamics can be applied to a variety of sciences and cases. Recent studies and work related to the thesis specifically are for instance the research of critical infrastructure interdependencies (Conrad et al. 2006) and implementation of system dynamics in a block-by-block concept (Canzani, 2016). Understanding system dynamics requires the user to interact with system components on a mathematical level to build models which can represent system behaviour. Because systems can be complex in both their appearance and function, building models that represent these can provide a simple, abstract figure in which the complex can be simplified and understood more easily for the user.

2.2 Critical Infrastructure

There is no set definition of a critical infrastructure (CI). This is because it is an evolving term as new infrastructure definitions emerge and are added to our society, such as the rapid development of ICT. This has since become a solid backbone infrastructure many other CIs depend on. Similarly, after events such as the 9/11-event in the US, there were added more CIs to the list (United States Government Accountability Office, 2013) which previously were not recognised as such. The concept refers to a part of society where the output is considered essential for day-to-day functions, and by some is defined as a lifeline-system (O'Rourke, 2007). The EU council as recently as in 2008 defined a CI as *"an asset, system or part thereof located in member states which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact on a member state as a result of the failure to maintain those functions."* (The Council of the European Union, 2008).

Because of their importance in society, it is imperative to be able to prepare for events which cause them to behave differently than their prescribed day-to-day functions. The simulation of CI behaviour has proved to be difficult for several reasons. These reasons are in most cases the availability of information regarding the infrastructure(s), their changing states, regulations and complexity. Considering that an infrastructure performs several functions, it was decided to aggregate these functions into overall definitions, such as “Water” or “Electricity”. This was done to primarily reduce model complexity. In the context of this work, the CI functions have been aggregated into Water, Transport, Energy, Financial and ICT CI, respectively.

2.3 CI interdependencies

Critical infrastructures are interconnected systems, which means they have interdependencies between themselves. Because of these interdependencies, it is inferred that should an event happen that incapacitates or reduces one infrastructure, this might cause the interdependent systems to suffer in various levels as well. Rinaldi suggests 4 distinct levels of interdependencies; geographical, cyber, logical and physical. Geographical refers to local events creating state changes in all CIs. Cyber interdependencies occur when systems are connected via information infrastructure and their state is regulated accordingly. Physical interdependency is when infrastructure states depend on the material output of each CI. Logical interdependency is when the states of each is regulated by some other means or mechanism that is not cyber, geographical or physical (Rinaldi, 2004).

Social studies suggest ICT (if defined as the Internet) is more important than other CI’s because of its “indispensability” in the current society (Tosuna et al. 2011). ICT however depends on all the CI in this project to function properly. Examples of interdependencies could be an online bank service being disabled due to a power outage, a water plant is unreachable because of faulty communication lines or ICT systems not functioning due to not receiving proper water cooling. These are basic examples which show that due to interdependencies it is crucial for managers and system administrators to understand how they are connected and model their policies and strategies accordingly. When they do, they can prepare more effectively for events that may occur. Because there are numerous ways CIs are connected however, modelling this is a somewhat limited approach. It is acknowledged that models that attempt to describe CI interdependencies during disruptions are always false because they cannot contain every detail. They are however an attempt at finding the best possible representation of reality.

Considering recent catastrophic events from reality which have had a cascading effect is the ransomware 'WannaCry'. The cascading effects of the ransomware on the NHS (National Health Service) in the UK in May 2017 from the cyberattack were 'thousands of appointments and operations were cancelled' to mention a few (National Audit Office , 2017). Another event is the flooding which occurred in the southern region of Norway in October 2017. Among the cascading effects (in relation to the previously mentioned infrastructures) were electricity outings for industry buildings, rendering them unable to perform their work as normal and major transportation issues. A select number of recent studies in interdependencies include hybrid systems modelling (Heracleous, et al. 2017) where finite state machines are used to model CI and their interdependencies' behaviour and a cascading failure after a terrorist attack is modelled. (Wu, et al. 2016)

2.4 Epidemics modelling

The SIRS-model, short for Susceptible, Infected, Recovering and a return to the Susceptible state, is an epidemic-type model developed by Kermack and McKendrick (1927). The model is expressly built with a purpose to show the relationship between the three states S (Susceptible), I (Infected), and R (Recovered) that people are in during a disease epidemic. The states are functions over time *t*, where the functions are described in sets of differential equations. The Susceptible state are the people which are not infected but have the potential to become infected. The Infected are people which have been infected and can transmit the disease to the Susceptible group. The Recovered group are people which have been exposed the disease and have recovered (i.e. become immune) and cannot transmit or receive the disease for some time, then becomes Susceptible again.

For the model to be considered appropriate for epidemic modelling there must be an infection which occurs when the susceptible people interact with the infected, which in turn causes more people to get infected. Table 1 shows the differential equations for the three states and describes with rates how they are reduced or increased. Based on the equations it becomes clear that Susceptible state reduction with rate α is connected to the increase in the Infected state, which in turn is reduced by rate β and so on.

Table 1. The base differential equations used to express the three states, adapted from (W. O. Kermack et al. 1927 p. 713)

Susceptible state	$\frac{d}{dt}S = -\alpha IS + \gamma R$, where α is a positive infection-constant, determining the rate of which an individual can transfer into the Infected state.
Infected state	$\frac{d}{dt}I = \alpha IS - \beta I,$ where β is a positive constant, determining the rate of which an infected individual can transfer into the Recovered state.
Recovery state	$\frac{d}{dt}R = \beta I - \gamma R,$ where γ is the rate of which some individual leaves the Recovering state and returns to the Susceptible state.
S+I+R	Total number of the population

2.4.1 SIRS-model adaptation and review

Canzani's model which forms the basis of this thesis was created to describe the cascading effects in networked critical infrastructures following a disruption. This segment is necessary because many of the same structures and mathematical equations are used in the thesis model. The different states in the SIRS-structure have been repurposed to fit the networked critical infrastructures. The three states Susceptible, Infected and Recovering are redefined as Running operations, Down operations and Recovering operations-stocks, respectively. The sum of these stocks now equals the total number of operations the respective CI can perform at any one time. This contrasts with the total number of the population as listed in the SIRS-model. The disruption that occurs to a CI at time *t* has been modelled as the introduction of an "infection" (but, importantly, such "infection" does not propagate analogously as in an epidemic, where infected people transmit the infection to susceptible people). When interconnected, each CI is considered a block which becomes part of an array with dimension *n*, where *n* is the total number of CIs. The disruption is considered the first block. The CI, no matter how many there are, are each represented as block number two. These are interconnected by a third block, called Services Provided. Each CI-block has an index *n* and is connected to each other through the services-provided block. The cascading effect occurs when the services provided in a CI *j*, is reduced. The services provided represent the cascade into the networked infrastructure *i*.

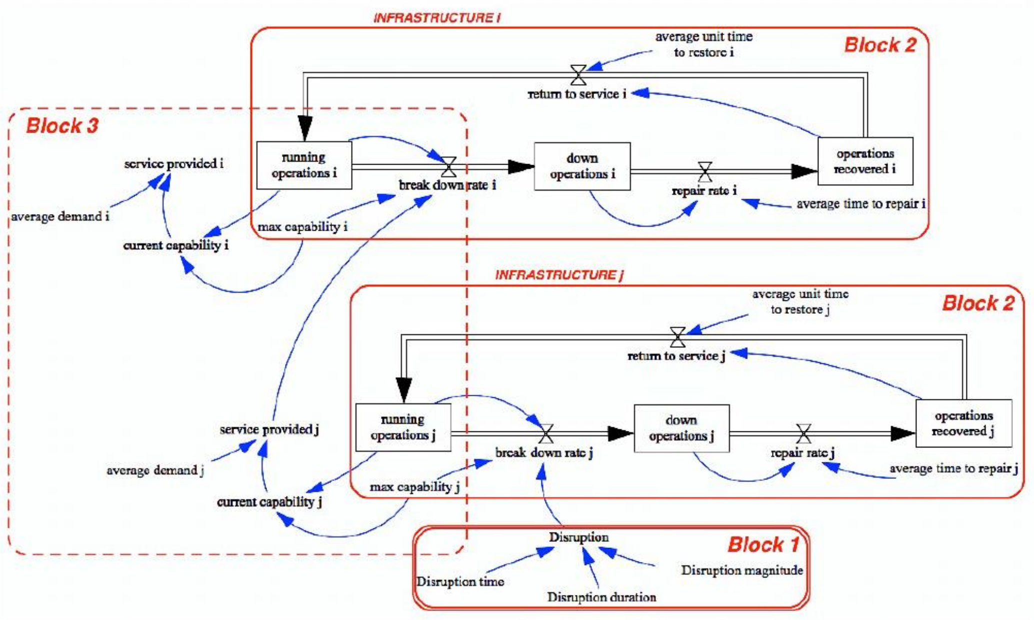

Figure 2. Overview of Canzani's model structure. It contains stocks, flows and variables that aim to simulate cascading effects in networked CI (2016, p. 7).

Figure 2 illustrates the interconnected blocks and begins with the disruption, as block one, which is connected to infrastructure *j* which performs at some service level which is affected by the disruption. This service level disruption cascades into the other infrastructure *i* which can be however many other CI which are connected. In Canzani's work the number of these infrastructure-blocks (Block 2) are 5, indicating the 5 CI Water, Financial, Transport, ICT and Energy CI. The disruption block contains the function *d(t)* which is modelled as a factor m_d = "disruption magnitude" multiplied by a pulse function, named "Disruption". The pulse sends at disruption time t_d a value of 1, lasting for a disruption duration of ΔT_d. Hence, the disruption is modelled as $d(t) = m_d \times \text{PULSE}(t_d, \Delta T_d)$. The disruption is considered an additive term to the breakdown rate $-\alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right)$

Table 2. The differential equations in Canzani's model, adapted from the SIRS-model.

Running operations	$\frac{d}{dt}OP_{run}(t) = -\alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right) + \gamma OP_{rec}(t)$	$OP_{run}(t)$ = Running operations	n_{OP} = Total number of CI operations
Down operations	$\frac{d}{dt}OP_{down}(t) = \alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right) - \beta OP_{down}(t)$	$OP_{down}(t)$ = Down operations	
Recovering operations	$\frac{d}{dt}OP_{down}(t) = \beta OP_{down}(t) - \gamma OP_{rec}(t)$	$OP_{down}(t)$ = Recovering operations	

Table 2 depicts the repurposed differential equations used in block 2 and consecutive blocks for each CI. The breakdown rate (flow) α is affected by the ratio between the Running operations and maximum number of operations that the CI can perform at any given time. The behaviour based on the equations, compared to the SIRS-model equations listed in Table 1 indicates that similar results could be expected because the equations can be considered a direct mapping. However, there are assumptions made that the rates γ and β are constant average rates; a ratio of average repair time and a ratio of the restore time. This means that the disruption occurring at time *t* does not happen at any other state of operations than when operations are running. This leaves out what can happen during the repairs and sequentially the recovering of the operations.

Furthermore, there is an assumption made that when a CI is recovering, there is no chance of a disruption happening at that stage. In the SIRS model a person which has been infected and recovered, may have some type of immunity before he becomes susceptible again. In terms of critical infrastructures, a disruption can happen at any time, even during a recovery process. Because there is no protection against this for networked CI's, the usage of the SIRS model in this case is conceptually wrong. From the epidemic point of view, the susceptible people mingle with the infected and this creates the epidemic. In Canzani's model the epidemic effect does not in occur because the Running and Down operations do not "mingle". In the SIRS model, the Infected and Susceptible people mingle and propagate the epidemic. The epidemic is modelled as a disruption that causes the stock level of Running Operations to decrease. The disruption only occurs at this state whereas an infection can happen during recovery, or when down even. This shows that the usage of the SIRS model to describe cascading events in networked critical infrastructures is not appropriate. For the third block, services provided, a new function has been created to represent this and the create a type of cascade into the other CIs.

Table 3. The control function used to assess services provided between CI.

Services provided	$S^i(t) := \begin{cases} 1, & C^i(t) \geq D^i_{Av} \\ \frac{C^i(t)}{D^i_{Av}}, & otherwise \end{cases}$	C^i_{max} represents the maximum capability of any CI and is set to 100 *operations.*
Current CI capability	$C^i(t) = \frac{OP^i{}_{run}(t)}{C^i_{max}}$	
Average CI demand	D^i_{Av} = assumed 90% of C^i_{max}	

The function $S^i(t)$ is used to generate a relative value between 0 and 1 and is responsible for assessing the service provided from one CI to the other CI. It is not described in Canzani's article (2016, p. 6) a specific unit of measurement for these values. This poses a challenge when creating a model which should be in accordance with the tests described in Sterman's book (2000, pp. 859-861), to be considered reliable. His book serves in many cases as a reference for system dynamics best practice and the tests have been developed by countless scientists since the inception of system dynamics. A requirement for a model to be reliable is that there should be cohesiveness in the units across the entire model. Because the breakdown rate α^i is affected by this function, the interdependencies of the CI are modelled as a formula where:

$$\alpha^i(t) = \sum_{j \in J} \frac{e_{ij}(1 - S^j(t))}{|J|}$$

The cardinality (sum of all elements in a set) of *J* represents the set of 5 CI; Water, Financial, ICT, Energy and Transport and it acts as a normalisation. This means that it ensures the breakdown rates for each CI has the same scale. The factor e_{ij} is a value which represents the effects of an infrastructure disruption over a given time. These were collected by Canzani from a quantitative survey conducted in Ana Laugé's doctoral dissertation at the the Faculty of technology of the Universidad de Navarra, Tecnun (Laugé, 2014). The e_{ij}-table created from these contains the cascading effects on the five CI during a time interval of less than two hours. (Canzani, 2016, p. 7) This creates a problem for the simulations because these values are used by Canzani in simulations which lasts for up to 2 weeks and the disruption last for 24 hours. Only in a closed scenario where the disruption length is of less than two hours can these values be considered appropriate, as it does not show in the article other values used for longer-lasting simulations.

Based on this review of Canzani's work it became apparent that a SIRS-adaptation to represent cascading effects is not ideal and a different model should be created. The proposed model must solve the inconsistencies of Canzani's model and pass the tests outlined in Sterman's book (Sterman, 2000) to be considered a valid substitute. The replicated model can be found in Appendix I.

3 Methods

To develop a working model and simulation of the cascading effects in linked critical infrastructures, it was necessary to create several working phases to the project. These phases corresponded directly to the goals described in the thesis introduction. The phases were research, development, testing and analysis of results. In the research phase the goal was to understand the current state of the field of study. This was done by conducting a literature study of the sources used by Canzani and finding other articles and work related to the field of study. The physical method of obtaining these articles and projects used involved using various academic search engines such as Google Scholar and ScienceDirect with key words such as "critical infrastructures" and "interdependency system dynamics". Each article was studied, summarised and key points were written down and combined with each other to create a state of the art. A second part of the study was to review the previous work by Canzani and to establish if it was incorrect, inconsistent or inaccurate and make factual explanations as to why, if any. Furthermore, there was then a need to show how it could be changed or restructured into a more accurate, consistent, appropriate model.

In the development phase there were several objects that needed to be created. First, the model used by Canzani had to be replicated in such a way that it would give the same results. An important part of this was selecting the program to use for simulations and modelling. There are several programs which are developed for system dynamics simulations and modelling, such as Powersim Studio (Powersim Software AS , 2018), Stella (isee systems, 2018), Vensim (Ventana Systems, 2018) and Goldsim (GoldSim Technology Group, 2018).

Vensim DSS was selected because Canzani's model was created in it and Vensim DSS is widely used. The DSS version of Vensim is an academic version of the program which was available from the University of Agder and previous courses had generated experience in using the software. User interface and figure representation were not considered when selecting the modelling software. Secondly, to replicate the model an in-depth study of it was conducted. It was apparent from Canzani's results (2016, pp. 8-11) that the critical infrastructures were expected to behave in a certain way when a triggering disruption occurred. To replicate the behaviour, it was necessary to understand the underlying mathematical equations of the stocks and flows in the model, as well as the causal relationships between the various blocks representing the infrastructures. Each variable, stock and flow in the model was identified (e.g. running operations ICT = $OP_{run}(t)$) and the model assembled together in iterations. During each step, Canzani's article was consulted for accuracy. To verify that the thesis model simulations were run with the same parameters as the main article, iterations of the thesis model were sent via e-mail and reviewed by third parties and by Canzani to confirm accuracy. The results of the simulations were thus compared to the original results to verify that Canzani's model was replicated to the maximum extent possible, without having access to the physical model.

The results from the analysis of the replicated model was also used in determining how the thesis model needed to be and the possibility of it being a more suitable model to represent the cascading effects after a disruption. The thesis model was then derived from the replicated model, the literature study and a review of how epidemics behaves. The method of creating it was identical to the replication of Canzani's model and parts were removed and variables redefined to reflect the new model. Test simulations were run during the creation of the thesis model to compare results iteratively. During the testing phase, the thesis model was subjected to the applicable tests outlined in Sterman's book to build trust in the model that it is a viable alternative. (2000, pp. 859-861). This was followed by running simulations and analysing the results, according to the last phase. Furthermore, a worst-case scenario was created by analysing the selected CI and discovering the most significant elements, through a literature study. This was done to create a scenario in which a disruption would cause the maximum amount of damage possible. This information from the literature study was then used to propose a scenario where the disruption(s) would create the most damage across all infrastructure and simulated with the thesis model.

3.1 Survey

To explore different scenarios where the model could be applied, an online, quantitative survey was created to gain an insight, if possible, to what cascading effects can occur if there is a disruption of critical infrastructures in Norway. The questions in this survey were derived from the survey conducted by Laugé (2014, p. 53) which asked experts in the field to rate on a scale of 1 to 5 the effects of one disrupted CI on other CI in different time intervals. This survey was distributed to experts in the field in Norway by e-mail. By expert it is meant those who oversee infrastructure security on a per-county level in Norway. The answers sought were percentage levels of performance of each CI during three separate time intervals where one of the five CI is down and affecting the others. The questions asked were "Assume that the *j* CI gets fully disrupted (i.e., 0% performance level) for 2 hours, 24 hours or 7 days respectively. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the ICT CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for ICT, and similarly for the other CIs". The questions were asked in three iterations for each time interval, with the only change being the time interval itself and there was a last question which allowed the survey taker to comment on the quality of the survey. The percentage answers were mapped to a 1 to 5 scale, inserted into a table of e_{ij}-values and used in the simulations. The complete survey can be found in Appendix A.

3.2 Worst-case scenario

Because the scenarios simulated have their limitations in that they deal with single disruptions, it is of interest to see how the thesis model performs during scenarios that have different parameters, such as multiple disruptions or other parameters. By worst-case it is meant a situation in which the disruption causes an unprecedented amount of damage. A worst-case scenario simulation is valuable because it shows that the thesis model can accommodate extreme cases and give usable results. Because this thesis is heavily associated with ICT, it is natural to create a worst-case scenario which is seen from the ICT-perspective. An example of this is mentioned previously in section 2.3, where health infrastructure was severely impacted by the ICT CI being disrupted by a cyber-attack. However, it is worth considering that conducting a cyber-attack on ICT CI that inflicts catastrophic damage to all networked infrastructures, is unlikely (Direktoratet for samfunnssikkerhet og beredskap, 2015, p. 18). According to the tables representing the effects of downtime for CI created by Laugé (2014, pp. 170-175) Transport and Water are both less affected by cascading effects from ICT CI being disrupted than the Energy and Financial CI. With this as a background, it is feasible to describe a worst-case scenario in which an ICT attack vector is used on the Financial and Energy CI because these have larger dependency factors to ICT.

The thesis model asserts that the modelled disruption *d(t)* has a certain magnitude, has a set duration and then it is passed. The nature of the disruption itself has no impact on the simulations, only its magnitude, length and time of occurrence. When constructing the worst-case scenario, the nature of the disruption must be taken into consideration because it can affect these three variables. In ICT a disruption can come from a seemingly endless supply of attack vectors. As an example, a new text processing-program is launched to the public, written in less-than-secure code which has not been tested properly. It is assumed that this somehow passes inspection by chief information officer (CIO) of a given company and the program is distributed in the company. A disgruntled IT-employee that is let go due to downsizing decides to seek revenge and looks online for ways to injure the company. He comes across a database of hacks against this program the company recently acquired. He then proceeds to use his inside-knowledge of the company to distribute a malicious piece of software inside an e-mail, sent to his previous staff-manager which does not have IT-experience or proper training. The malicious software executes and propagates itself, causing the company to suffer a revenue-disruption for a week before the malicious software is successfully purged from the system and the software patched. This scenario is one of many that can be thought of but serves to illustrate that there are several factors to consider. In connection to the elements in the thesis model, the time of the hack was when the malicious software was executed the first time in the company systems. The disruption length of the hack was a week and the magnitude of the disruption was so large that it caused loss in revenue. In the thesis model this disruption magnitude is estimated to be between 7 and 10.

The example scenario refers to essentially a one-man disruption against a local company. In terms of networked CI, the size required of a disruption causing catastrophic damage to all CI is enlarged. The CI must be dissected in a way that shows the core components that makes it possible to create a general attack scenario that would disrupt all CI significantly. In a literature study of the CI identified in this thesis, the core components were narrowed down to 4 or 5 elements, depending on the CI. This limitation stems from there being numerous elements, devices or units making up a CI operation, making it a broad, out of scope part of this thesis. The process of selecting a core component was based on the components description and how literature documented their relevance in a given CI.

Table 4. The core components of the ICT and Energy CI respectively. For the ICT CI the core components are essentially devices that allow for communication, storage and display of information. For the Energy CI they reflect the distribution of energy and generation of energy from sources. Despite parts of both CI being automated, manpower is necessary to monitor, install or maintain systems. (Unicorn Systems a.s , 2016), (Farrell, et al. 2004)

ICT CI	**Energy CI**
Servers Routers/Switches Wireless radio communications/phones Computers People (system administrators, employees etc.)	Transformers Distribution networks (cabling) Energy sources (Power plants, etc) People (Employees, technical personnel etc.)

Table 5. The Water, Financial and Transport CI components follow the same pattern as the ICT and Energy in that manpower is essential for daily upkeep. The Water components are those that maintain a flow of water in whichever form necessary. The Financial components are somewhat more abstract, yet the components are crucial for enabling trade, banking and other financial work. The Transport components are those necessary to enable the transportation on a vehicular level, though there exist other definitions of what kind of operations transport infrastructure perform. (Hooper, 2006), (Norges Bank, 2014), (Zdeněk Dvořáka et al. 2017)

Water CI	**Financial CI**	**Transport CI**
Aggregates Asphalt/concrete Piping Hydraulic pumps People (general manpower, plumbers etc.)	Interbank systems Bank settlement systems Stock markets Banks People (Employees, bankers etc.)	Road networks Fuel Bridges Tunnels People (Drivers, operators etc.)

From the components in the tables and the literature studied it shows that to perform a worst-case scenario-type of attack would require multiple attacks from several different angles to create maximum amount of damage. According to the Norwegian Directorate for Civil Protection (Direktoratet for samfunnssikkerhet og beredskap, 2015) several Norwegian CI have their own communication systems which are shut off from public interference, which would limit the success a single ICT attack from the outside might have. However, because of interdependencies at some or several levels, cascading effects do occur after the disruption of one CI happens. This infers that if multiple disruptions are targeted towards the respective CIs and launched sequentially, but not necessarily at the same time, they could possibly do a lot of damage combined.

In Canzani's model and simulations, multiple disruptions were demonstrated and showed that disruptions in ICT, followed by Energy afterwards, ensured that ICT CI took longer to recover (2016, p. 10). In this worst-case scenario the Energy CI is subject to an attack first, ICT CI follows and lastly the Financial CI are attacked. The order of the attack is decided based upon the level of interdependency each CI has on the other. The simulation time is one week and the disruption time t_d for the Energy CI is at 15 hours, which emulates the attack happening in the evening and that time t = 0 is at 06:00 in the morning. Each CI is assumed attacked via an ICT vector, be it a hack or some type other ICT-related interference (SCADA systems in the Energy CI being disrupted directly or indirectly etc.) The magnitude of each attack will be identical, the reasoning being that the attackers goal is to ensure that the respective CI are completely disrupted, i.e. Running operations and services provided are equal to 0 for as long as possible. The length of the disruption for each CI will be 24 hours. The example of the 'Wannacry'-disruption in section 2.3 is the basis for this, because the length of that disruption before it was stopped, was less than 24 hours. The interval between each disruption will be 6 hours, allowing the cascading effects to take place and then be subject to further disruption. Another important factor is the average repair and restore time for the CI to return to service. Building on the length of the disruption, the Energy CI average repair and restore time will be set to 24 hours. Each consecutive CI that suffers a disruption will have an average repair and restore time that is 6 hours longer than the previous, representing that the cascading effects have taken a toll on the CI being repaired and restored.

4 The thesis model

From the review of Canzani's model and model replication it was discovered that it could be improved in several ways. Due to the limitation of not having Canzani's model as Vensim model file in hand, I had to build the replicated model based on the description given in (Canzani, 2016). The proposed thesis model would not be considered a SIRS-model adaptation because as discussed in chapter 2.4.1 there are significant elements lacking that prohibits the SIRS-model to be effective for simulating cascading infrastructure disruptions. Because of this, the thesis model would not be related to epidemiology in any form. It would need to be rigorously tested to ensure that it fulfils the passes the tests and requirements as described in (Sterman, 2000, pp. 859-861) so it can be trusted as a reliable model. To create the thesis model, two major changes had to happen. Firstly, the Recovered state had to be removed altogether. Secondly, the e_{ij}-table values used to model interdependencies would have to be corrected to correspond to the actual disruption length, be it less than two hours, 24 hours or more. The structures in the model are divided into three types which are variables, stocks and flows.

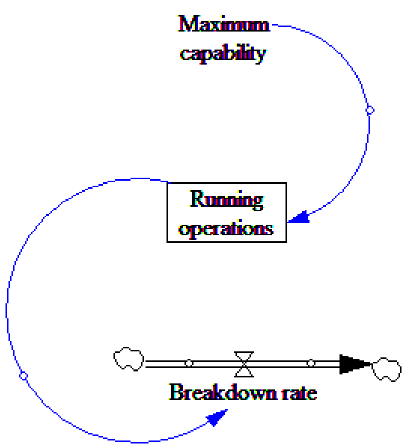

Figure 3. The box Running operations represents the stock, the Maximum capability is a variable influencing the stock, and the Breakdown rate is a flow of either reduction or increase and is in this example affected by the running operations. The connection between the variable, stock and flow is represented by the blue arrows. Created in Vensim DSS.

Table 6. The table shows the variables, stocks and flows which are used in the thesis model. The suffix *j* represents the CI which suffer a direct disruption, whereas the suffix *i* represents the set of networked CIs, which suffer the cascading effects of the disruption on CI *j*.

Variables	Stocks	Flows
Average demand *i*	Running operations *i*	Breakdown rate *j*
Average demand *j*	Running operations *j*	Breakdown rate *i*
Services provided *i*	Down operations *i*	
Services provided *j*	Down operations *j*	
Current capability *i*		
Current capability *j*		
Max capability *i*		
Max capability *j*		
Average repair and restore time *i*		
Average repair and restore time *j*		
Disruption		

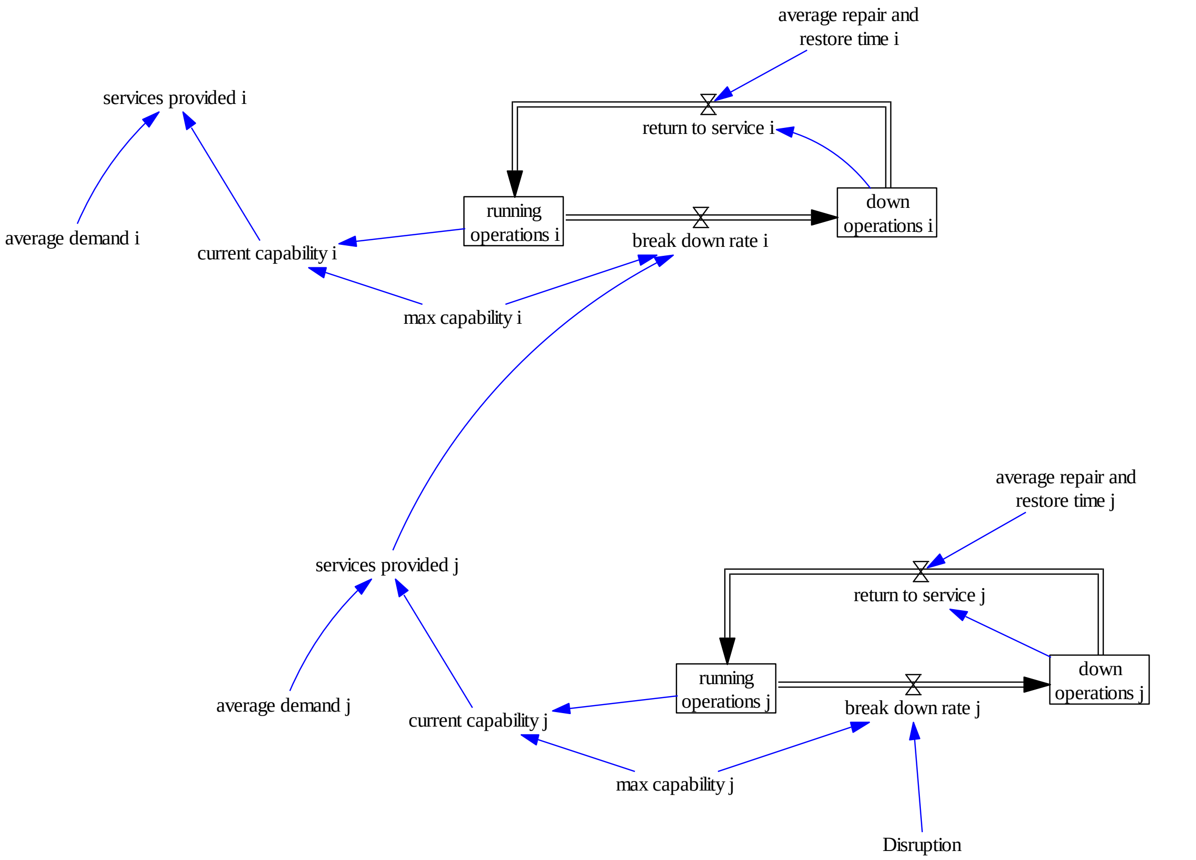

Figure 4. The proposed thesis model with the Recovered state removed where *i* represents the set of 4 CI affected by the disruption occurring in CI *j*. Created in Vensim DSS.

The mathematical equations have been altered to reflect the change in states. The thesis model does not conform to the SIRS-model representation or equations, but this does not limit the usage of them in the thesis model. It naturally means that it cannot be claimed that it is a SIRS model. The relations between the two states have been kept the same. The variables from Canzani's model, "average repair time" and "average unit time to restore" have been aggregated into one new variable. This new variable has been renamed to "average repair and restore time" and is found in each CI. Setting the new value for this was equal to the sum of the "average repair time" and "average unit time to restore" variables. According to Canzani[1] there was no decisive data or reasoning behind the value of these other than setting it to a seemingly reasonable value related to the simulation length.

Because of this, the reasoning behind the new aggregated variable is the same but it does create a new area of study. If a disruption in the Energy CI causes the lack in production of fuel, this could harm the Transport CI but presumptuously would not cripple it immediately. However, the repair and restoration time could, also presumptuously, be considered more significant compared to if there is a short power outage, causing traffic lights flickering for a limited time before power is restored. This example shows that the value of the average repair and restore time would highly depend on the type of disruption that occurs. Because the repair and restoration time can thus change drastically depending on the disruption type, it ultimately led to the sum of the two variables being used but it could be subject to change.

Table 7. The new differential equations used in the thesis model

Running operations	$\frac{d}{dt}OP_{run}(t) = -\alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right) + \gamma OP_{down}(t)$	$OP_{run}(t)$ = Running operations
Down operations	$\frac{d}{dt}OP_{down}(t) = \alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right) - \gamma OP_{down}(t)$	$OP_{down}(t)$ = Down operations

When comparing Table 7 with Table 3 the equations for the states Running operations and Down operations are like Canzani's model but different due to the variable γ having absorbed the previous unit restoration constant β and the removed Recovered operations state. The services provided-function in block 3 remains identical to Canzani's-model. Because of the lack of access to the Canzani's model there are as previously discussed a limitation to the

[1] Canzani E. 2018. *System dynamics modelling.* E-mail correspondence 21.01.2018. (Farstad T.)

knowledge about how it looks and works in detail. When going through the measurement units for each element in the Canzani's-model, there was discovered a problem in unit definition for the services provided. This problem followed into the thesis model, naturally because the services provided block is the same. The problem was that no valid unit of measurement for it the output of the function $S^i(t)$ that gives a number between 0 and 1. When this value is used in the breakdown rate of CI *i*, it creates unit definition errors in the breakdown rates. To correct this, each unit in the thesis model was assessed and the meaning of each evaluated. Each CI has a set amount of *operations* it can perform at any time. The maximum capability C^i_{max} is set to 100 *operations.* It follows then that the increase or decrease in the Running operations should be the measured by a ratio of *operations over time.* Unfortunately, Canzani's model is not describing this in the paper in detail, therefore it could not confidently be said say that this is how the unit is measured, but from the understanding of system dynamics and modelling it is logical that it should be measured this way.

The e_{ij}-parameters became the solution to the problem with unit measurement. They are answers in response to the survey-question: "Which effect would your CI have if the following CI were down for…" (Laugé, 2014, p. 166) The average value of the answers was then calculated and represents the effect of one CI disruption would have on another. It is argued that assigning the ratio unit *operations/time* to the e_{ij}-values is appropriate because the experts answering the survey in terms of system dynamics were interpreting the value of the rate $-\alpha\left(\frac{OP_{run}(t)}{n_{OP}}\right)$. This also comes from considering the rate describes the reduction of operations at time *t* when the disruption occurs. In the physical modelling, a factor called Unit normalisation was introduced and multiplied with each breakdown rate for every CI. It contains a value of 1 operations/hour. This also ensured that even though the services provided output between 0 and 1 is dimensionless, it is appropriate. There was no studied literature or data that showed a viable option of unit of measurement for services provided by a CI. Considering that the services provided is affected also by a percentage of demand, this makes the constant D^i_{Av} also dimensionless. After solving this problem, all variables and elements in the thesis model had an appropriate unit of measurement. The complete thesis model that shows the variables and their units of measurements is found in Appendix J.

To solve the third problem regarding the use of correct e_{ij}-parameters for the correct disruption length in the simulations, the survey-tables created by Laugé (2014, pp. 170-175) were reviewed and the table values for the e_{ij} parameters were adjusted manually to the appropriate disruption length. These have been mapped into tables 8-10 directly.

Table 8. The e_{ij}-parameters corresponding to a disruption which lasts for less than 2 hours.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	Energy	N/A	0.86	1.33	2.67	2.40
	ICT	2.67	N/A	1.00	2.33	2.40
	Water	0.57	0.83	N/A	0.00	0.20
	Financial	0.71	0.17	0.00	N/A	0.60
	Transport	1.00	1.17	0.00	1.00	N/A

Table 9. The e_{ij}-parameters corresponding to a disruption which lasts for less than 24 hours.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	Energy	N/A	3.71	3.00	4.00	3.00
	ICT	3.71	N/A	2.33	4.00	3.40
	Water	2.14	2.83	N/A	0.33	1.40
	Financial	1.14	1.83	0.00	N/A	1.40
	Transport	1.43	2.00	1.33	2.00	N/A

Table 10. The e_{ij}-parameters corresponding to a disruption which lasts for more than one week.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	Energy	N/A	4.57	4.57	4.67	4.20
	ICT	4.67	N/A	3.67	4.67	4.60
	Water	3.43	3.50	N/A	1.00	2.60
	Financial	2.43	3.00	2.00	N/A	2.20
	Transport	3.00	3.83	3.67	3.67	N/A

The parameters in the tables are read as columns, i.e. if the ICT CI is down for less than two hours, Energy (Table 8, column one, row two) is affected by a value of 0.86 *operations/hour*, Water for 0.83 *operations/hour*, and so forth. (Laugé et al. 2014). The online survey questionnaire in this thesis asked the experts to evaluate cascading effects for three set intervals, 2 hours, 24 hours and 7 days. These are different from those conducted by Laugé (2014) because the time intervals are fixed and not an inequality, i.e. less than two hours, more than two hours, and so on. The questions in the online survey are also phrased differently. This ensured that the survey is unique and not a mere replica. The responses from the survey sent out to experts were mapped to the tables 11-13 and is read identically to tables

8-10. The mapping from percentage to integer was done by dividing the percentage answered with 100 and multiply by 5. This value was then subtracted from 5, yielding the respective e_{ij}-parameter. In cases where there were more than one answer, the average was then calculated of all the answers and mapped with the same mathematical method.

Table 11. The mapped e_{ij}-parameters representing the cascading effects on CI from disruptions lasting for two hours, taken from the online survey results.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	Energy	N/A	0.50	0.00	0.50	0.25
	ICT	0.00	N/A	0.00	0.00	0.25
	Water	0.00	0.00	N/A	0.00	0.00
	Financial	0.00	0.00	0.00	N/A	0.00
	Transport	0.00	0.00	0.00	0.00	N/A

Table 12. The mapped e_{ij}-parameters representing the cascading effects on CI from disruptions lasting for 24 hours, taken from the online survey results. The asterisk * indicates a response which is likely to be erroneous when compared to earlier responses from the same expert. It is included however and have been used in the simulations.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	ICT	N/A	1.00	2.50	5.00*	1.00
	Energy	0.00	N/A	0.00	0.00	0.25
	Water	0.00	0.00	N/A	0.00	2.00
	Financial	0.00	0.00	0.00	N/A	0.00
	Transport	0.00	0.00	0.00	0.00	N/A

Table 13. The mapped e_{ij}-parameters representing the cascading effects on CI from disruptions lasting for 7 days, taken from the online survey results.

		Effect on CI				
		Energy	ICT	Water	Financial	Transport
Failed CI	Energy	N/A	3.00	3.50	3.50	1.38
	ICT	3.00	N/A	1.00	1.00	0.38
	Water	0.00	0.00	N/A	0.00	2.25
	Financial	1.00	1.00	0.00	N/A	0.63
	Transport	0.00	0.00	0.00	0.00	N/A

5 Testing

The purpose of testing the system dynamics model was to develop a trust that it is suitable for its purpose and the problem it addresses, according to the desired specifications (Sterman, 2000) (Barlas, 1996). Consequently, this allows decision makers and users of the system dynamics model to trust the accuracy of its results. To ensure this, there are several tests which can assess the thesis model from various perspectives. The thesis model would be tested against all applicable tests (Sterman, 2000, pp. 859-861). In the rest of this section each test will be described, shown if it is applicable to the thesis model and an assessment if the thesis model passed the respective test will be presented.

5.1 Boundary Adequacy

The boundary adequacy test examines if the thesis model contains all relevant aspects of a structure. In this work the relevant structures are those that enable a successful representation of how cascading effects happen after a disruption in networked CI. There should be some level (stock) which represents operations of a given CI. When a CI experiences reduction in operations in whichever form they may take, there needs to be a reduction rate, or in this case a breakdown rate (flow). To show that the CI can return to its original level of function, there must accordingly be a restore rate, i.e. return to service. Emulating the cascading effects from one CI to the other requires some variable that represents the effect a CI has on the other, which in turn affects the corresponding CI. In the thesis model the physical structures Running operations, Down operations, breakdown rates and return to service represent each individual CI. These are linked via services provided by each CI. The services provided is a function which assesses the services a CI has at any time which is added to the interdependent other CIs breakdown rate and is affected by the cascading parameters e_{ij}. Accordingly, the thesis model contains all relevant and needed structure to pass the boundary test.

5.2 Structure assessment

The purpose of this test is to assess the structure of the thesis model. This means that we want to see if the model has a real-world application and that it can represent a real-world system. In relation to the thesis model, it is to see if the thesis model appropriately represents a real CI. It must conform to physics and be logical to represent a real CI. It conforms to physics by having all the stocks represent physical operations performed by a CI, and the reduction/increase are logical. The disruption causes a decrease in the operations level. A restoration causes the operations level to increase. The thesis model contains these stocks and flows which also are in Canzani's model, but the Recovered operations stock and the repair flow have been eliminated. The repair flow has been aggregated into a composite flow, exiting Down operations stock and entering the Running operations stock. This aggregation is logical because it represents the real-world time it would take to repair a CI and restore its operations. This represents the real world more appropriately because the working, non-working and recovered CIs does not resemble the SIRS model in terms of having an immunity period during which no disruption can occur. This is evaluated from a realistic point of view that a CI is either running or down.

5.3 Dimensional consistency

For a model to be sustainable and realistic, it is important that each variable has a unit of measurement which is dimensionally consistent with the rest of the model. As the stocks and flows are based on sets of differential equations, each side of these equations should have the same unit, which shows that the equations are legitimate equations. As an example, in the thesis model CI output is defined as *operations*. A reduction in operations would then be with a rate of *operations/hour*, as discussed in section 2.4.1. Each variable, stock and flow in the thesis model consists of either operations, operations/hour or dimensionless units. Vensim DSS was used to successfully test the unit consistency without errors, making the model dimensionally consistent. Therefore, the thesis model passes this test. A listing of all variables and their units of measurement is included in the thesis model found in Appendix J

5.4 Parameter assessment

The purpose of the parameter assessment is to examine if "the parameter values are consistent with the relevant descriptive and numerical knowledge of the system" (Sterman, 2000, p. 859) The e_{ij}-parameters represent the cascading effect one CI has on the other CI it is connected. This means that each e_{ij}-parameter has a meaning behind it. The parameters numerical data were collected via a survey conducted in the thesis project as well as a survey conducted by Laugé (2014, pp. 155-167) These two requirements are fulfilled, and the thesis model passes the test.

5.5 Extreme conditions

This test is designed to see if the mathematical equations behave correctly or reasonably when inputs exceed the allowed limits, representing a shock factor to the system or unexpected behaviour. Because infrastructure behaviour modelling serves as a simplified version of actual behaviour, this test serves as a reality check because it is possible for external events to exceed expected limits. When conducting this test, several of the key variables, such as the e_{ij}, average demand and capability-parameters were adjusted to unexpected values and simulations were run. When the e_{ij}-table values were set to values that exceeded 5, the thesis model gave expected results. This is because when the interdependency level of the CI exceeds 5, the results after a disruption should be that the all the CI have their performance levels reduced further. This is because the reduction in operations/hour is increased even more. When the e_{ij}-values were $0 \le e_{ij} < 1$, the thesis model behaved as it should, albeit not without significant changes because the cascade effects for some infrastructures became 0. This does however show that the cascade effects are happening when there is a value greater than 0. In the thesis model it is not logical that the e_{ij}-parameters should be less than 0, as this means that the CI are gaining a higher number of running operations when a disruption occurs. However illogical, it was tested and shown that the thesis model performed expectedly when $e_{ij}<0$.

When the average demand was adjusted to higher than 100% the thesis model performed expectedly. This scenario does however not hold any logical relevance when working under the assumption that an infrastructure cannot at any point in time yield higher than 100% output. The demand could be considered higher than 100% but the output cannot logically exceed 100%. When the average demand was lower than 90% the thesis model behaved as expected because service provided was less affected by the disruption, which follows since the demand for the services were lower. The last variable tested was the maximum capability of the CI. The maximum capability cannot be less than 0. A CI cannot have negative capability, which would be illogical. Because the ratio of Current capability = Running operations/maximum capability, when the maximum capability is 0 there is a mathematical inconsistency when dividing with 0. It could theoretically occur that a CI has no capability at all, but this scenario does not seem probable because CI are considered critical to everyday operations in society as discussed in section 2.2. This implies that 0 operations in output would disqualify it as a CI. When testing this unlikely scenario, the expected results were errors due to the division with 0. In Vensim this error was solved by inserting a MIN-function inside an IF THEN ELSE-clause in the breakdown rates for each CI. The MIN-function returns the smaller value of A and B. A is considered the breakdown rate and B represents the maximum capability divided by the time step and the IF THEN ELSE ensures that the running operations never go below zero and the zero-division problem disappears, and the results are expected. The running operations are assumed to be at 100 at time t=0 which they all were when the maximum capability was 0. The service provided was equal to 0, which also was expected. After testing the relevant variables and rates, the thesis model passes this test. The relevant graphs for this test are found in Appendix B.

5.6 Integration test

When the thesis model equations are simulated using a specific numerical integration method and/or specific time-step, it is important to be sure that it is not dependent on either the integration method or the time-step. The thesis model should behave the same way regardless of changes to the integration methods or time step used. By testing different time-step values starting from a small time step in combination with different integration methods in Vensim DSS, it is proved that it passes the test because there were no significant changes in the results aside from two integration methods (Runge-Kutta 2/4 Auto methods) which caused alert messages but still provided the same results, regardless of change in time step.

5.7 Behaviour reproduction test

The model passes this test if it reproduces the behaviour of the original real-time system. However, this test requires a historical behaviour of the original system (reference mode) to compare the thesis model behaviour against. Accordingly, it is not applicable to the thesis model because there has not been found a reference mode for it to compare the results with.

5.8 Family member test

The family test assesses if the thesis model can represent more than one instance of the system, i.e. reproduce the behaviour of different instances of the same time. In the context of this thesis the 5 CI contained in the thesis model could be applied to different counties in Norway. Parameter values for each county should be used and fed to the thesis model to reproduce individual results specific for that county. Because this data is not present in the thesis and the results from the thesis survey are not sufficient to evaluate this, this test is not applicable to the thesis model.

5.9 Sensitivity analysis

The purpose of the test is to find out how the thesis model behaves when confronted with uncertainties regarding assumptions made in the modelling. As an example, an assumption in the thesis model is that the average time to repair and restore the CI is set to a certain value. This value can then be tested to see if the simulations changes significantly if this value is different. The sensitivity test is comprised of two parts, numerical and behavioural. For this thesis model, the numerical test is not applicable because there is no reference mode with which to compare the output. The behavioural test is applicable because it shows how the tested variables are behaving when the input is changing. This means that if the behaviour, or output of the thesis model, changes when alternate assumptions are made, then the thesis model is considered sensitive to behaviour mode. There are two types of methods for testing behaviour, univariate and multivariate. In univariate, the value of one parameter is being changed at a time meanwhile all other parameters included in the test are kept at their original values, whereas in multivariate all parameters being tested are changed at the same time. When approaching this test, it was important to identify key parameters, then see how the stocks i.e. running operations or down operations, respond to the change. The thesis model is simulated several times and applies a range of values to the selected variables. For this test, the number of simulations selected was 200, which is the default-value in Vensim DSS. Tables 14 and 15 show the variables tested and the corresponding stocks monitored after the simulations were run.

Table 14. Variables tested in the sensitivity test.

Variable
Average repair and restore time Energy
Average repair and restore time ICT
Average repair and restore time Water
Average repair and restore time Financial
Average repair and restore time Transport
Effect on CI1 from CI2
Average Demand Energy
Average Demand ICT
Average Demand Water
Average Demand Financial
Average Demand Transport

Table 15. Stocks monitored during the sensitivity test.

Stocks
Running Operations Energy
Running Operations ICT
Running Operations Water
Running Operations Financial
Running Operations Transport

For the average repair and restore time variables, the base value was set to 47 hours, as discussed in section 4 previously. The sensitivity test was then conducted as a multivariate test, with values ranging from 0 hour to 72 hours for each average repair and restore variable, representing the varying degree of disruption that might occur and that in some cases the average time to repair and restore can be shorter and vice versa.

The Average Demand variables are assumed to be 90% of maximum capability for each CI. In the sensitivity test the tested range for these variables were set to a starting value of 50%, and maximum value of 100%, reflecting that the demand for can change over time. This test was also conducted with the multivariate method because there are 5 Average Demand-variables in total, in which the outcome is expected to be similar.

The final part of the behaviour sensitivity testing is the array which consists of all the e_{ij}-parameters that describe the effects of the cascade each CI has on the others. Because the array consists of values ranging from 0 to 5, it is applicable to test for all values in the range. When testing, it was performed as a combination of univariate and multivariate. For each CI (univariate), each effect-variable (e_{ij}) from the networked CI (multivariate) was then tested with values ranging from 0 to 5 and the Running operations-stock for the respective CI tested was monitored.

With all the relevant variables tested, the test-results show that the thesis model output-change in the stocks is expected and the thesis model does not express behaviour mode sensitivity regardless of the change in the parameter-values used. Based on this it is appropriate to say that the model passes this test. With all the applicable tests performed on the thesis model and the passing of the tests, the thesis model can be trusted to behave realistically and within the confines of the boundaries it was created for.

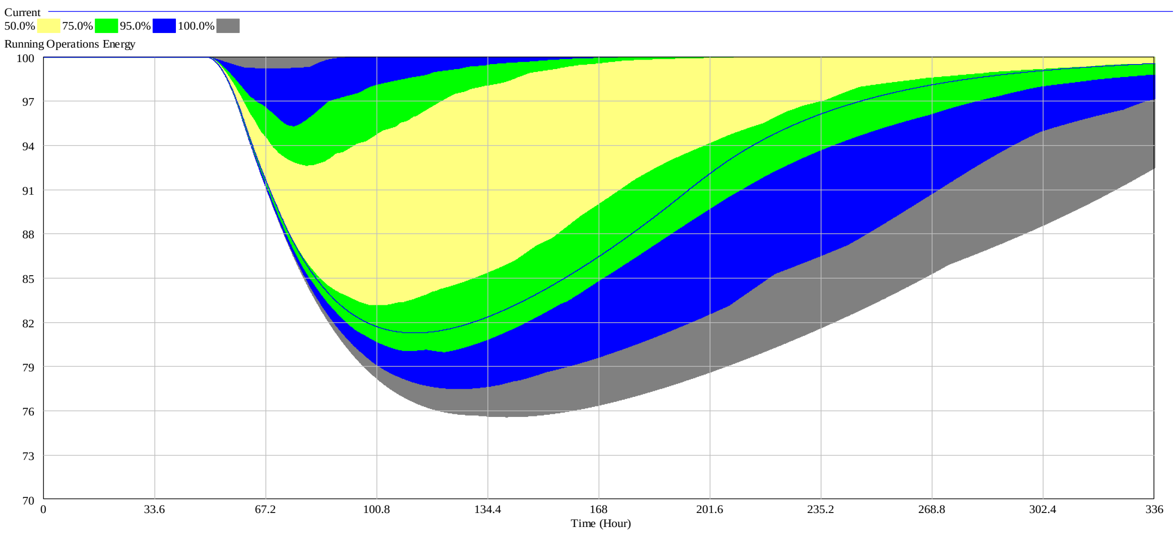

Figure 5. The results of multivariate sensitivity testing of the average repair and restore time variable for the Energy CI. The graph shows that after 200 simulations, the average repair and restore value can be anything between 0 and 72 hours and still *shows the same type of output i.e. the graph follows the same pattern regardless of the value.* This is also true for all the other CI with their corresponding average repair and restore time variables. The results for the respective CI can be found in Appendix C.

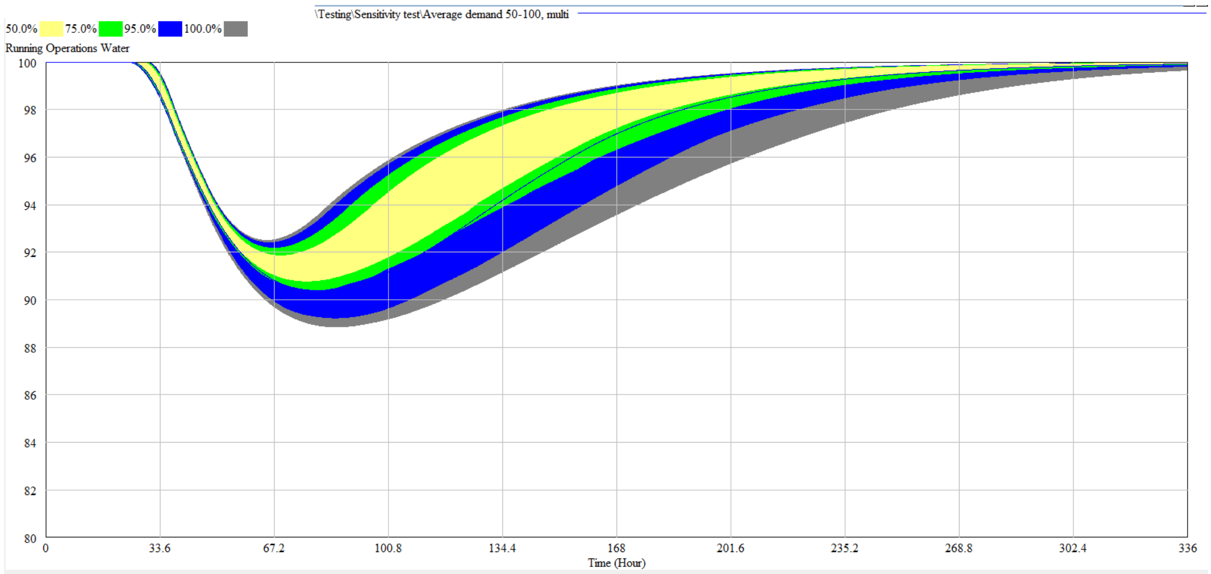

Figure 6. The results from the multivariate sensitivity testing of the average demand for the Water CI. The figure shows that any demand between 50 and 100% will yield the type of behaviour in that the running operations show the same pattern in the graph, regardless of what the demand is. This also holds for all the CI, and the respective results can be found in the Appendix D.

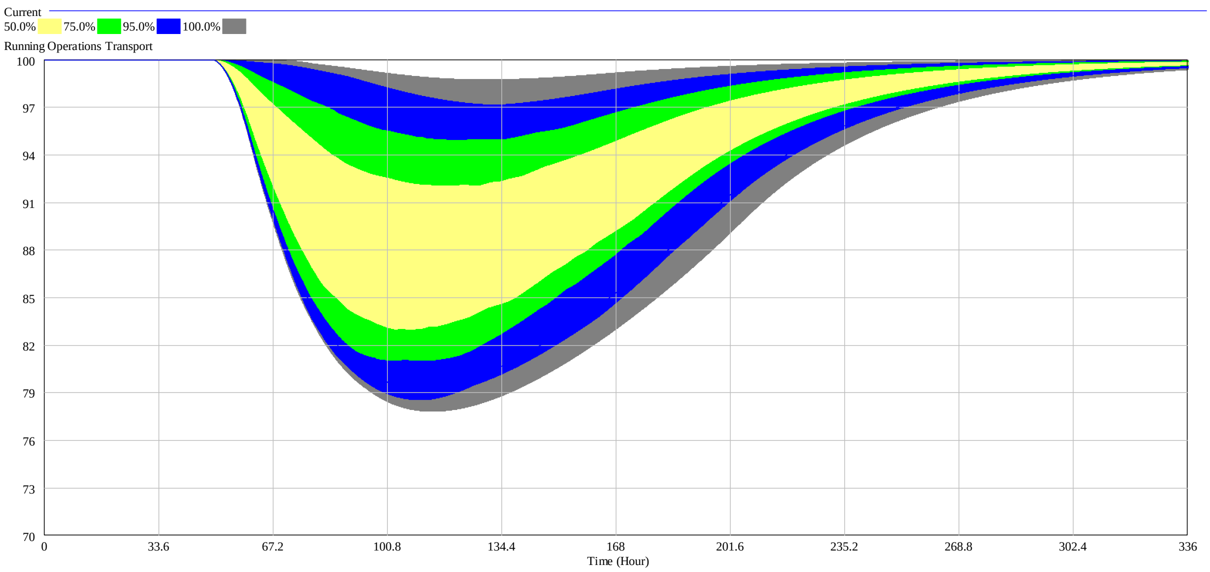

Figure 7. The results of a multivariate behavioural sensitivity test for each cascading factor affecting the Transport CI. The figure shows that no matter the value of the cascading factors, the output can be expected and is similar. The behaviour of the Running operations for each CI shows the same pattern of behaviour when evaluating the graph results. All the results for each CIs Running Operations in this test can be found in Appendix E.

6 Results

A significant part of the thesis was to replicate Canzani's model. However, the results from the simulations run with replicated model are not included in section because they only show how well the model was replicated when compared to Canzani's model, and do not contain any new results as such. They are found in Appendix F. The results from the simulated scenarios with the thesis model are in this section divided into three parts. The first part contains the results from running one scenario Canzani created, this time simulated with the thesis model. The parameters used will be identical to Canzani's simulations. The second part of the results are those where the simulations were run using correct e_{ij}-parameters taken from tables 8-10 which corresponding to the respective disruption length, and results from using the e_{ij}-parameters in tables 11-13 created from the survey responses. Further, there are three disruption magnitudes (2, 4 and 9) for each e_{ij}-parameter interval (less than 2 hours, less than 24 hours and more than one week) and the respective disruption length. The simulations with the thesis model yielded many result-graphs, which for the sake of brevity have been shortened, and the complete results are found in the appendices G-H. The third part contains the results of simulating the designed worst-case scenario with the thesis model.

6.1 Canzani's scenario

6.1.1 Single disruption with large magnitude

This part contains the results from simulating an ICT CI disruption with magnitude $m_d = 9$, indicative of a large disruption. The disruption occurs at time $t_d = 48$ hours of the simulation and lasts for $\Delta T_d = 24$ hours with the e_{ij}-parameters from table 8 in section 4. The results show that the running operations of the ICT CI are in the space of 12 hours reduced to 0% output, which lasts for another 12 hours before the recovery process starts. The ICT CI does not recover to 100% output for the rest of the simulation time. The operations of the other CIs are reduced to 87% (Energy CI) at the most before they start recovering. They recover to 100% by the end of the simulation time. The ICT services provided are reduced to none but recovers to 100% on day 7.5 of the simulation time. The other CIs are not affected significantly by the reduced services from the ICT CI. The graph results are shown in figures 8 and 9.

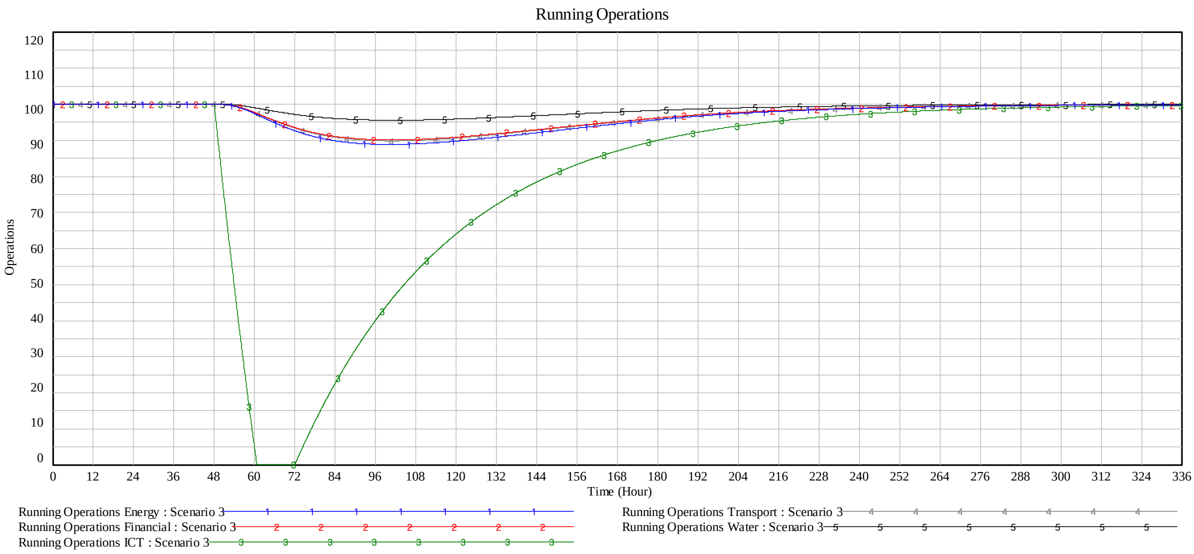

Figure 8. The running operations of the ICT CI is reduced to 0% for 12 hours before recovery starts. The other CIs are affected by this down to about 87% at the most, for Transport, Energy and Financial CI. The recovery for the linked CI is complete by the end of the simulation time.

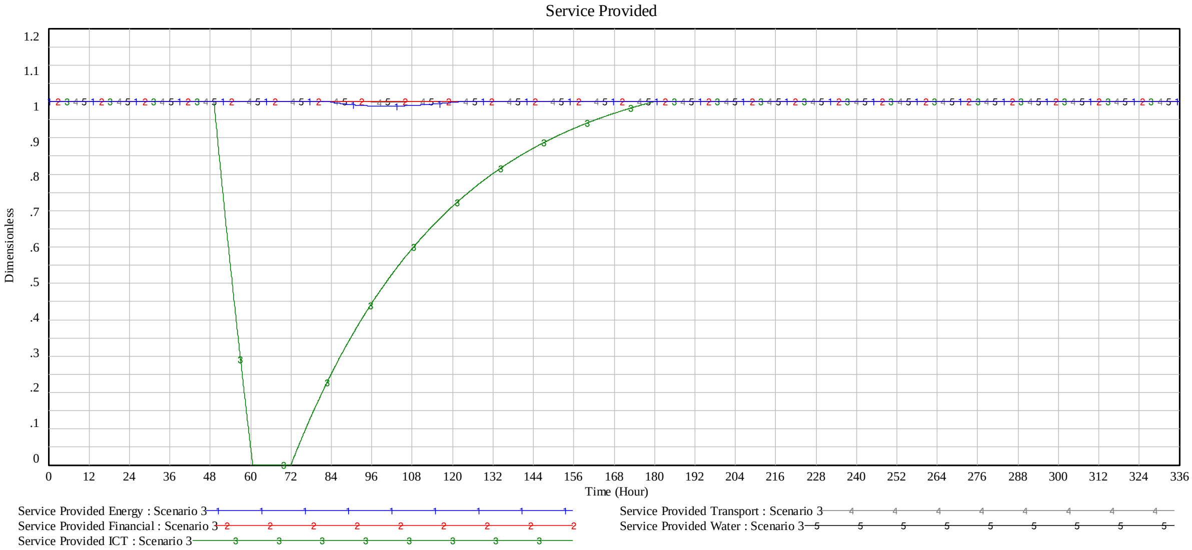

Figure 9. The services provided by the ICT CI are reduced to 0% for 12 hours before recovery starts. ICT services are restored by day 7.5 of the simulation time. The Energy CI is the only CI that is affected by the reduced ICT services, but not more than a few percent reduction, which is restored after 5 days of the simulation time.

6.2 Revised scenarios with correct e_{ij}-parameters and disruption length

6.2.1 Single disruption with large magnitude for less than 24 hours

This simulation uses the e_{ij}-parameters corresponding to the CI being down for less than 24 hours as observed by Laugé (2014, p. 173). These are found in table 9 in section 4. The disruption with magnitude $m_d = 9$ occurs in the ICT CI at $t_d = 48$ hours and lasts for $\Delta T_d = 24$ hours. The running operations of the ICT CI are reduced to 0% for 12 hours before recovery starts. The linked CI are all affected by the disruption and the financial CI is reduced the most to about 83% before recovery starts. The service provided by the ICT CI is also disrupted and reduced to 0% for 12 hours before recovering. The services of the other CIs are reduced to about 93%, with the financial services suffering the most from the disruption. By day 7.5 the services are restored to 100% and by the end of the simulation period the running operations of all CI has been restored to 100%. All results for this section are found in Appendix H. This is shown in figures 10 and 11.

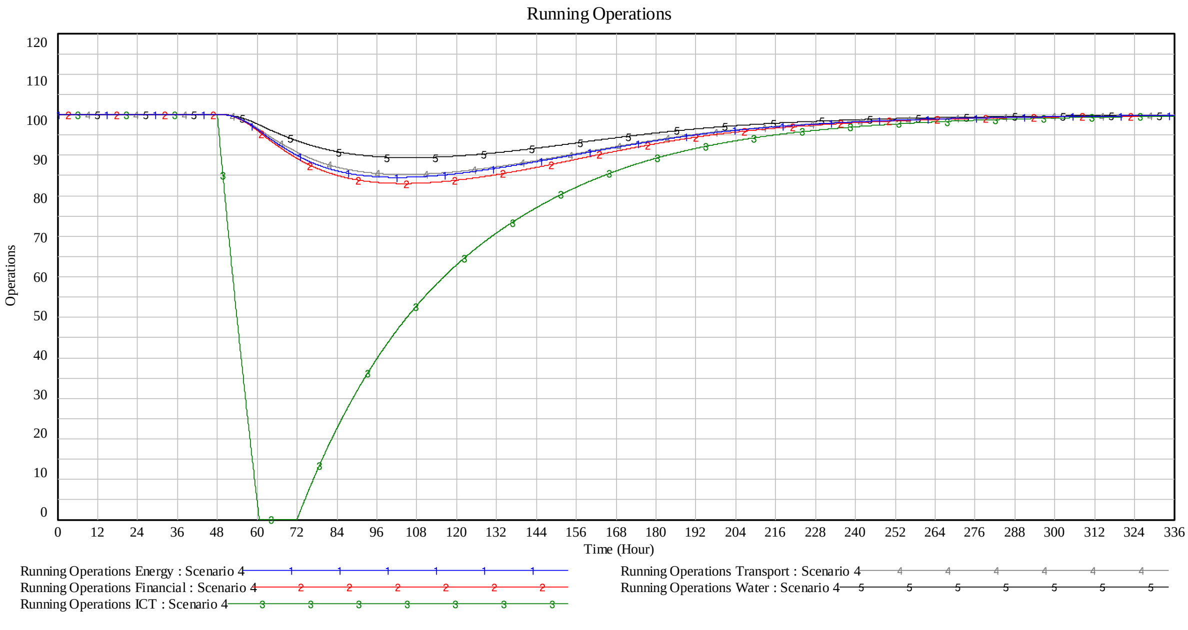

Figure 10. The results from ICT CI being disrupted with a magnitude of 9 for less than 24 hours. The ICT CI is reduced to 0% 12 hours after the disruption first occurred. It remains at 0% for 12 hours before recovery starts. The other CIs are being affected, the financial CI being hit the hardest and reduced to about 83% before recovering. By the end of the two-week simulation the operations are restored for all CI.

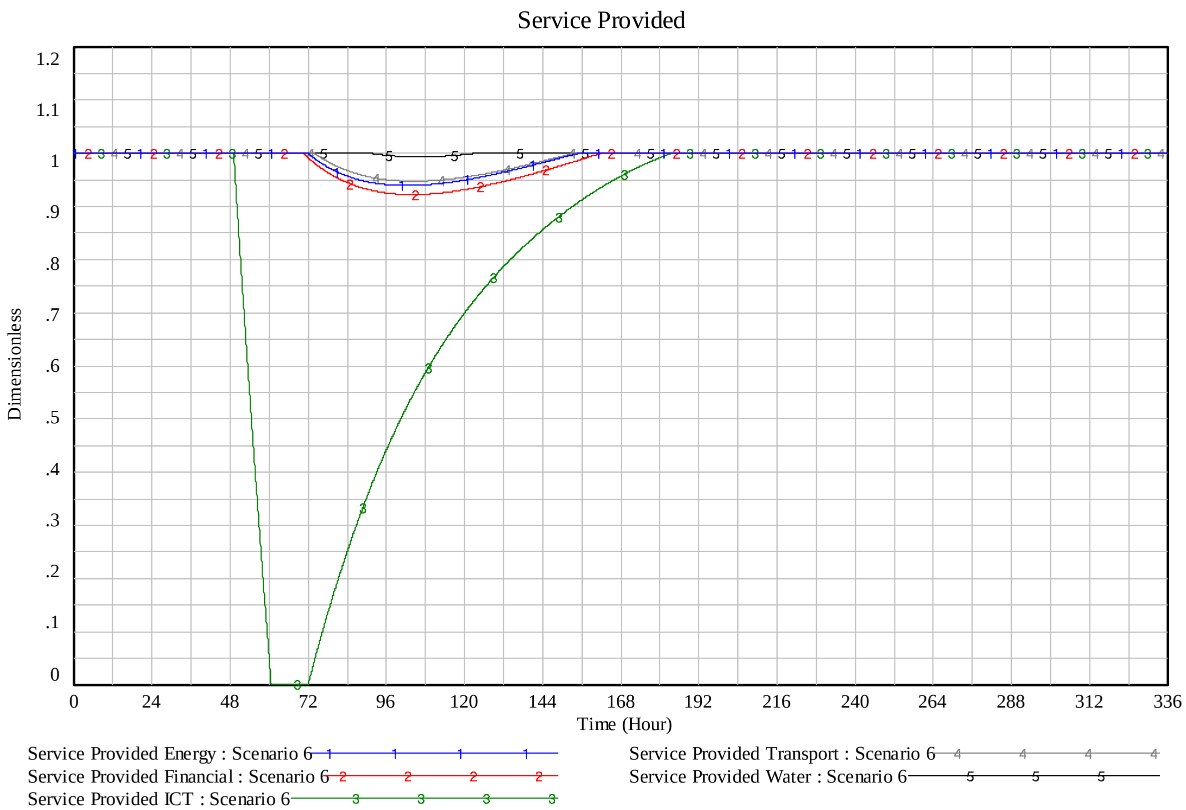

Figure 11. The service provided by the ICT CI is reduced when a disruption occurs at time 48 hours. 12 hours after the disruption, the ICT services are 0 and remain 0 for 12 more hours before they start recovering. The other CIs are reduced to about 93% at most before they start recovering. By day 7.5 all the CI services have been restored.

6.2.2 Single disruption with large magnitude for more than one week.

In this scenario the disruption m_d = 9 has been kept the same as the simulation done in section 6.2.1. The e_{ij}-parameters have been changed to reflect how the CI are affected by a cascading disruption which lasts for more than one week, which are found in table 10 in section 4. The running operations of the ICT CI are disrupted at time t_d = 48 hours which lasts for ΔT_d = 168 hours. 12 hours after the disruption the operations of the ICT CI are at 0%. They remain there for another 6.5 days before recovery starts. The other CIs are affected and reduced to about 59% at the most (Energy CI) before they start to recover. None of the CI operations return to 100% by the end of the two-week simulation. The results are shown in figures 12 and 13.

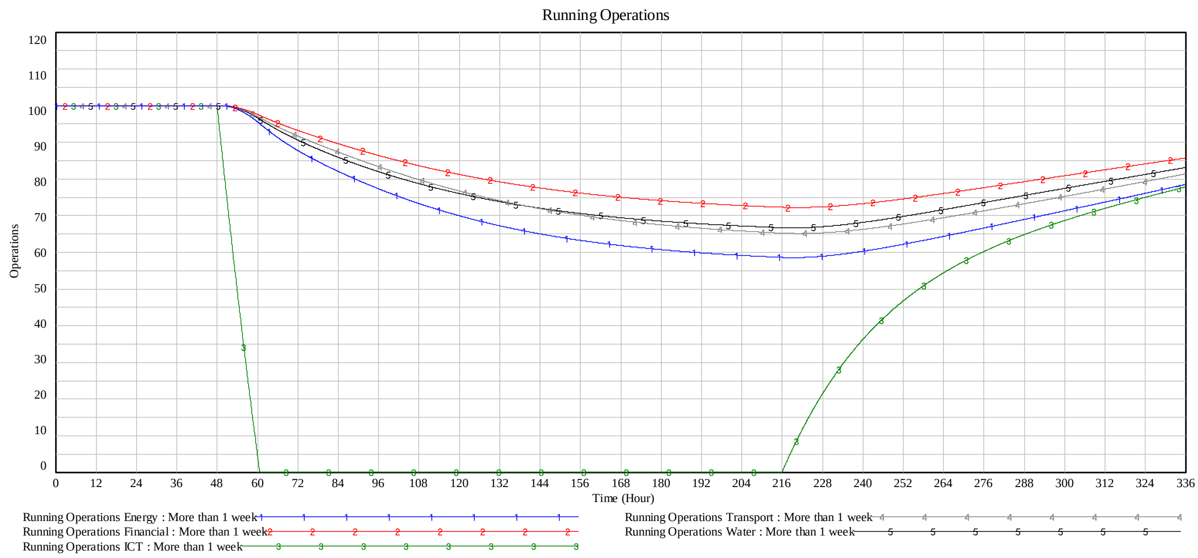

Figure 12. The results of a disruption of the ICT CI with a magnitude of 9, occurring at 48 hours and lasting for 168 hours. The ICT CI is down to 0 operations 12 hours after the disruption occurs and remains at 0% for another 6.5 days before recovery starts. The other CIs are affected by this and reduced to about 59%% at most before they start recovering. The running operations never fully recover higher than about 95% during the simulation time.

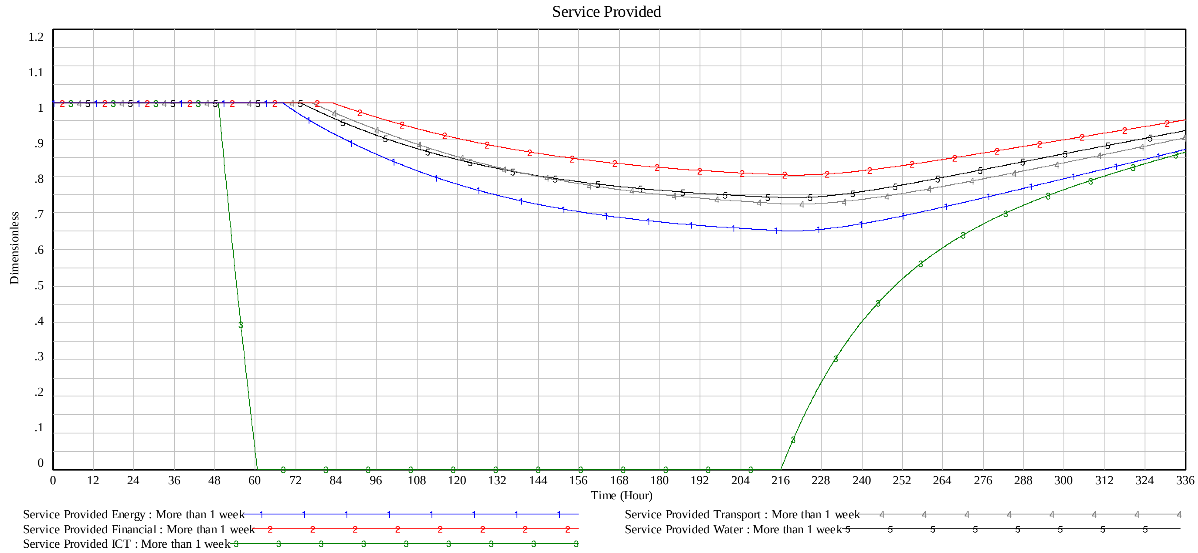

Figure 13. The service provided by the ICT CI is reduced when a disruption occurs at time 48 hours. 12 hours after the disruption, the ICT services are 0% and remain 0% for 6.5 more days before they start recovering. The other CI services are reduced to about 65% at most before they start recovering. The services are not restored by the end of the 2 week simulation.

6.3 Results from scenarios with parameters from the online survey

The scenarios simulated in this section have the same outline as in section 6.2.2 This means that the disruption lasts for one week, the disruption magnitude is 9 and occurs at 48 hours. The e_{ij}-parameters have been changed to those found in table 13. The parameters for table 13 have been calculated from the responses to the online survey. The other results from simulating the same scenarios as 6.1 and 6.2.1, this time with tables 11-12, can be found in Appendix G. The results show that the ICT CI is reduced to 0% output in operations and services 12 hours after the disruption occurs and it stays down for 6.5 days before recovering. The other CIs are affected by this disruption to some degree. The Energy CI suffers the most from the cascading effects, but operations are only reduced to about 78% at the most before it starts recovery. None of the CI are fully restored to 100% running operations by the end of the two weeks. The service provided results follow the same pattern as the running operations, except all the CI fully recovers by the end of the simulations.

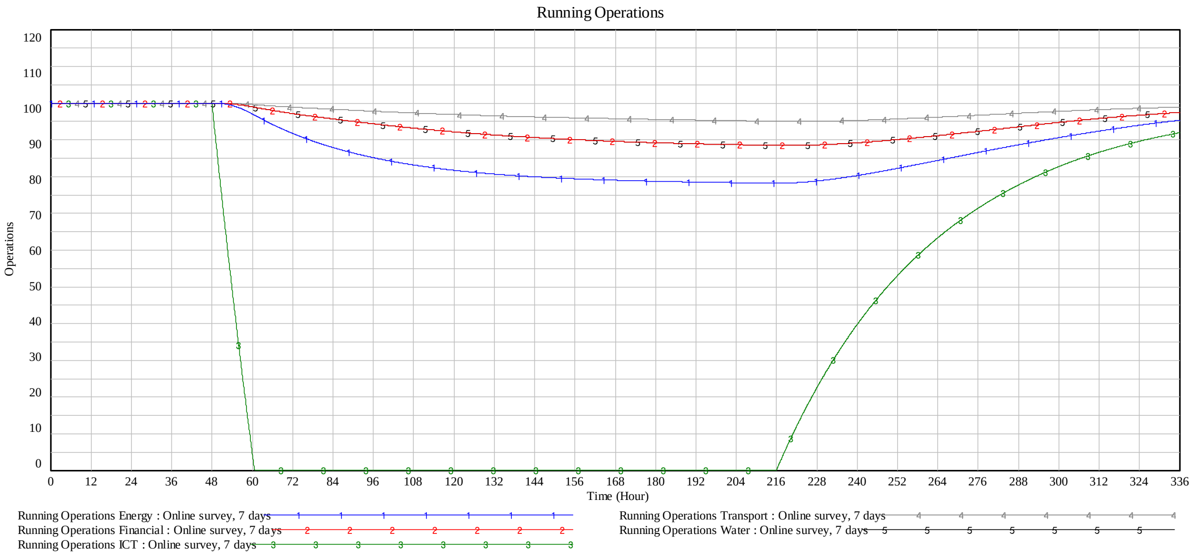

Figure 14. The results from simulating a one week disruption using the e_{ij}-parameters from the online survey. The ICT CI is reduced to 0% 12 hours after the disruption occurs and is down for another 6.5 days before the recovery begins. The other CIs are affected, Energy CI being reduced the most to about 78% before recovering. None of the CI fully recover by the end of the two weeks.

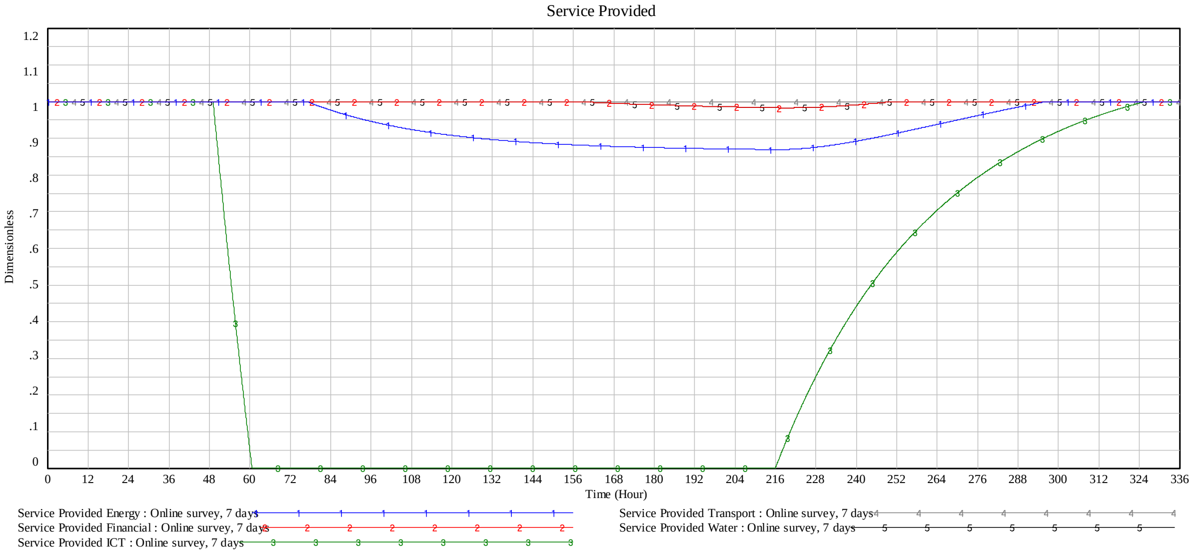

Figure 15. The service provided during the week long disruption. The ICT CI is reduced to 0% 12 hours after the disruption and gives no service for 6.5 days before recovery starts. The CI services fully recovers by the end of the two weeks. The other CIs are lightly affected, the Energy CI being reduced to about 88% at the most before recovering.

6.4 Results from simulating the proposed worst-case scenario

The simulations for the worst-case scenario follow the parameters outlined in the description of the scenario in section 3.2. The disruption magnitude m_d is set to 9 for all disruptions. The length of the simulation is one week. The disruptions occur to the Energy CI, ICT CI and Financial CI at time t = 15, 21 and 27 hours, respectively. The disruption duration for each CI is 24 hours. The average repair and restore time for the Energy CI is 24 hours, ICT CI 30 and Financial CI is 36 hours. The results show that the multiple disruptions occur at 6 hours intervals of each other and they cause the other CIs affected to have a longer restore time to get back to full output. The Water and Transport CI are less affected by the all the disruptions. The Water CI is the least affected and does not go below 80% in performance. The Transport CI drops to about 87% performance at the lowest point before restoration starts. None of the operations for any CI are restored completely by the end of the week. The services provided by the disrupted CI show a similar pattern as the disrupted operations, but services are completely restored for all CI by day 6 of the simulations.

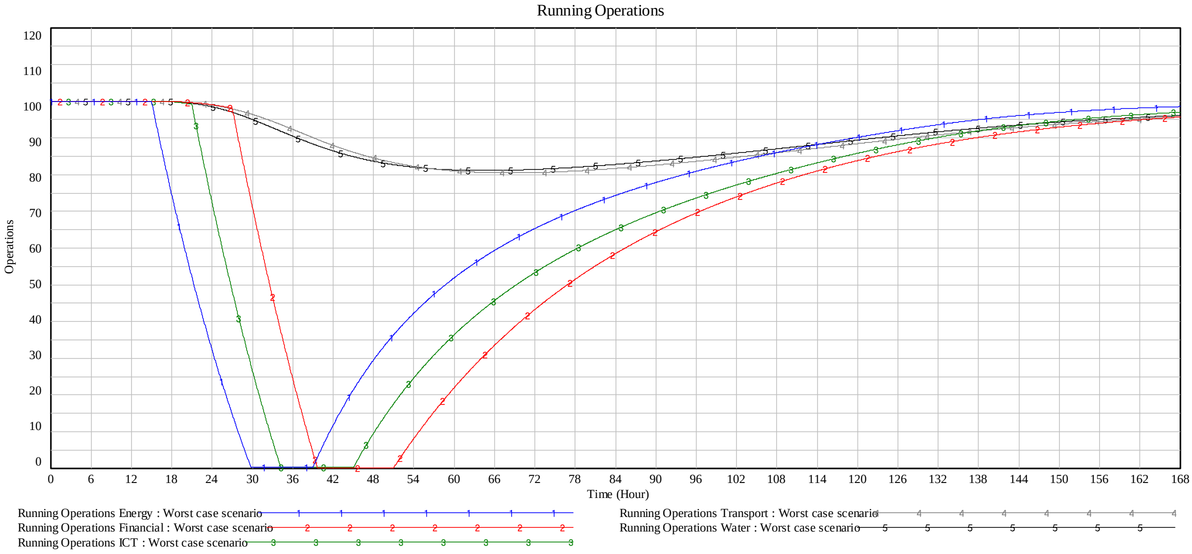

Figure 16. The results from running multiple disruptions consecutively with the thesis model. The directly disrupted CI are all reduced to 0 operations for 12 hours each before they start recovering. Due to multiple disruptions and increased repair and restore time for the CI affected, the restore time for all CI has increased and none of the CI are fully recovered to 100% by the end of the week.

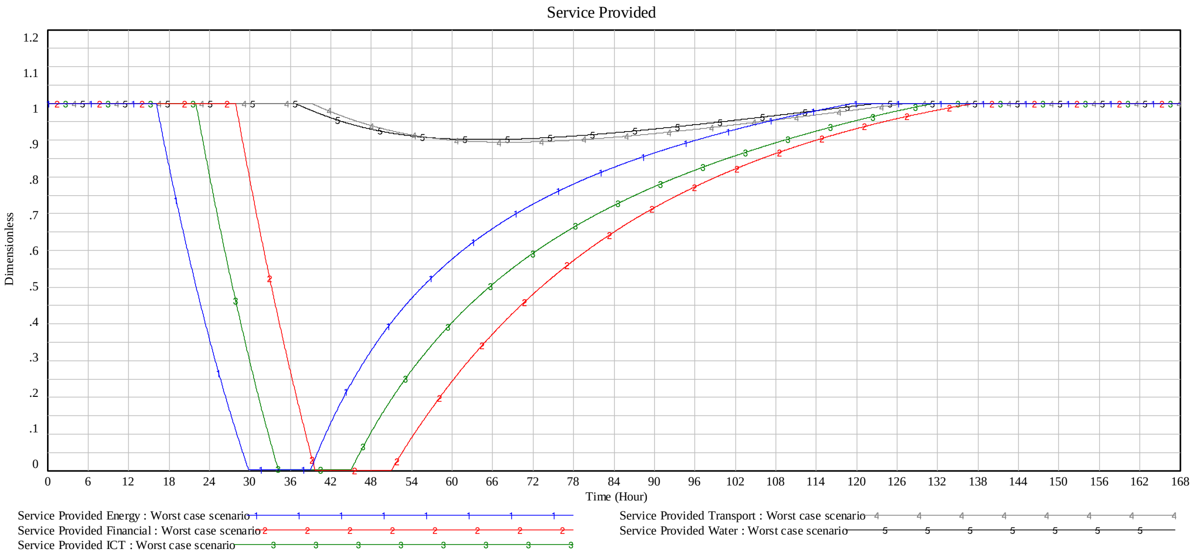

Figure 17. The results from simulating multiple consecutive disruptions against the Energy, ICT and Financial CIs. The services are reduced to 0 % for all CI suffering a direct disruption and the cascading effects causes the restoration time to increase before they are back to 100%. By day 6 the services have all been restored.

7. Discussion

The results from the simulations show a representation of cascading effects occurring during several disruptions. The scenarios used have been like those run by Canzani, the scenarios containing data from the online survey conducted and the worst-case scenario. The thesis model results are also like the results by Canzani which shows that the reasoning and ambition behind Canzani's model was indeed promising for the modelling of cascading effects, despite the incorrect usage of the SIRS-model to represent this as well as incorrect usage of e_{ij}-parameters. Because the thesis model passed the applicable tests as described in section 5 it has a foundation as a trustworthy model that can represent the cascading effects of disruptions whilst not being a SIRS-adaptation and it solves the problems with using a SIRS-model for this area of study. Due to the lack of responses from the online survey conducted, the simulations run with the responses received, cannot be representative for Norway as a country. At best it can be representative of the county expert responsible for that sector which answered the survey, which of itself could be beneficial to that county, if not representative. The results are differing significantly from the survey results of Laugé (2014, pp. 170-176) due to that fact. However, the results support the assertion that since many CI have internal communications channels that are not public, they can still manage some form of communication and an ICT CI disruption alone will most likely not destroy these completely (2015, p. 18). This is seen particularly in figures 14 and 15. The cascading effects the ICT disruption has on the other CIs, even when the magnitude is high, and the disruption length is one week, are low.

This causes the scenarios themselves to be hypothetical and several assumptions have been made which may be different in a real-life situation. This applies especially to the worst-case scenario, which mostly consist of assumptions and hypotheticals. To create the worst-case scenario however would be a seemingly impossible task due to the many variables that have to be considered for it to be effective. The thesis model itself contains only so many variables and this creates limited types of input. It can be argued that if variables were further investigated and where possible be further dissected to find more useful variables, they could have a more profound effect in the simulations. The average repair time and restore-variable is of interest but with little background to support its values. In the literature study of the CI interdependencies in section 2.3 there was not found much data to support the assigned value.

Canzani commented[2] about the equivalent values used in her model, the *average repair* and *average unit time to restore*-variables that she did not have a specific reasoning for their values. It can be reasoned though that the average repair and restore time would increase for each CI being affected by a disruption, as a type of add-on factor to the cascading effects. In the worst-case scenario this is modelled accordingly and shows that for each consecutive CI suffering a disruption, the respective recovery time is prolonged. The multiple disruptions do create the same type of behaviour for each CI, which is natural and logical because the disruptive function is modelled identically. This can also be a somewhat limited view because when looking at the core components in tables 4 and 5 of the various CI in section 3.2, it is apparent that the disruptions could be modelled more in detail for each CI specifically. However, the benefit with the disruption factor as it is used in the thesis model is that it gives an abstract impression without too much detail.

When the Energy, ICT and Financial CI went down with short time intervals between them, this caused them to have similar breakdown rates and the total recovery time was prolonged. The results from the multiple disruptions simulated (Canzani, 2016, p. 10) differ from the worst case simulation because they happen later in the simulated time. Her disruption of the Energy CI occurs at t_d = 96 hours, which is 72 hours after the initial ICT CI disruption. Furthermore, the disruptions have different magnitudes and durations. In the worst-case scenario the Energy, ICT and Financial CI disruptions occur at t_d = 15, 21 and 27 hours respectively, with identical disruption magnitudes and durations. It can be argued that Canzani's simulated scenario is more realistic regarding multiple disruptions because the probability of disrupting three different CI with the same magnitude, with only 6 hours between disruptions is not very likely. This gives the impression that the constructed worst-case scenario itself is not realistic, but it does not influence whether the thesis model is a good representation for cascading effects or not. This shows that the thesis model can be used for multiple disruptions as well as single disruptions, but the multiple disruptions should be constructed with more data to support variables such as magnitude, disruption time and length.

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[2] Canzani E. 2018. *System dynamics modelling.* E-mail correspondence 21.01.2018. (Farstad T.)

8. Conclusion

This thesis is an attempt at replicating Canzani's model which has been done to a certain degree successfully, and to develop a new model which is more appropriate to represent cascading effects on CI. The thesis has answered the problem statements and tested the hypothesis outlined in the introduction. The study and replication of Canzani's model showed her proposed model could be improved which answered the first problem statement. The development of the thesis model was a success and the model passed all applicable tests that serve to support it as a strong model. The SIRS-model is not an applicable approach to modelling cascading effects from disruptions. This hypothesis was tested by developing a new model that is found to be more appropriate in simulating cascading effects. The limited results from the online survey results differ significantly from Laugé's results (2014) which answers the second problem statement. The survey results were not representative of cascading effects in Norway however. This is due to the lack of responses and it can be considered a future work to obtain more data which can be added to further simulations. Another branch of future work is the further development of worst-case scenarios with system dynamics modelling which can lead to important results that can be used by decision makers and experts in preparing for possible disasters. It is acknowledged that the thesis model is a simplified representation of a system containing critical infrastructure relationships and interdependencies. There are limitations in the thesis model regarding input and output which can and should be assessed by the individual scenario regarding how effective the model simulations are. The thesis model and results will also be discussed in (Farstad, et al. 2018) and have been submitted to the IT in Disaster Risk Reduction (ITDDR2018) conference, and an extended second article by the same authors will be submitted to Hawaii International Conference of System Sciences (HICSS 2019).

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Appendix A – Critical Infrastructure survey

A survey for expressing the performance in critical infrastructures (CI) after suffering from cascading effects as concequence of disruption in one of the CI's, where the disruption lasts for three different time intervals.

We are in this survey considering the following five critical infrastructures (CIs): Energy, ICT, Water, Financial and Transport. The performance level of each CI is measured as a percentage: 100% means that a CI is running at normal operational level; 50% means it is running at half of the normal operational level and so on. The values you provide will be converted into this percentile system and will be used in a system dynamics model to assess the behaviour of networked Critical Infrastructures.

The estimated time to finish the survey is 10 minutes.
For questions, please contact me via e-mail: Tor-Edin Farstad - toredf13@student.uia.no

Survey Question 1

Assume that the Energy CI gets fully disrupted (i.e., 0% performance level) for 2 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the ICT CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for ICT, and similarly for the other CIs.

ICT ______________________________ Water ______________________________

Financial __________________________ Transport __________________________

Survey Question 2

Assume that the ICT CI gets fully disrupted (i.e., 0% performance level) for 2 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Water CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for Water, and similarly for the other CIs.

Energy ___________________________ Water _____________________________

Financial __________________________ Transport __________________________

Survey Question 3

Assume that the Water CI gets fully disrupted (i.e., 0% performance level) for 2 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Financial CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for Financial, and similarly for the other CIs.

Energy ___________________________ ICT ______________________________

Financial __________________________ Transport __________________________

Survey Question 4

Assume that the Financial CI gets fully disrupted (i.e., 0% performance level) for 2 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Transport CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for Transport, and similarly for the other CIs.

Energy ___________________________ ICT ______________________________

Water ____________________________ Transport __________________________

Survey Question 5

Assume that the Transport CI gets fully disrupted (i.e., 0% performance level) for 2 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the ICT CI will perform at eighty percent of its normal operational level, then you enter 80 in the field for ICT, and similarly for the other CIs.

Energy ____________________________ ICT _______________________________

Water _____________________________ Financial ___________________________

In this part of the survey we wish to assess the cascading effects when the length of the disruption is 24 hours.

Survey Question 6

Assume that the Energy CI gets fully disrupted (i.e., 0% performance level) for 24 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the ICT CI will perform at forty percent of its normal operational level, then you enter 40 in the field for ICT, and similarly for the other CIs.

ICT _______________________________ Financial ___________________________

Water ______________________________ Transport ___________________________

Survey Question 7

Assume that the ICT CI gets fully disrupted (i.e., 0% performance level) for 24 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect.E.g., if you believe that the Energy CI will perform at forty percent of its normal operational level, then you enter 40 in the field for Energy, and similarly for the other CIs.

Energy ____________________________ Financial ___________________________

Water ______________________________ Transport ___________________________

Survey Question 8

Assume that the Water CI gets fully disrupted (i.e., 0% performance level) for 24 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Financial CI will perform at forty percent of its normal operational level, then you enter 40 in the field for Financial, and similarly for the other CIs.

Energy ____________________________ Financial ___________________________

ICT _______________________________ Transport ___________________________

Survey Question 9

Assume that the Financial CI gets fully disrupted (i.e., 0% performance level) for 24 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Transport CI will perform at forty percent of its normal operational level, then you enter 40 in the field for Transport, and similarly for the other CIs.

Energy ____________________________ ICT _______________________________

Water _____________________________ Transport ___________________________

Survey Question 10

Assume that the Transport CI gets fully disrupted (i.e., 0% performance level) for 24 hours. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Water CI will perform at forty percent of its normal operational level, then you enter 40 in the field for Water, and similarly for the other CIs.

Energy ____________________________ ICT _______________________________

Water _____________________________ Financial ___________________________

In this part of the survey we wish to assess the cascading effects when the length of the disruption is 7 days.

Survey Question 11

Assume that the Energy CI gets fully disrupted (i.e., 0% performance level) for 7 days. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Water CI will perform at ten percent of its normal operational level, then you enter 10 in the field for Water, and similarly for the other CIs.

ICT ______________________________ Financial __________________________

Water _____________________________ Transport __________________________

Survey Question 12

Assume that the ICT CI gets fully disrupted (i.e., 0% performance level) for 7 days. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Energy CI will perform at ten percent of its normal operational level, then you enter 10 in the field for Energy, and similarly for the other CIs.

Energy ___________________________ Financial __________________________

Water _____________________________ Transport __________________________

Survey Question 13

Assume that the Water CI gets fully disrupted (i.e., 0% performance level) for 7 days. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Financial CI will perform at ten percent of its normal operational level, then you enter 10 in the field for Financial, and similarly for the other CIs.

Energy ____________________________ Financial ___________________________

ICT _______________________________ Transport ___________________________

Survey Question 14

Assume that the Financial CI gets fully disrupted (i.e., 0% performance level) for 7 days. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the Transport CI will perform at ten percent of its normal operational level, then you enter 10 in the field for Transport, and similarly for the other CIs.

Energy ____________________________ ICT _______________________________

Water _____________________________ Transport ___________________________

Survey Question 15

Assume that the Transport CI gets fully disrupted (i.e., 0% performance level) for 7 days. Such disruption will result in cascading effects, that is, to impact the performance level of the other CIs. Please provide your estimate for the performance level of the other CIs as consequence of the cascading effect. E.g., if you believe that the ICT CI will perform at ten percent of its normal operational level, then you enter 10 in the field for ICT, and similarly for the other CIs.

Energy ____________________________ ICT _______________________________

Water _____________________________ Financial ___________________________

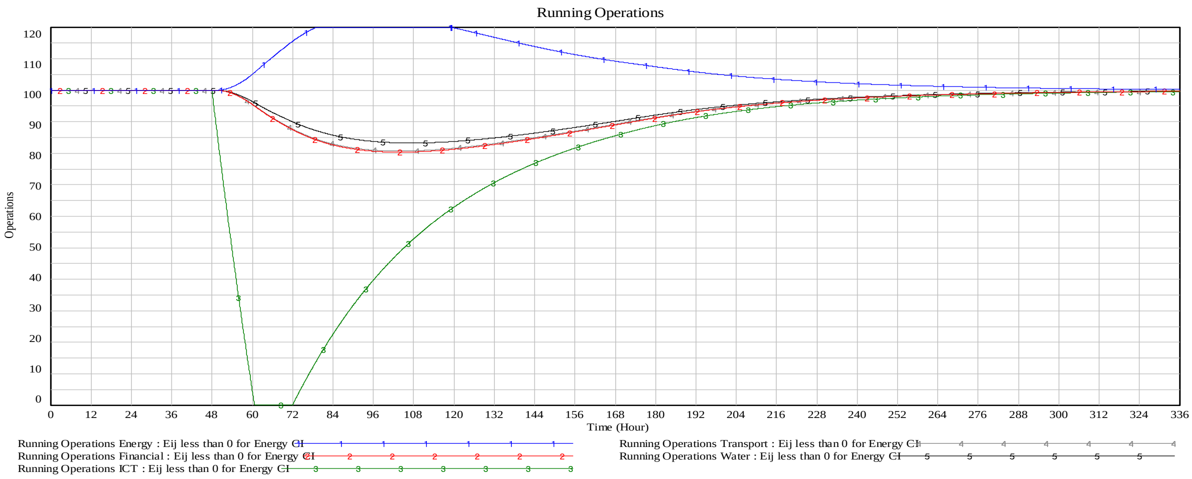
Survey Question 16

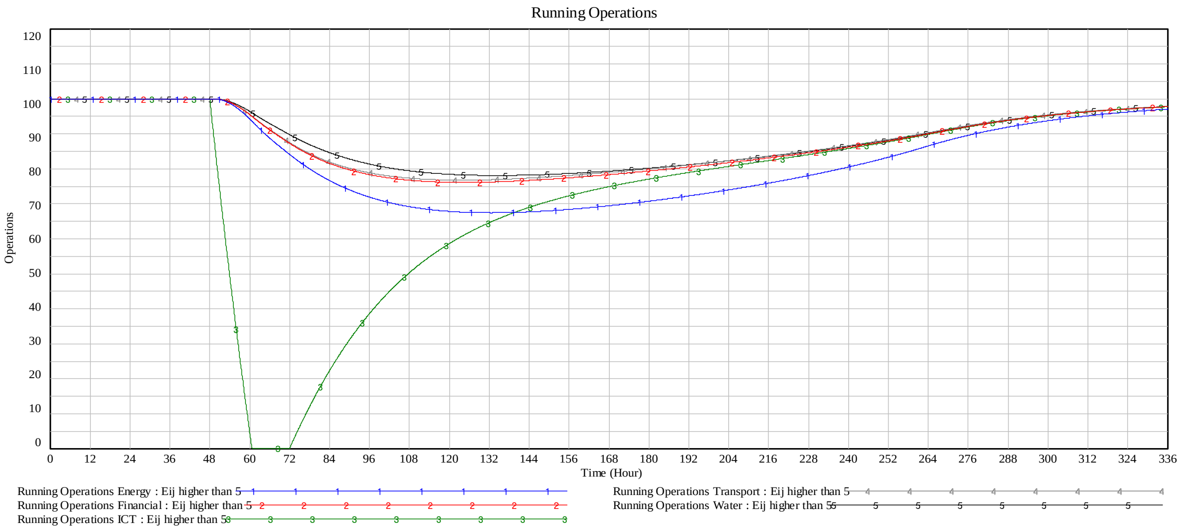
Do you have any other comments about the survey? (Optional)

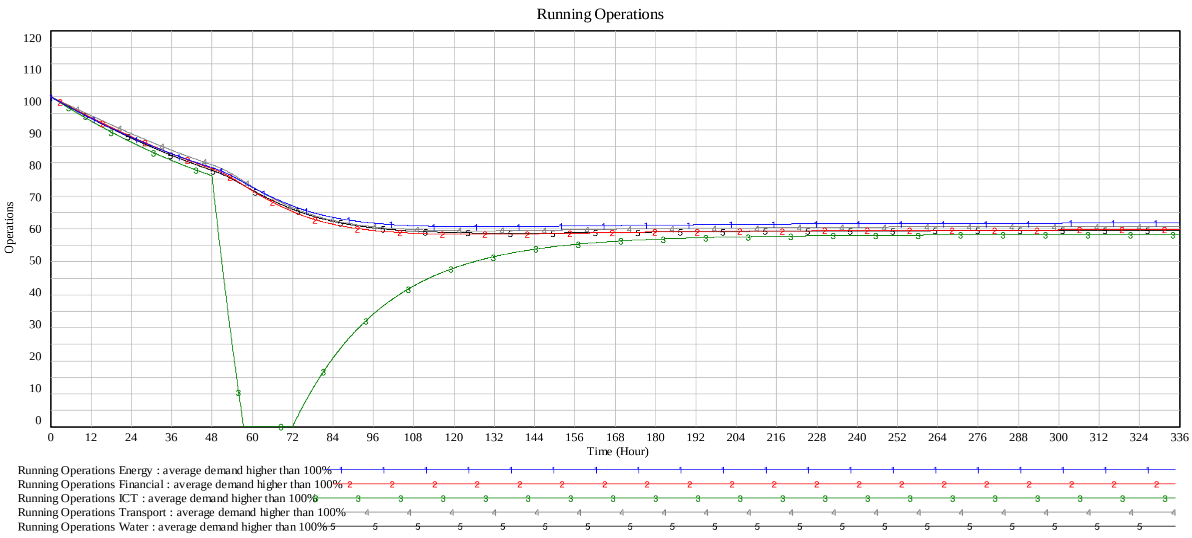
____

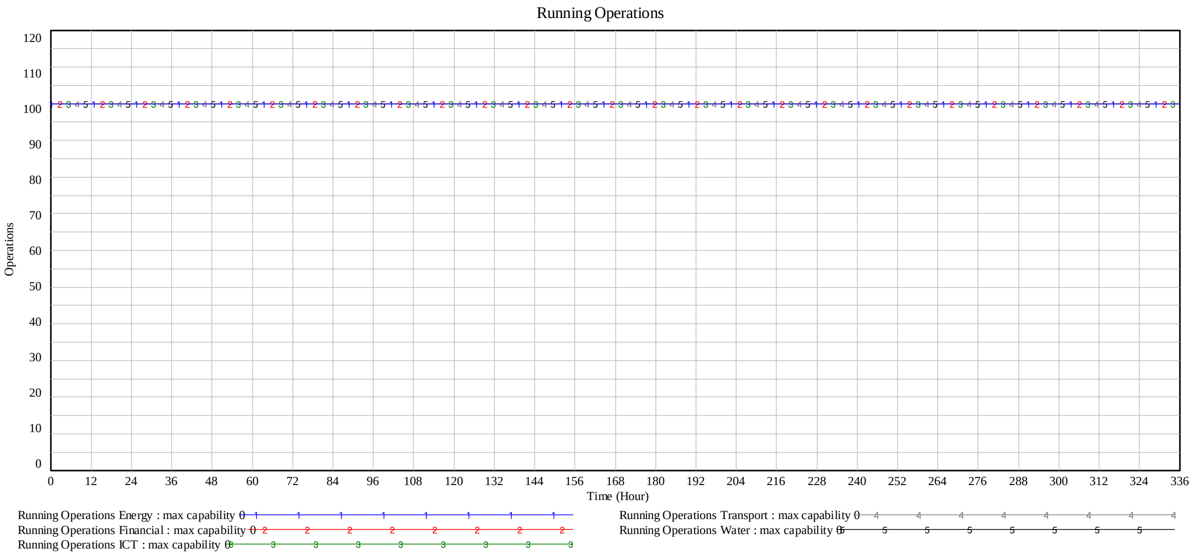
Thank you for your time!

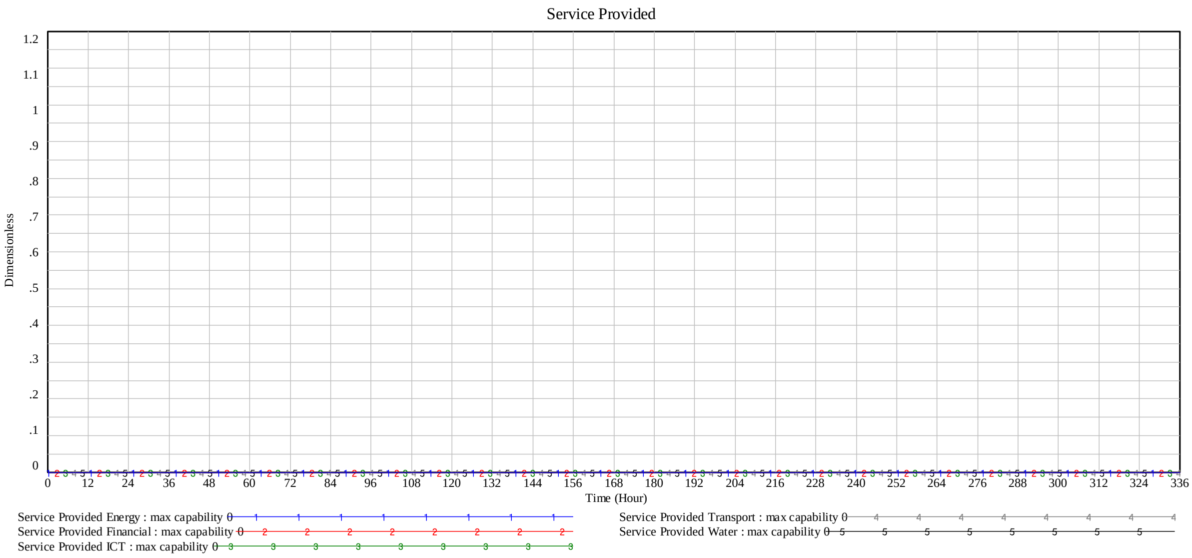
Appendix B – Results from extreme condition tests



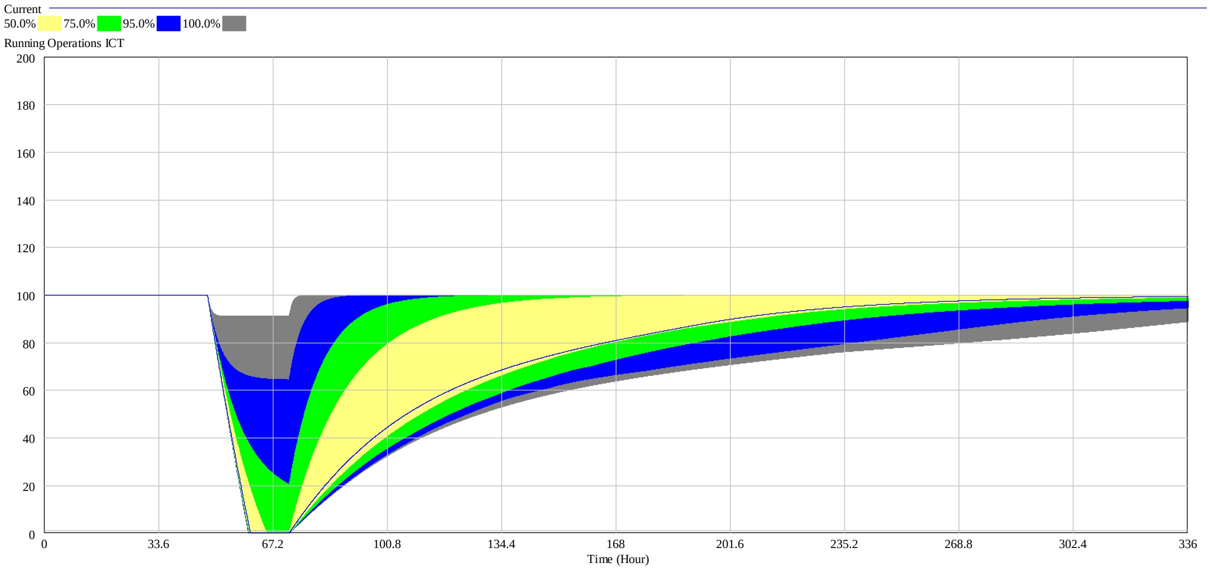


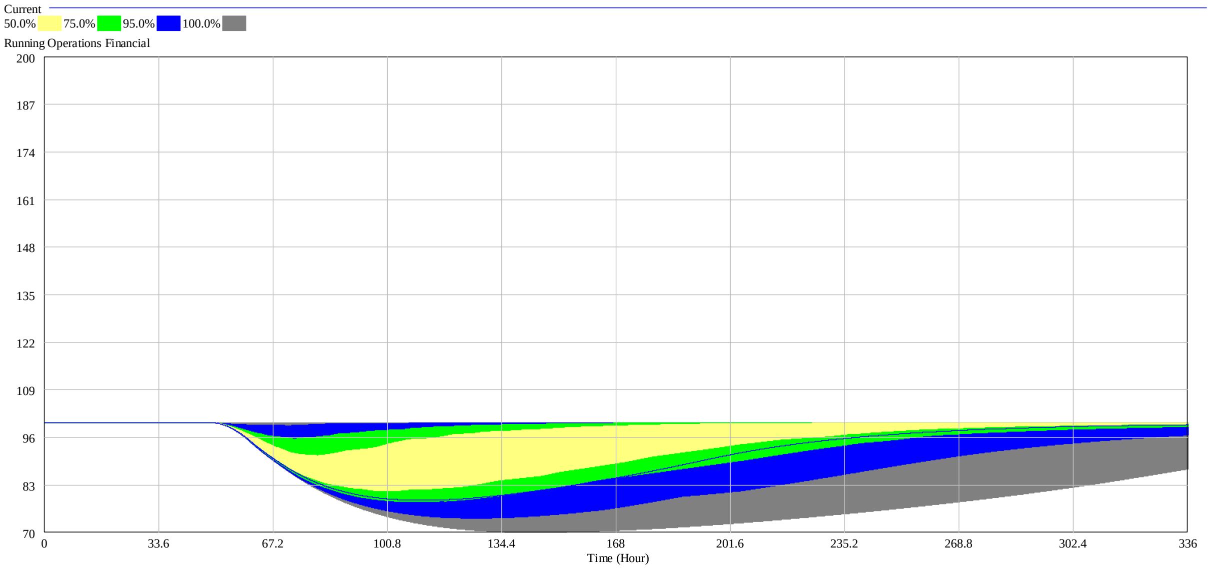


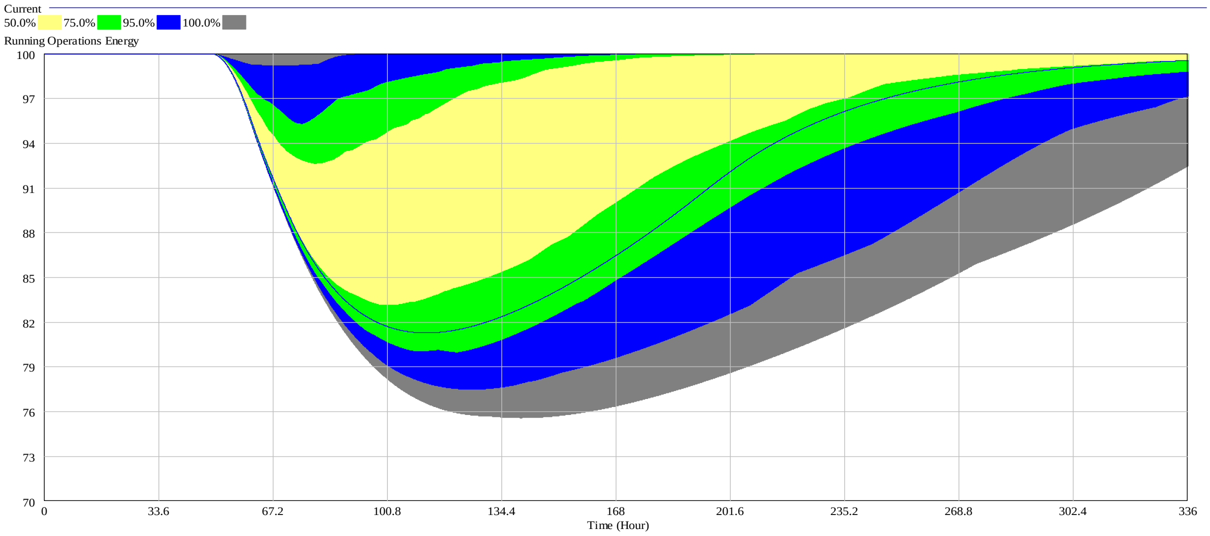

Running Operations
Operations
Time (Hour)
Running Operations Energy : max capability 0
Running Operations Financial : max capability 0
Running Operations ICT : max capability 0
Running Operations Transport : max capability 0
Running Operations Water : max capability 0

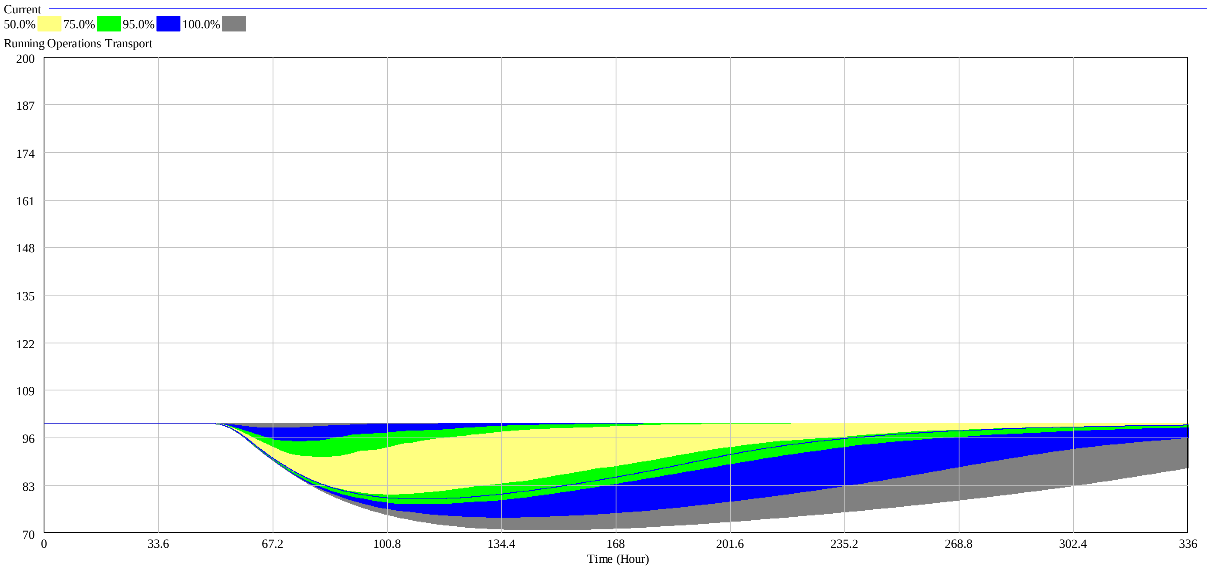

Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : max capability 0
Service Provided Financial : max capability 0
Service Provided ICT : max capability 0
Service Provided Transport : max capability 0
Service Provided Water : max capability 0

Appendix C – Results from multivariate method of testing the average repair and restore time for all CI

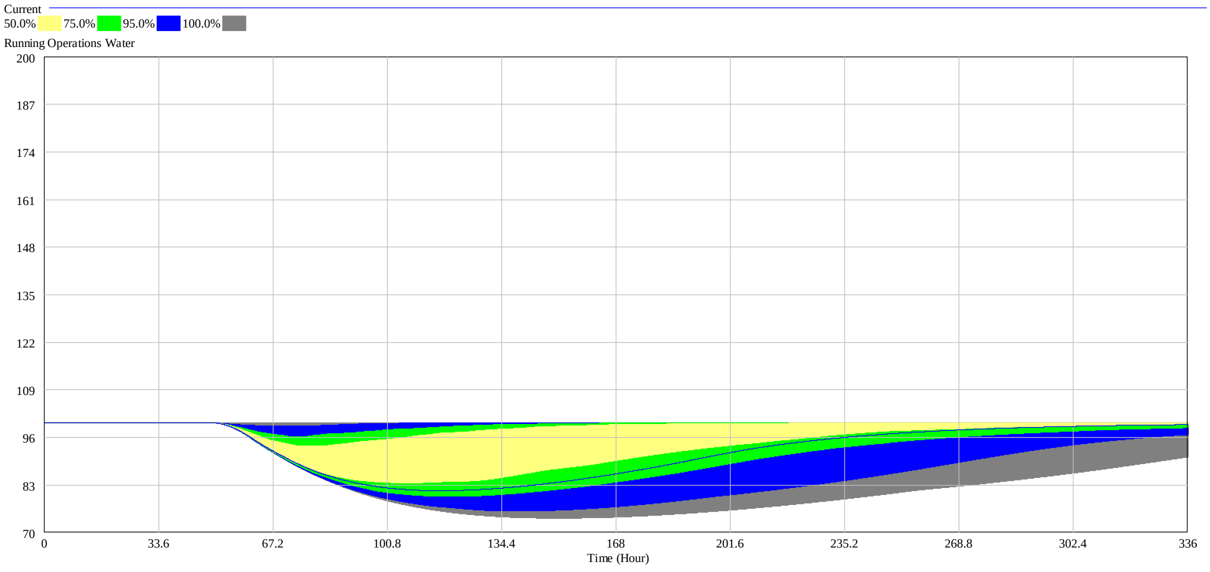






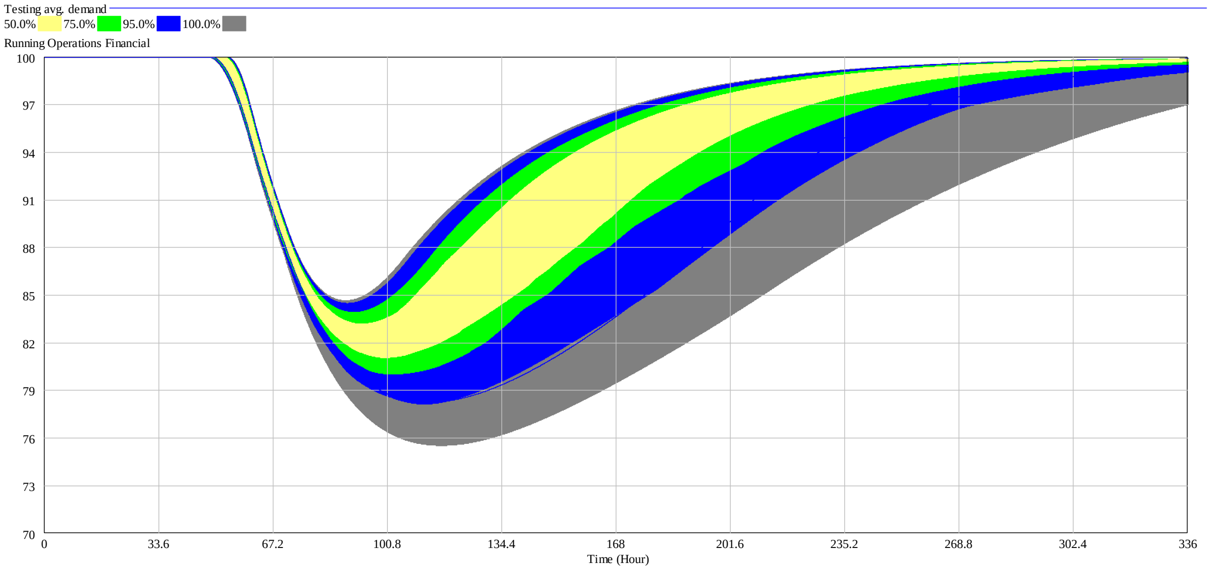


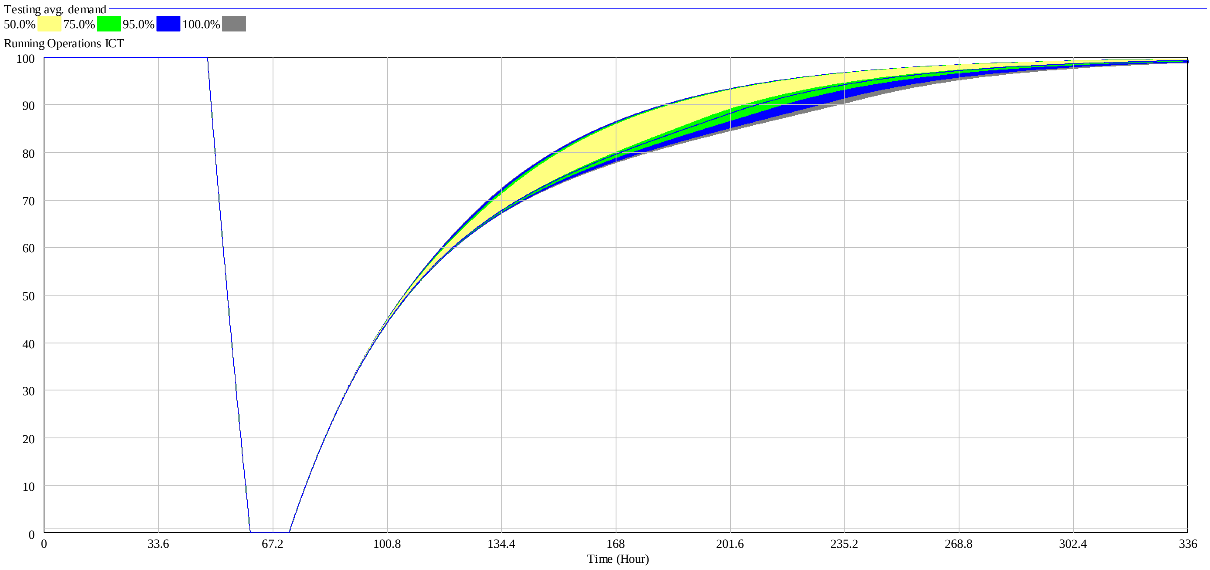
Current
50.0%
75.0%
95.0%
100.0%
Running Operations Transport
200
187
174
161
148
135
122
109
96
83
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

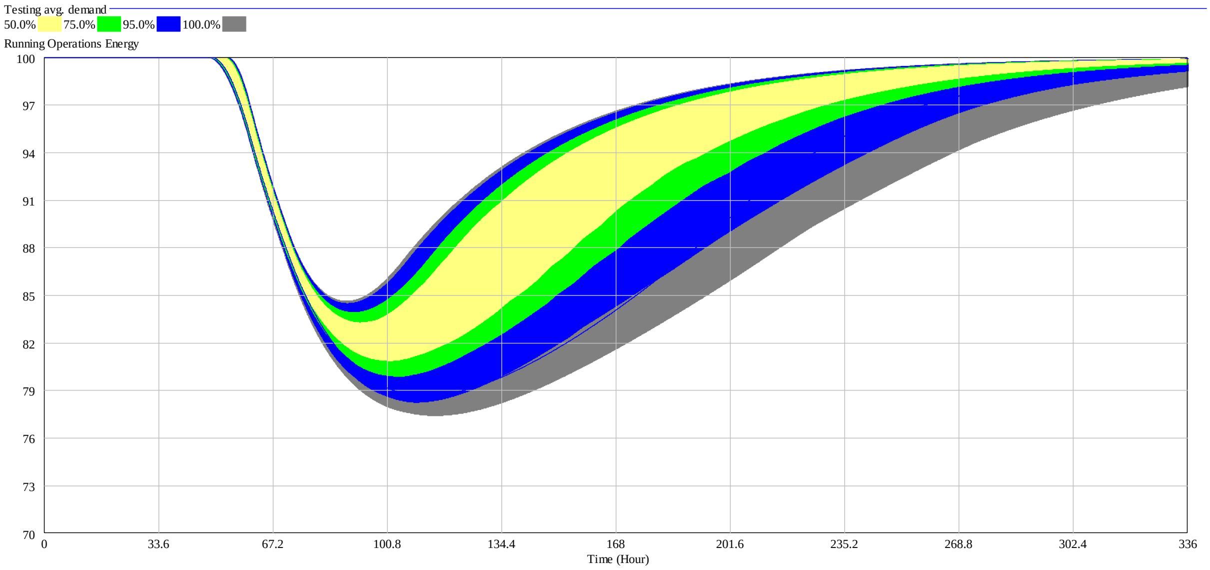


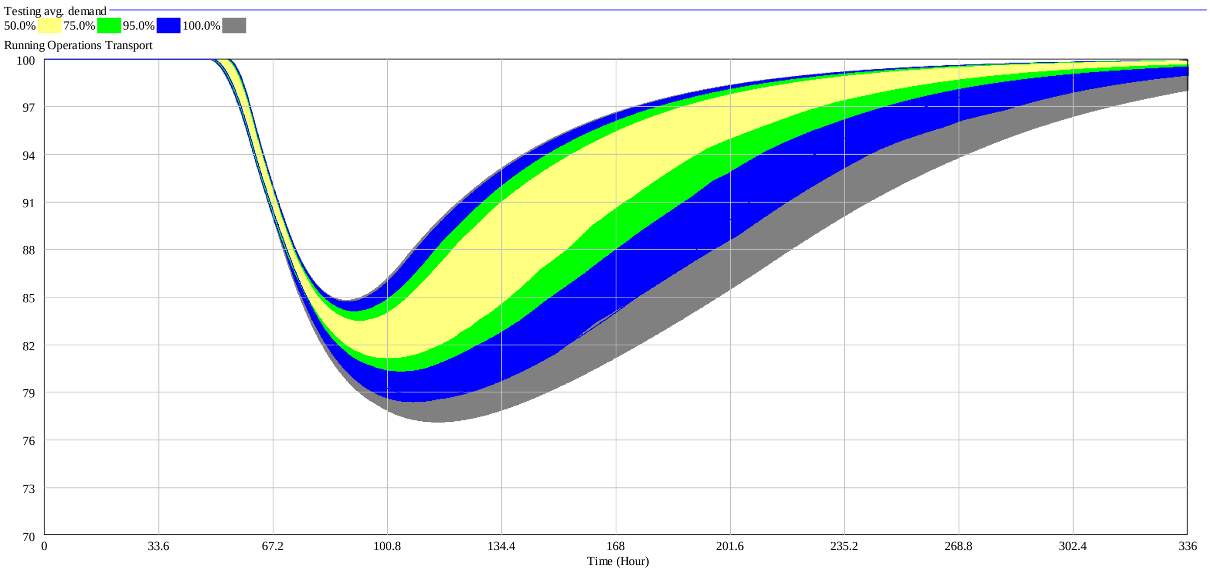
Current
50.0%
75.0%
95.0%
100.0%
Running Operations Water
200
187
174
161
148
135
122
109
96
83
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

Appendix D – Results from multivariate sensitivity tests of average demand variable for Financial, ICT, Energy and Transport CI

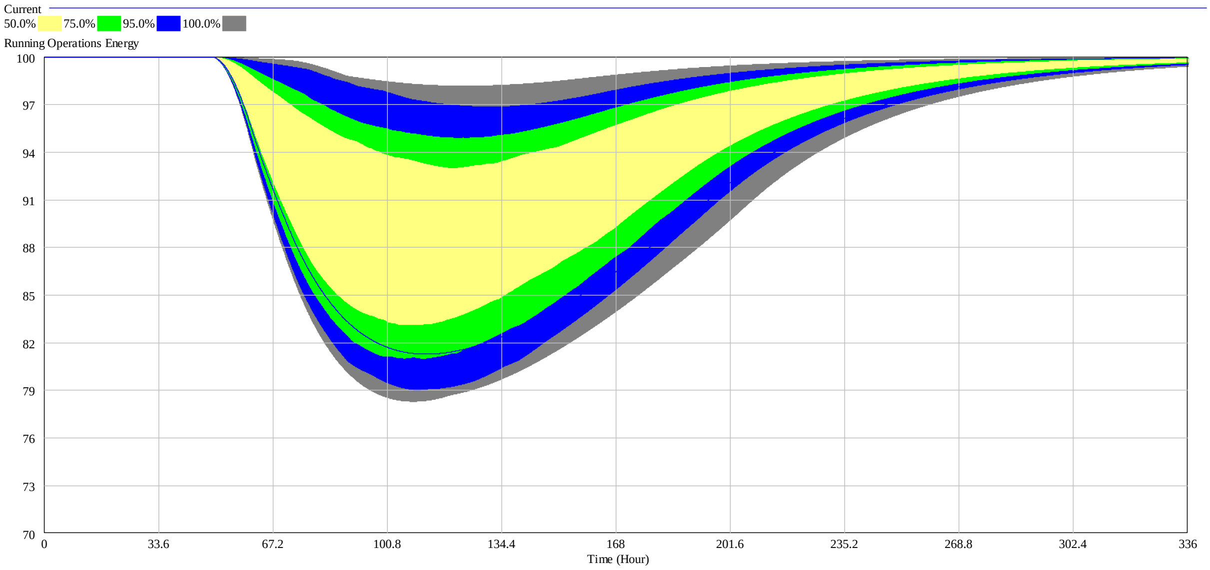


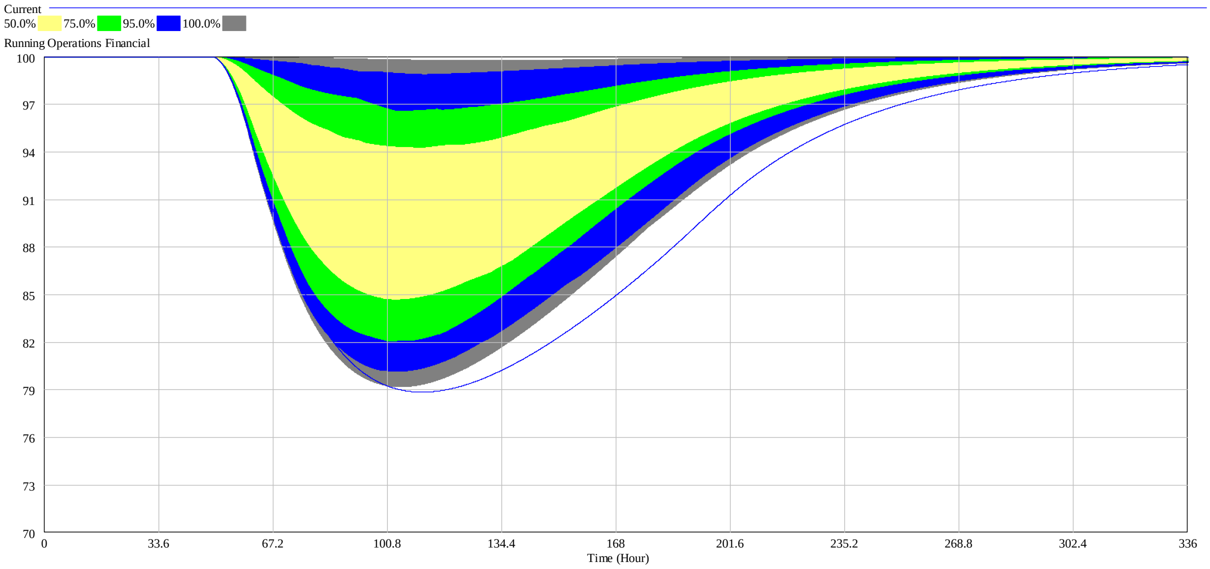


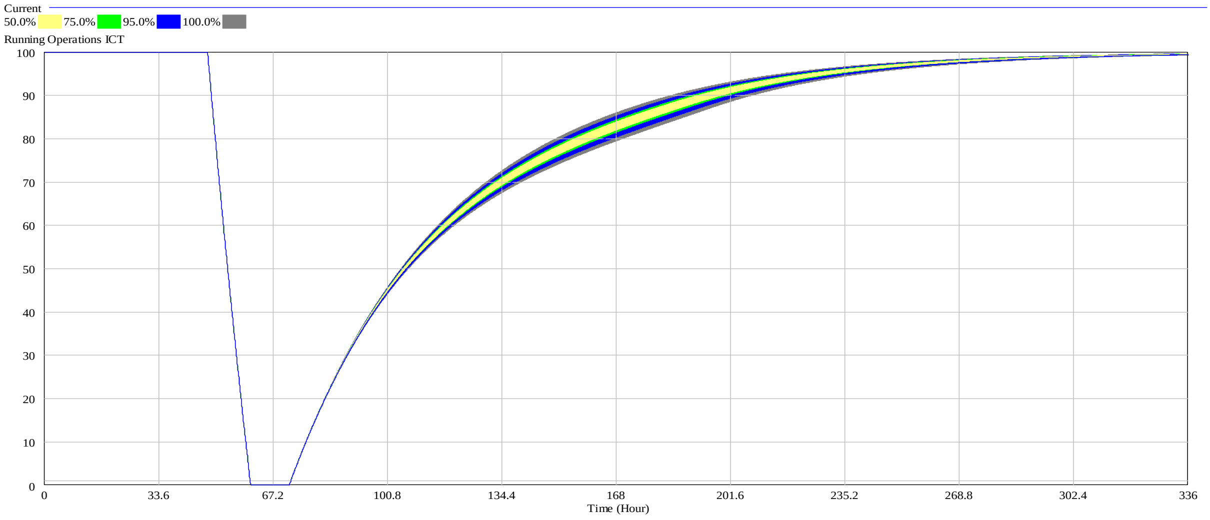

Testing avg. demand
50.0% 75.0% 95.0% 100.0%
Running Operations Energy
100
97
94
91
88
85
82
79
76
73
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

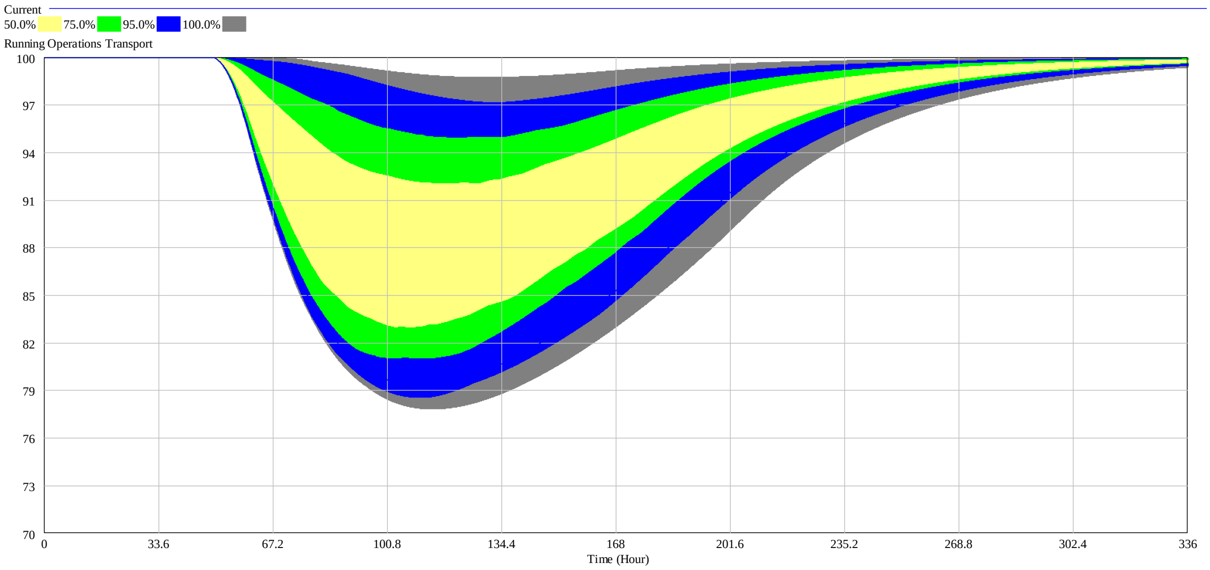

Testing avg. demand
50.0% 75.0% 95.0% 100.0%
Running Operations Transport
100
97
94
91
88
85
82
79
76
73
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

Appendix E – Results from multivariate testing of e_{ij}-parameters for all CI

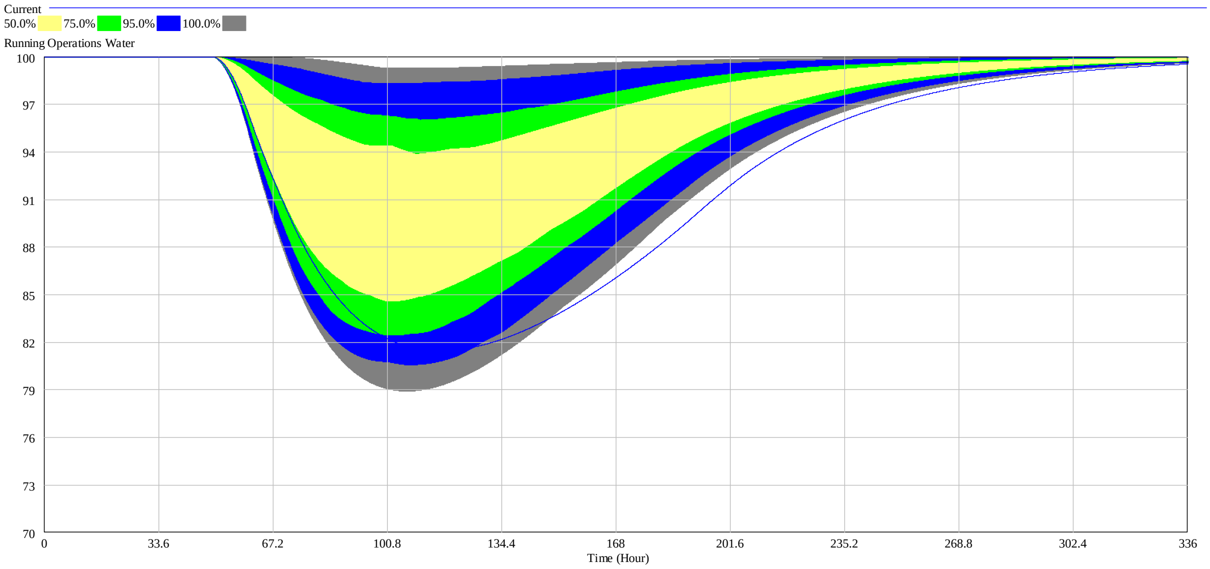






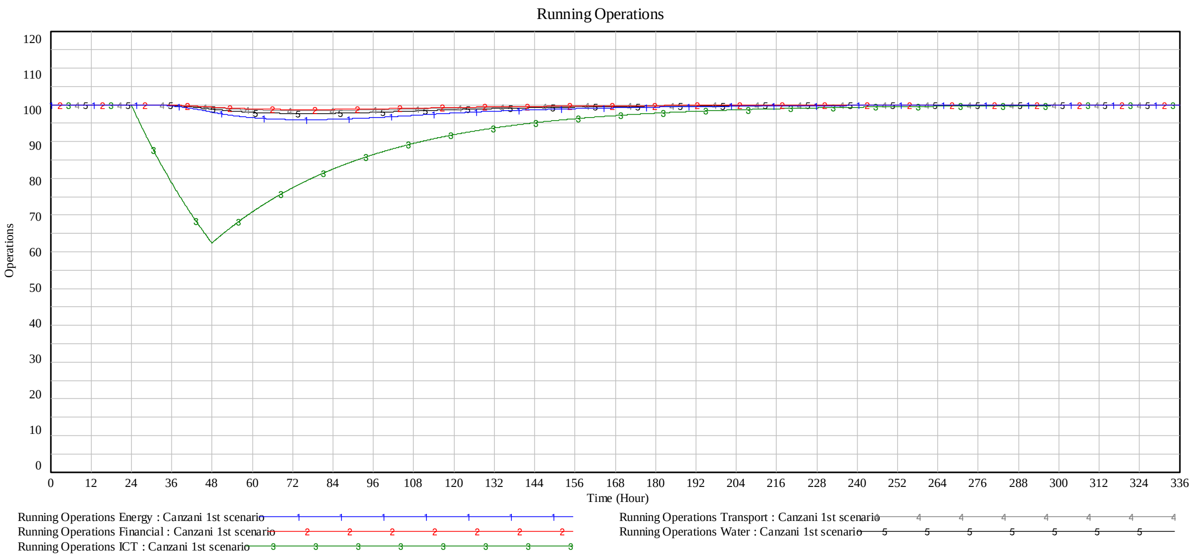


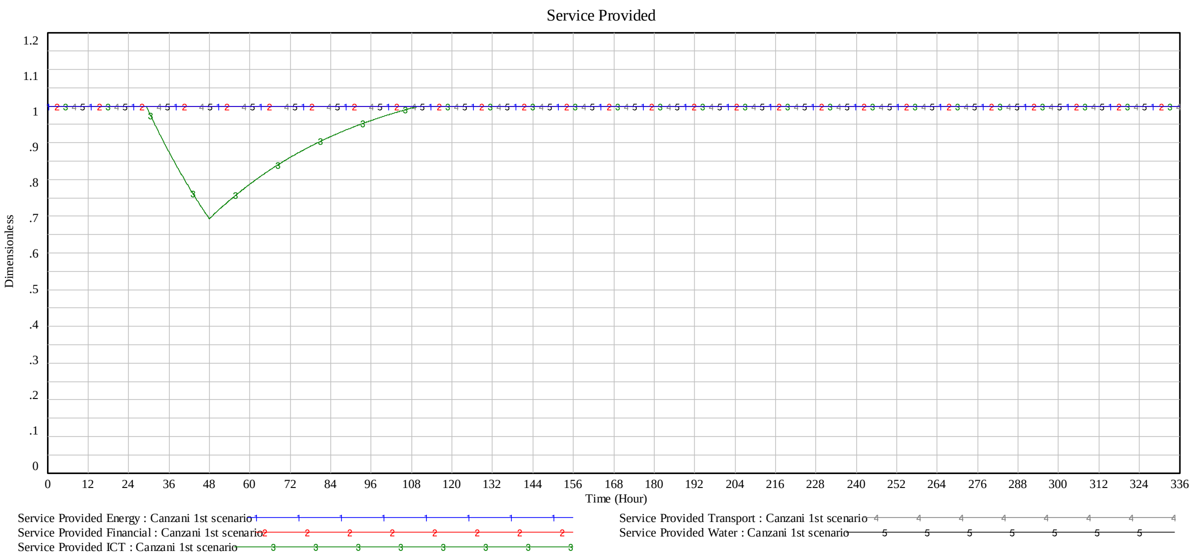
Current
50.0% 75.0% 95.0% 100.0%
Running Operations Transport
100
97
94
91
88
85
82
79
76
73
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

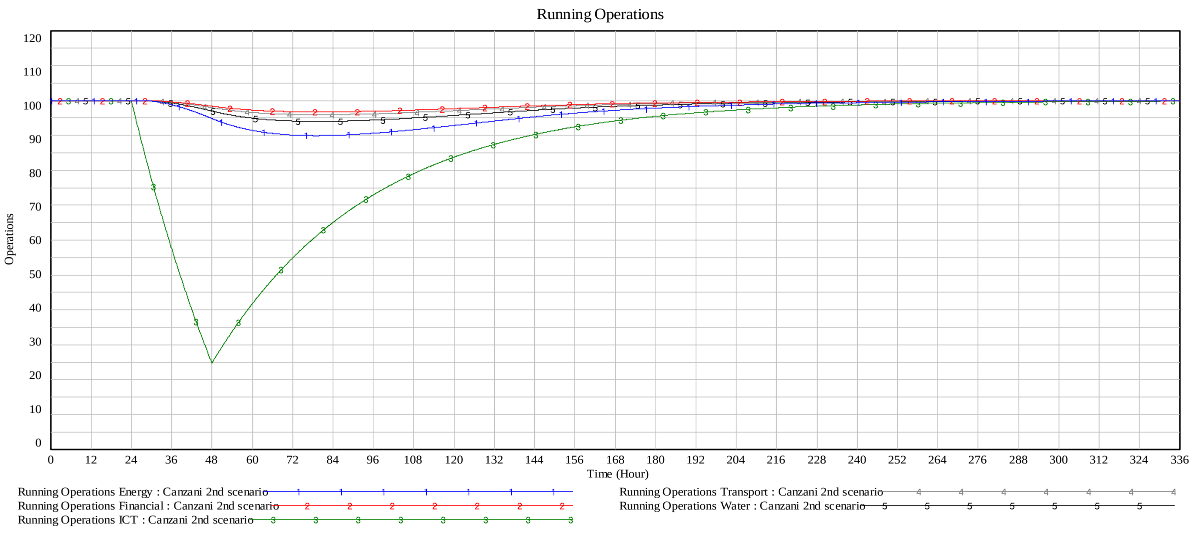


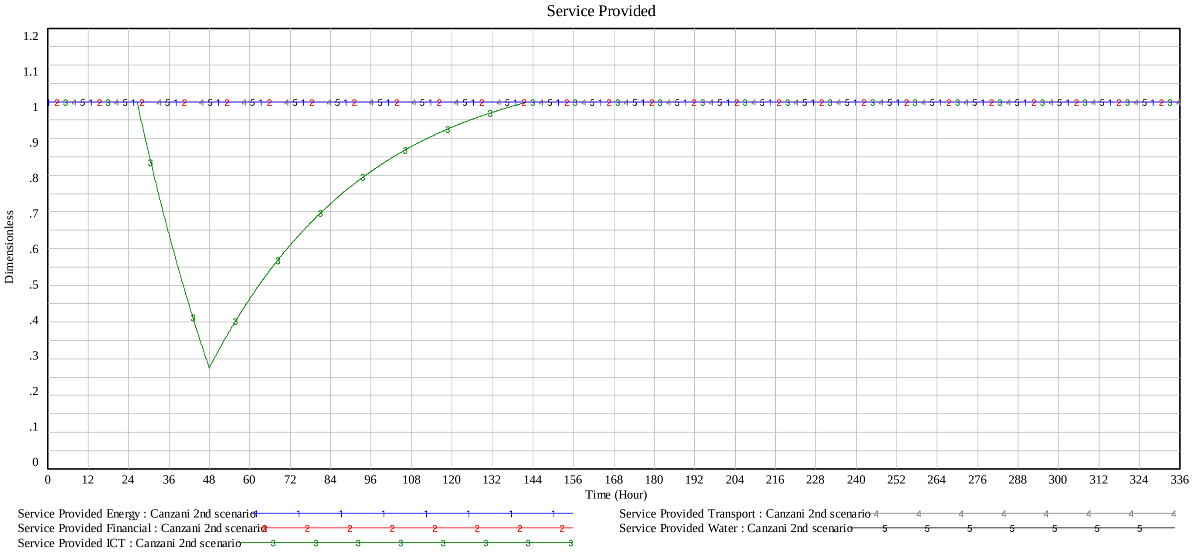
Current
50.0% 75.0% 95.0% 100.0%
Running Operations Water
100
97
94
91
88
85
82
79
76
73
70
0
33.6
67.2
100.8
134.4
168
201.6
235.2
268.8
302.4
336
Time (Hour)

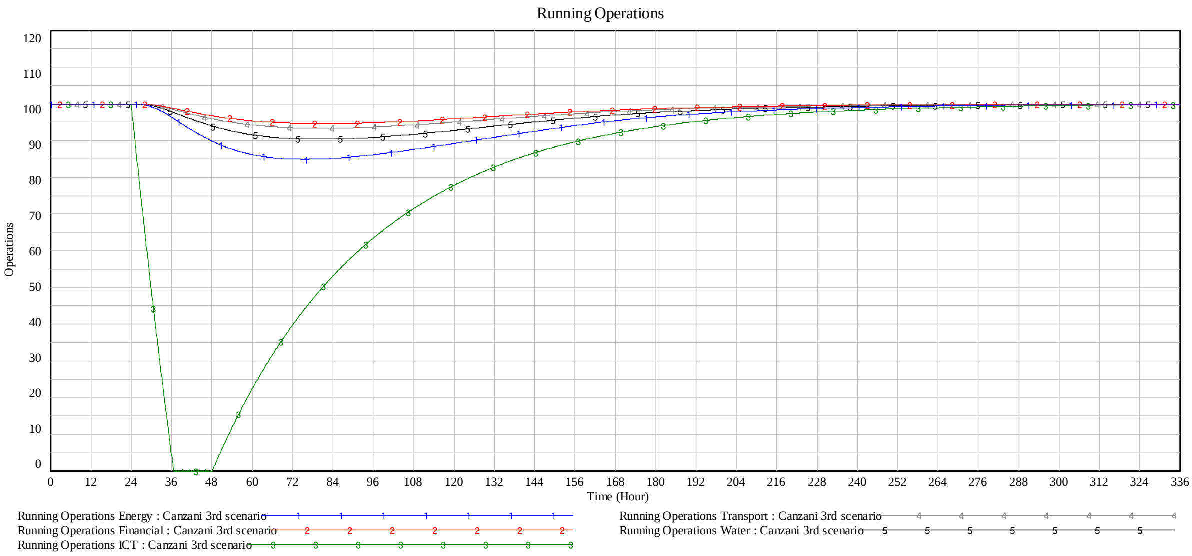
Appendix F – Results from Canzani's 3 scenarios, simulated with the replicated model, shown pairwise.

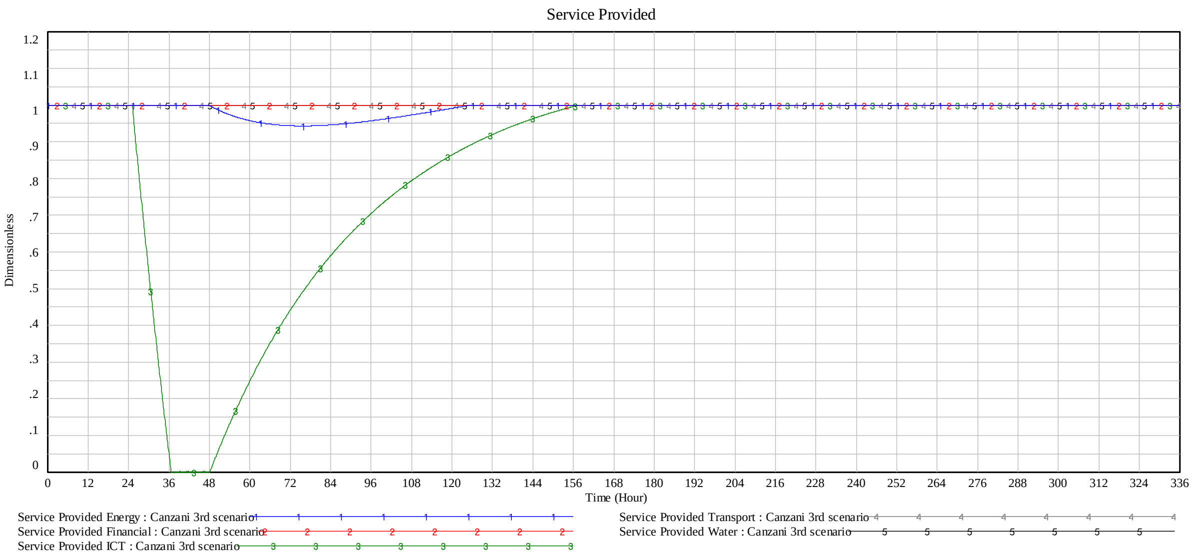




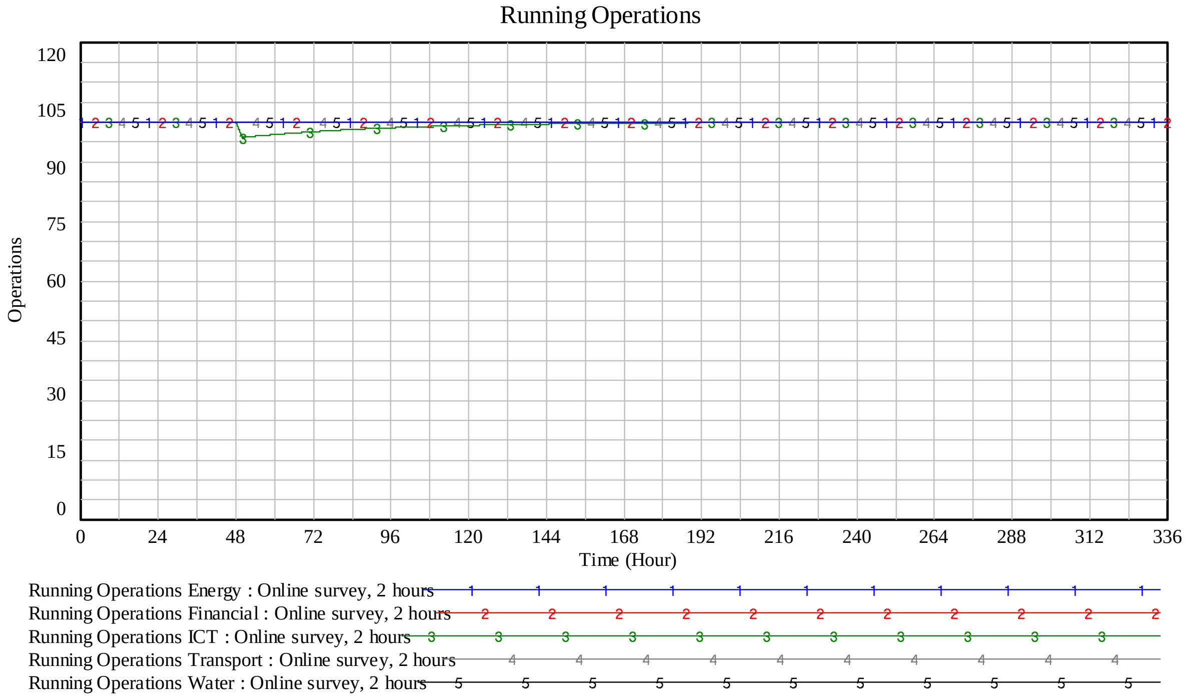


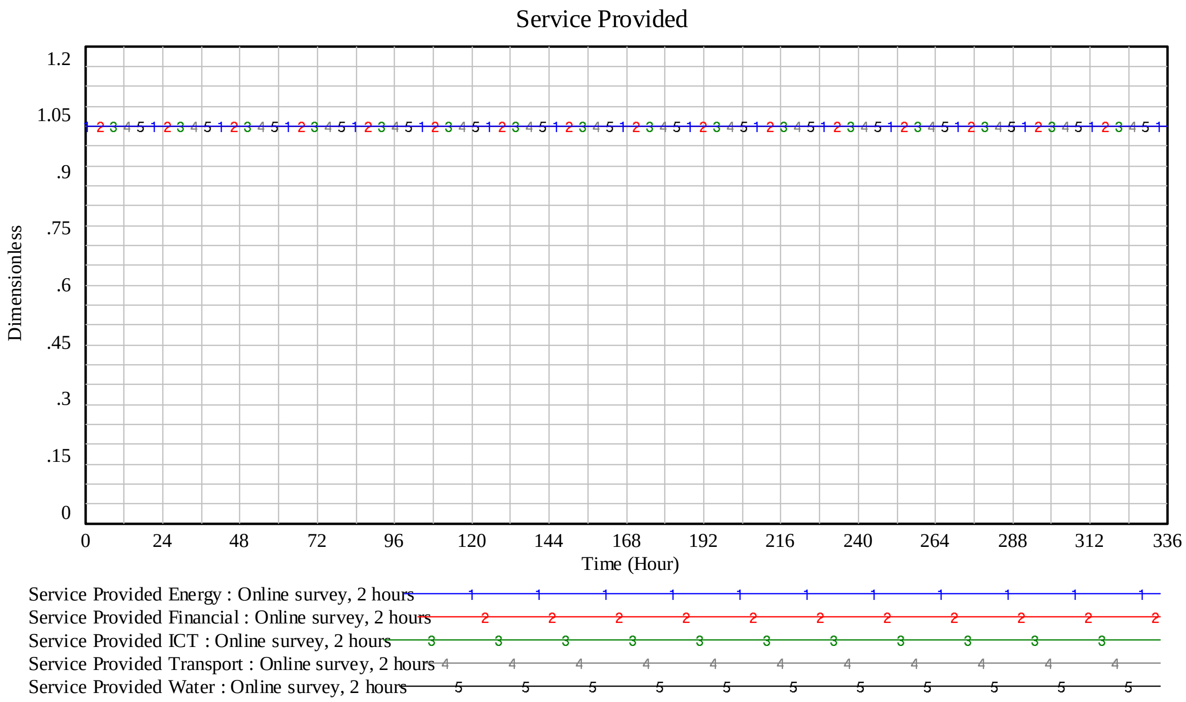

Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Canzani 2nd scenario
Service Provided Financial : Canzani 2nd scenario
Service Provided ICT : Canzani 2nd scenario
Service Provided Transport : Canzani 2nd scenario
Service Provided Water : Canzani 2nd scenario

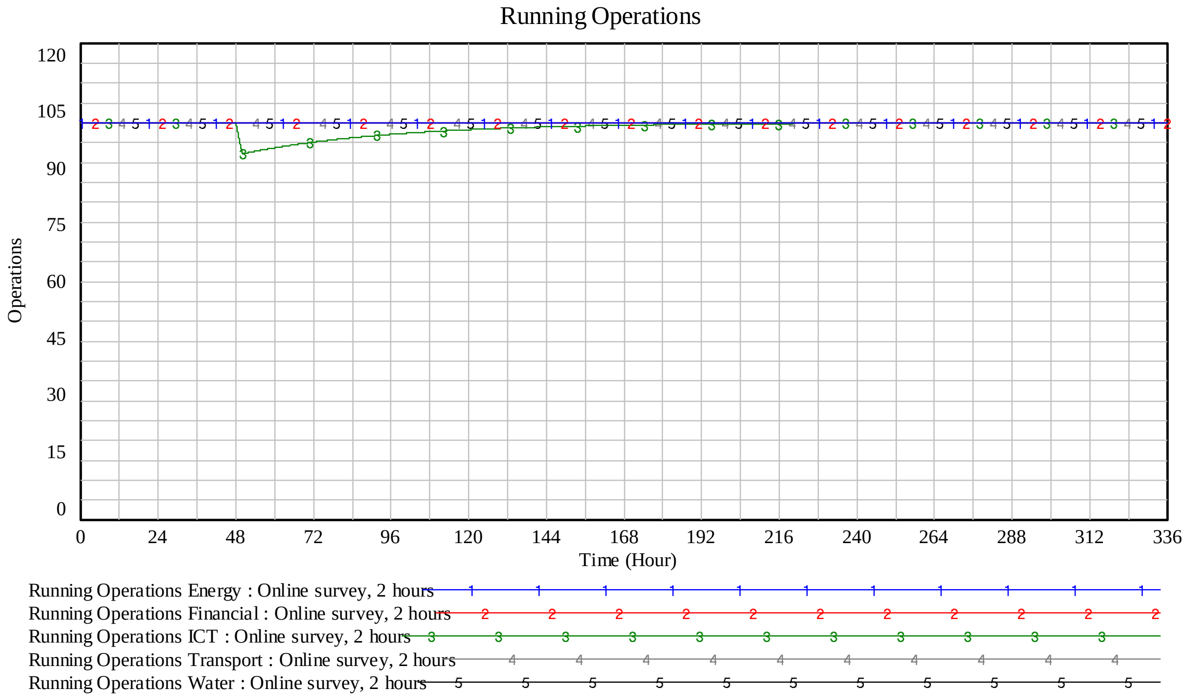

Running Operations
Operations
Time (Hour)
Running Operations Energy : Canzani 3rd scenario
Running Operations Financial : Canzani 3rd scenario
Running Operations ICT : Canzani 3rd scenario
Running Operations Transport : Canzani 3rd scenario
Running Operations Water : Canzani 3rd scenario

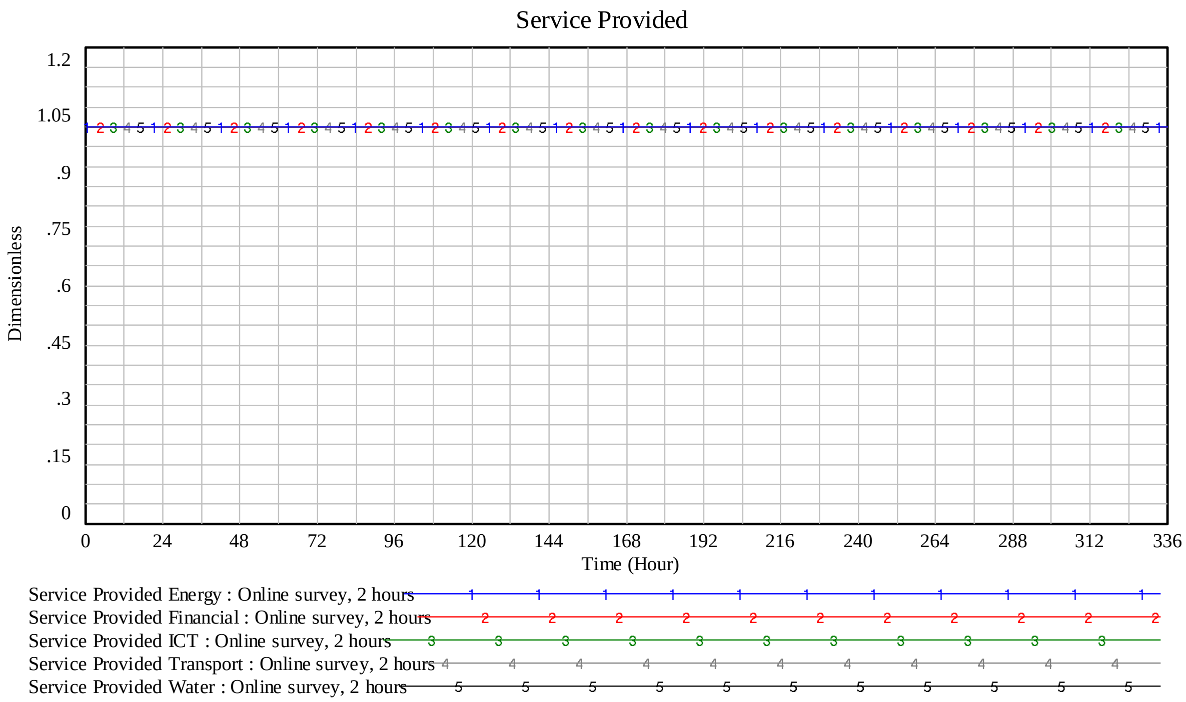

Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Canzani 3rd scenario
Service Provided Financial : Canzani 3rd scenario
Service Provided ICT : Canzani 3rd scenario
Service Provided Transport : Canzani 3rd scenario
Service Provided Water : Canzani 3rd scenario

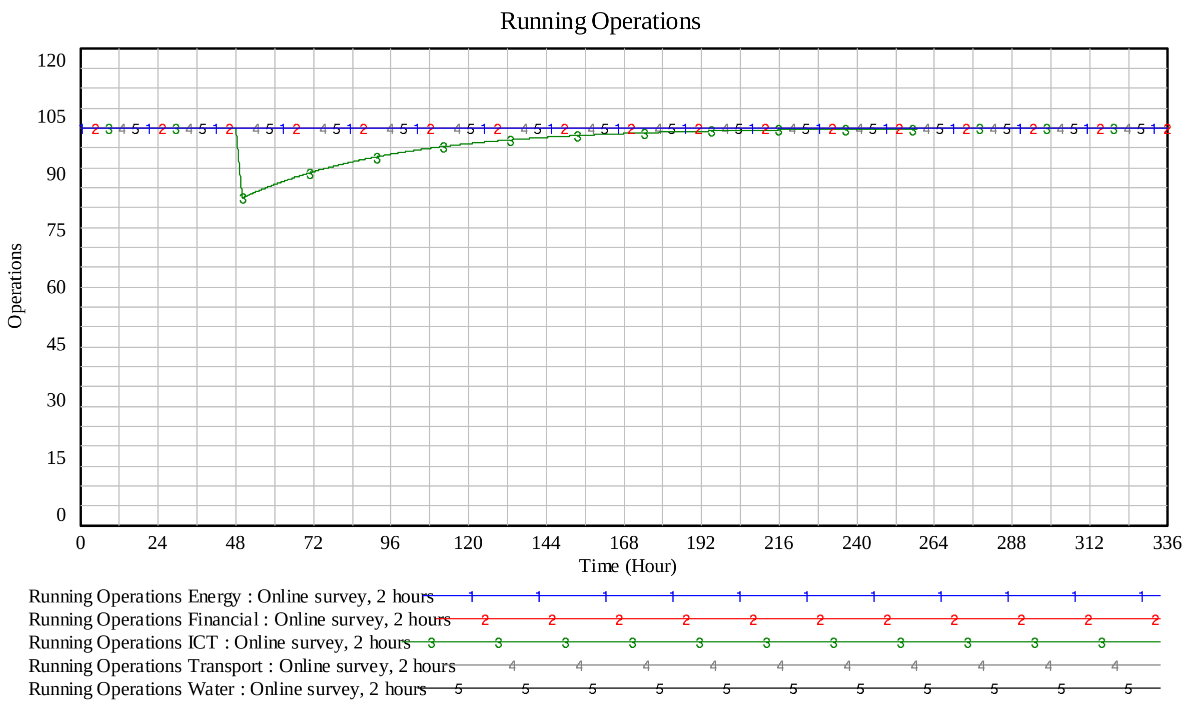
Appendix G – Results from all simulated disruptions with e_{ij}-parameters from the online survey, sorted pairwise by disruption length and magnitude

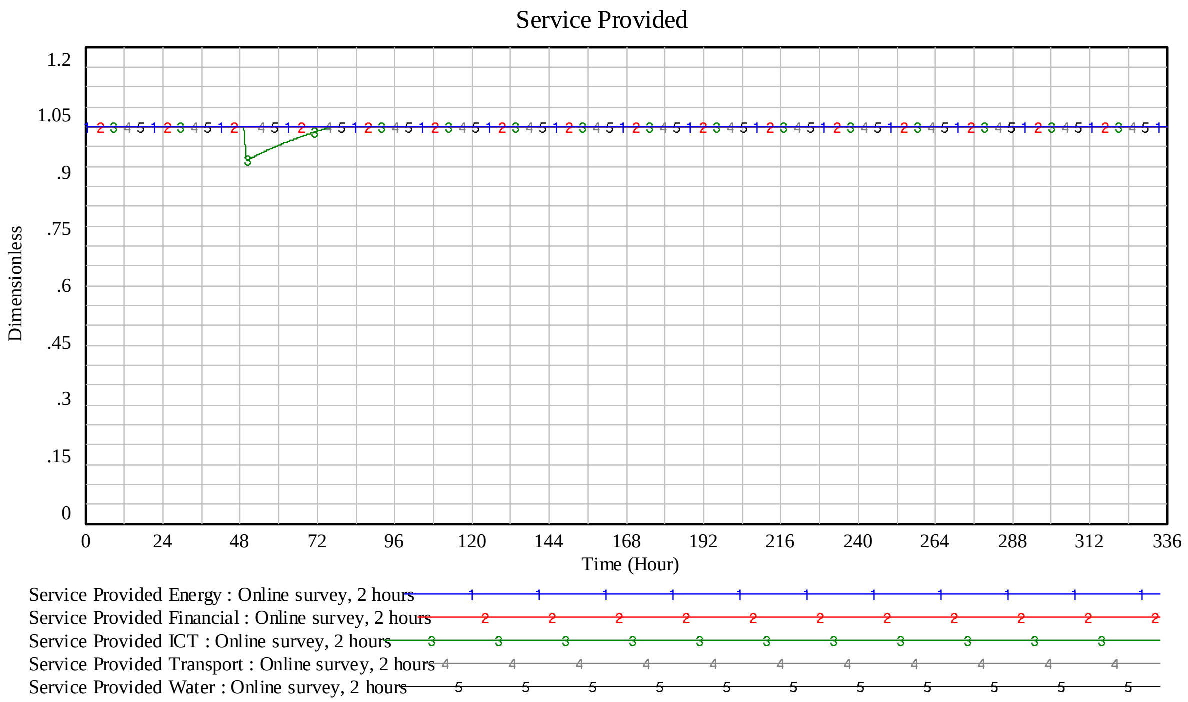


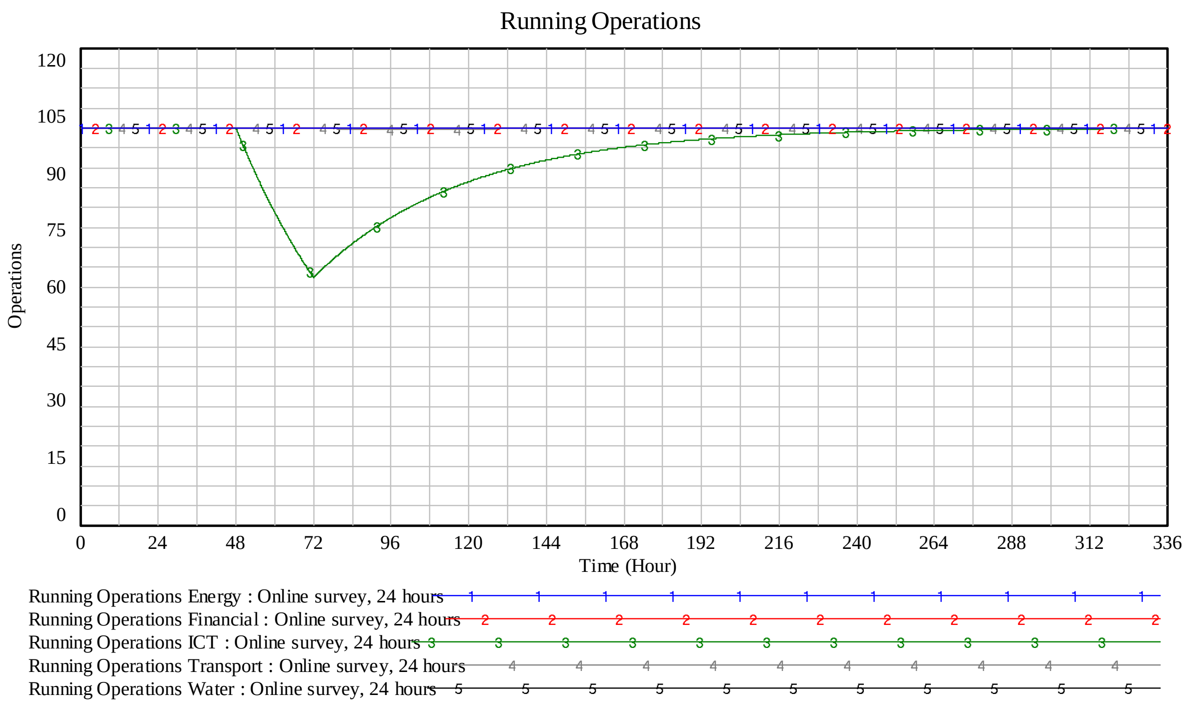


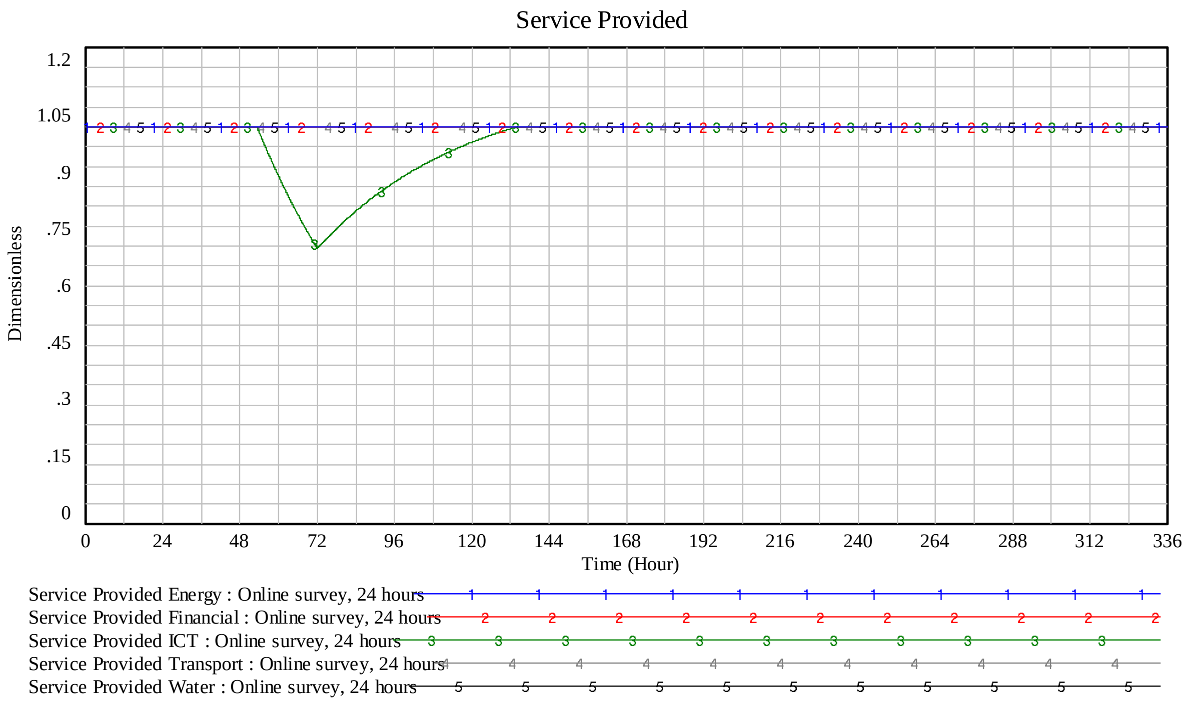

Running Operations
120
105
90
75
60
45
30
15
0
Operations
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 2 hours
Running Operations Financial : Online survey, 2 hours
Running Operations ICT : Online survey, 2 hours
Running Operations Transport : Online survey, 2 hours
Running Operations Water : Online survey, 2 hours

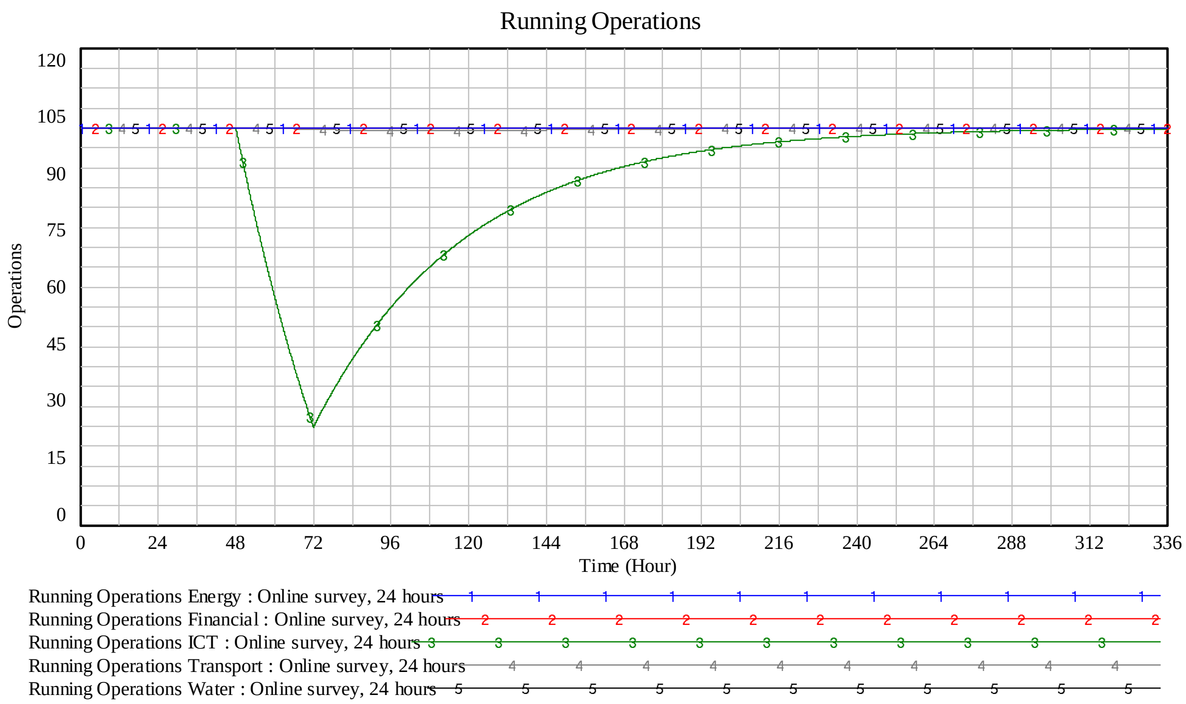

Service Provided
1.2
1.05
.9
.75
.6
.45
.3
.15
0
Dimensionless
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 2 hours
Service Provided Financial : Online survey, 2 hours
Service Provided ICT : Online survey, 2 hours
Service Provided Transport : Online survey, 2 hours
Service Provided Water : Online survey, 2 hours

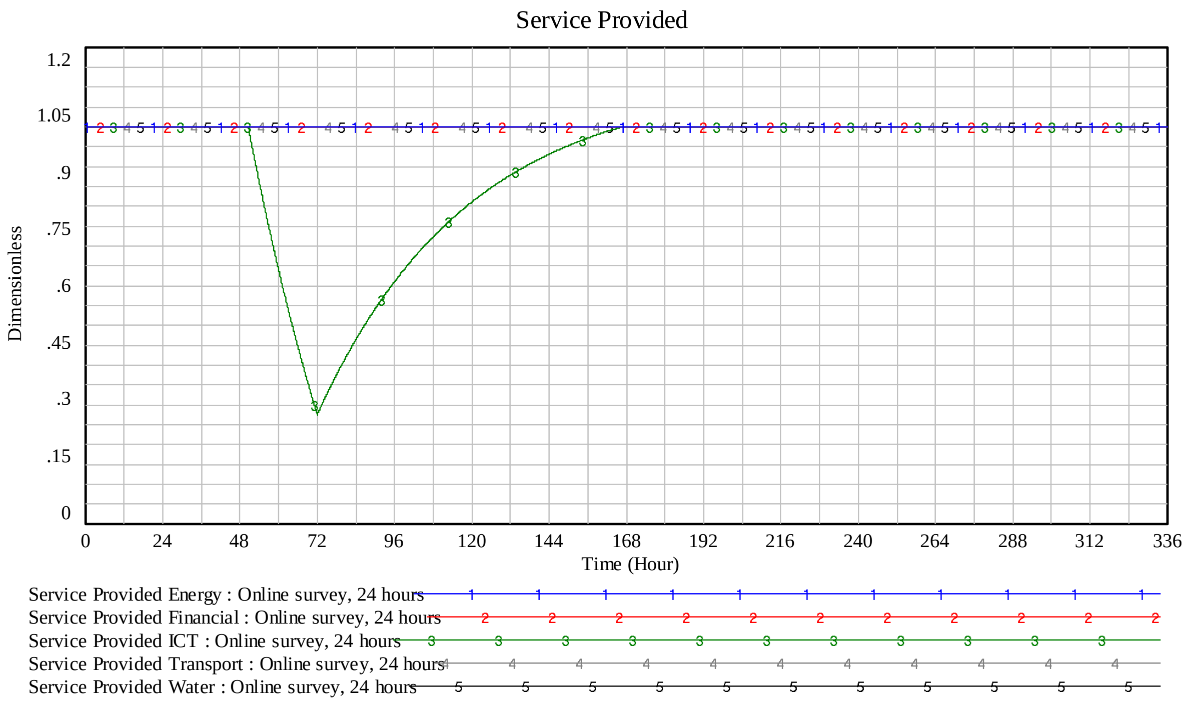

Running Operations
Operations
120
105
90
75
60
45
30
15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 2 hours
Running Operations Financial : Online survey, 2 hours
Running Operations ICT : Online survey, 2 hours
Running Operations Transport : Online survey, 2 hours
Running Operations Water : Online survey, 2 hours

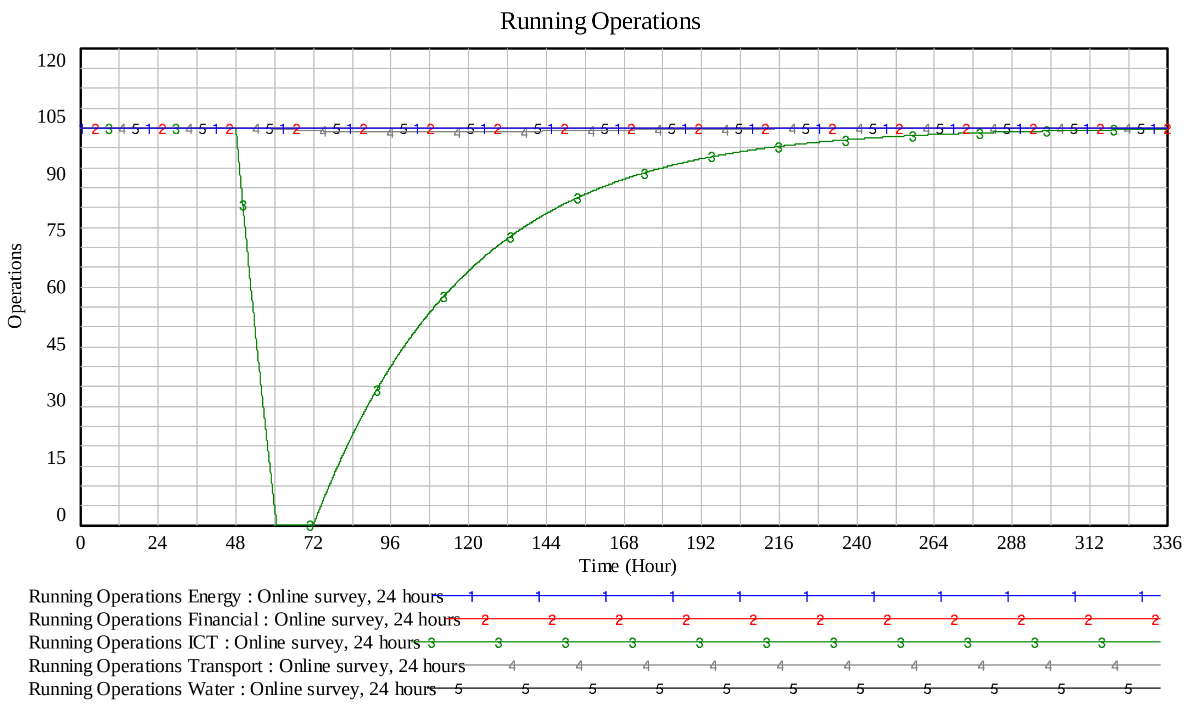

Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 2 hours
Service Provided Financial : Online survey, 2 hours
Service Provided ICT : Online survey, 2 hours
Service Provided Transport : Online survey, 2 hours
Service Provided Water : Online survey, 2 hours

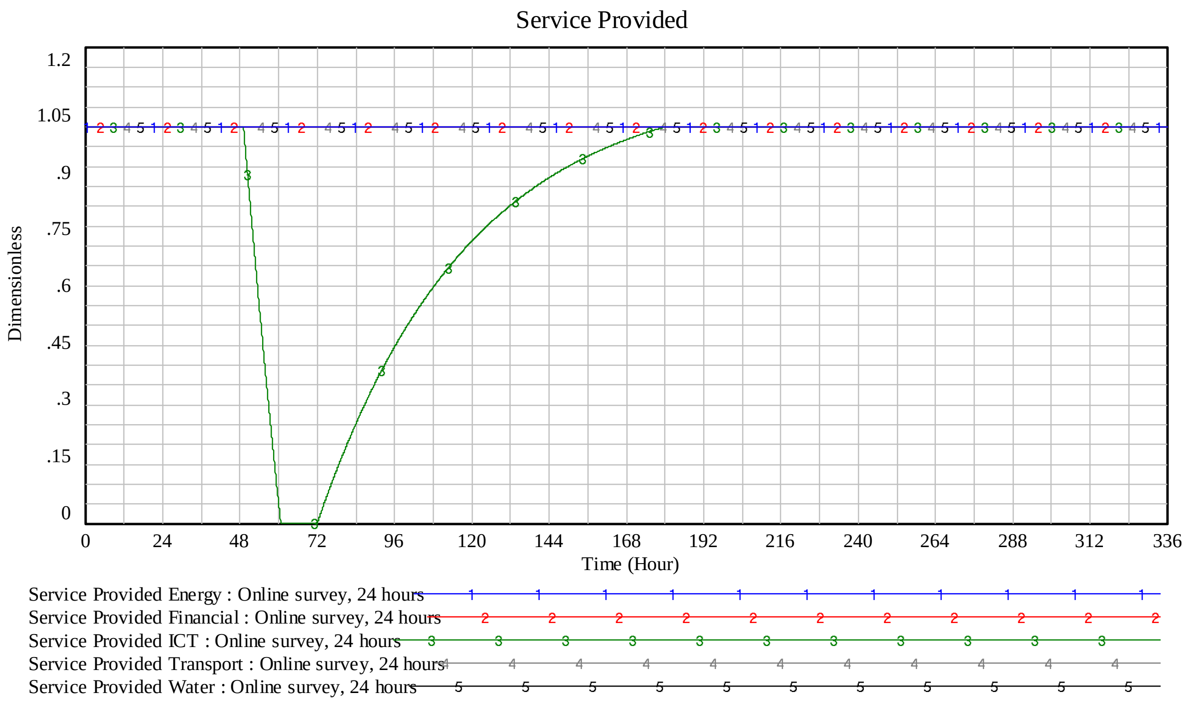

Running Operations
Operations
120
105
90
75
60
45
30
15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 24 hours
Running Operations Financial : Online survey, 24 hours
Running Operations ICT : Online survey, 24 hours
Running Operations Transport : Online survey, 24 hours
Running Operations Water : Online survey, 24 hours

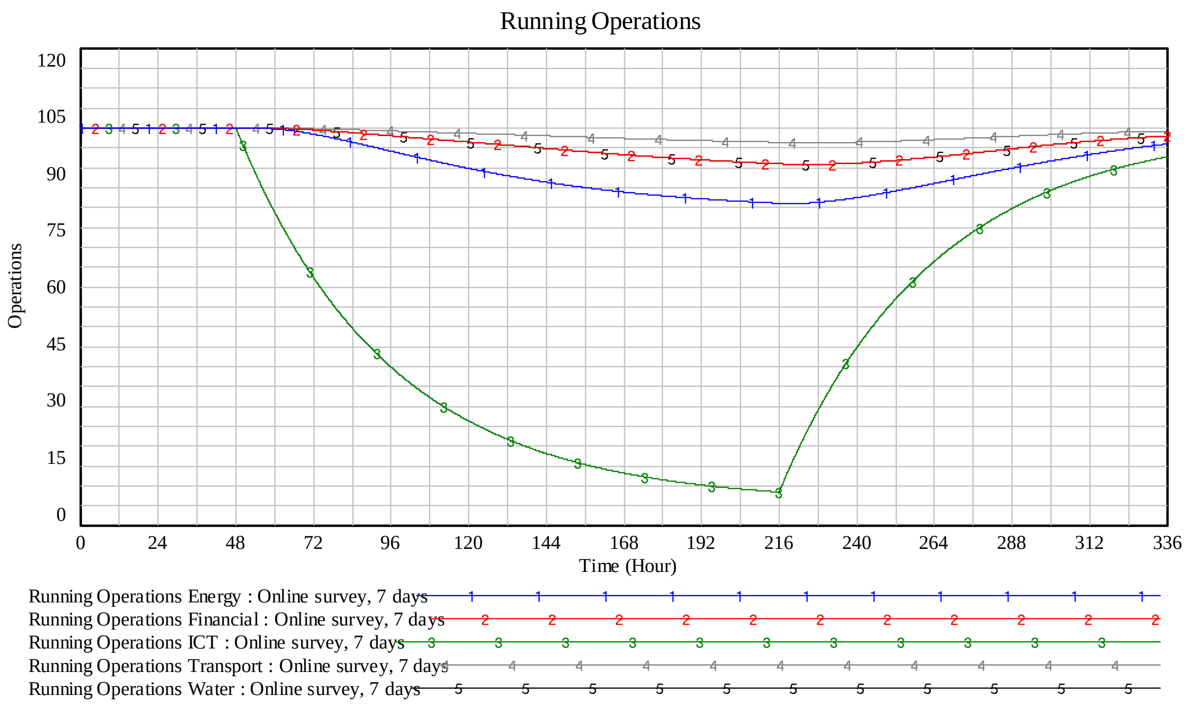

Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 24 hours
Service Provided Financial : Online survey, 24 hours
Service Provided ICT : Online survey, 24 hours
Service Provided Transport : Online survey, 24 hours
Service Provided Water : Online survey, 24 hours


Running Operations
Operations
120
105
90
75
60
45
30
15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 24 hours
Running Operations Financial : Online survey, 24 hours
Running Operations ICT : Online survey, 24 hours
Running Operations Transport : Online survey, 24 hours
Running Operations Water : Online survey, 24 hours

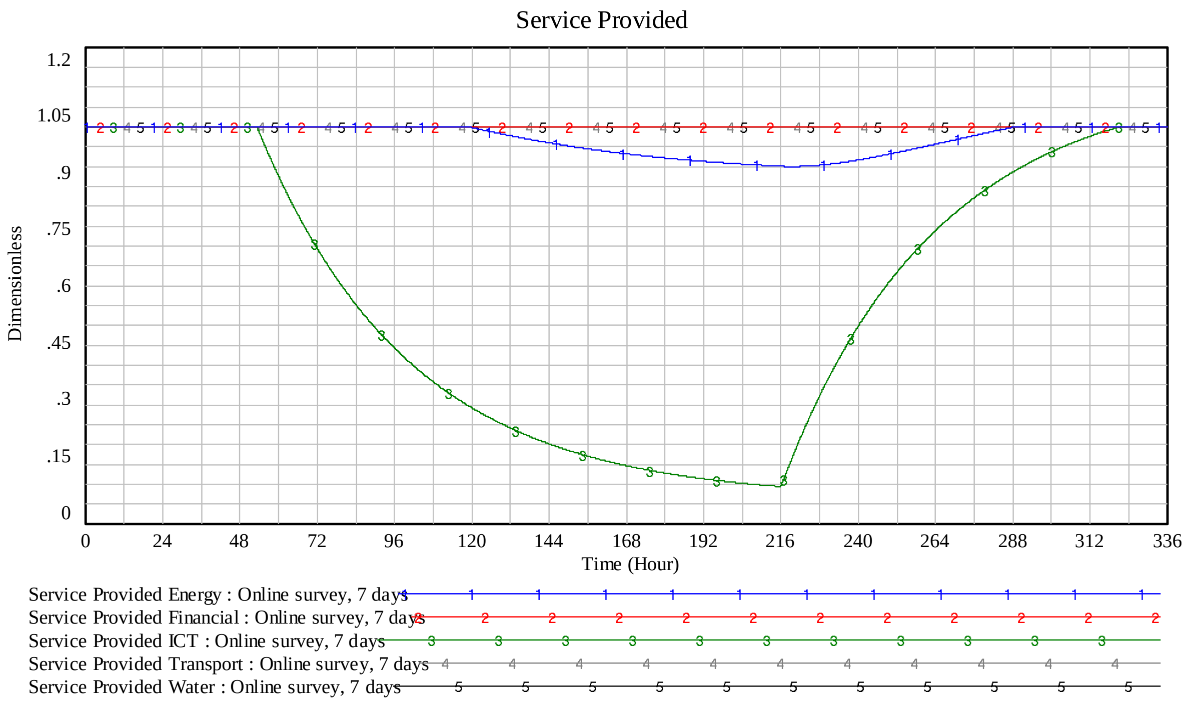

Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 24 hours
Service Provided Financial : Online survey, 24 hours
Service Provided ICT : Online survey, 24 hours
Service Provided Transport : Online survey, 24 hours
Service Provided Water : Online survey, 24 hours


Running Operations
Operations
Time (Hour)
Running Operations Energy : Online survey, 24 hours
Running Operations Financial : Online survey, 24 hours
Running Operations ICT : Online survey, 24 hours
Running Operations Transport : Online survey, 24 hours
Running Operations Water : Online survey, 24 hours

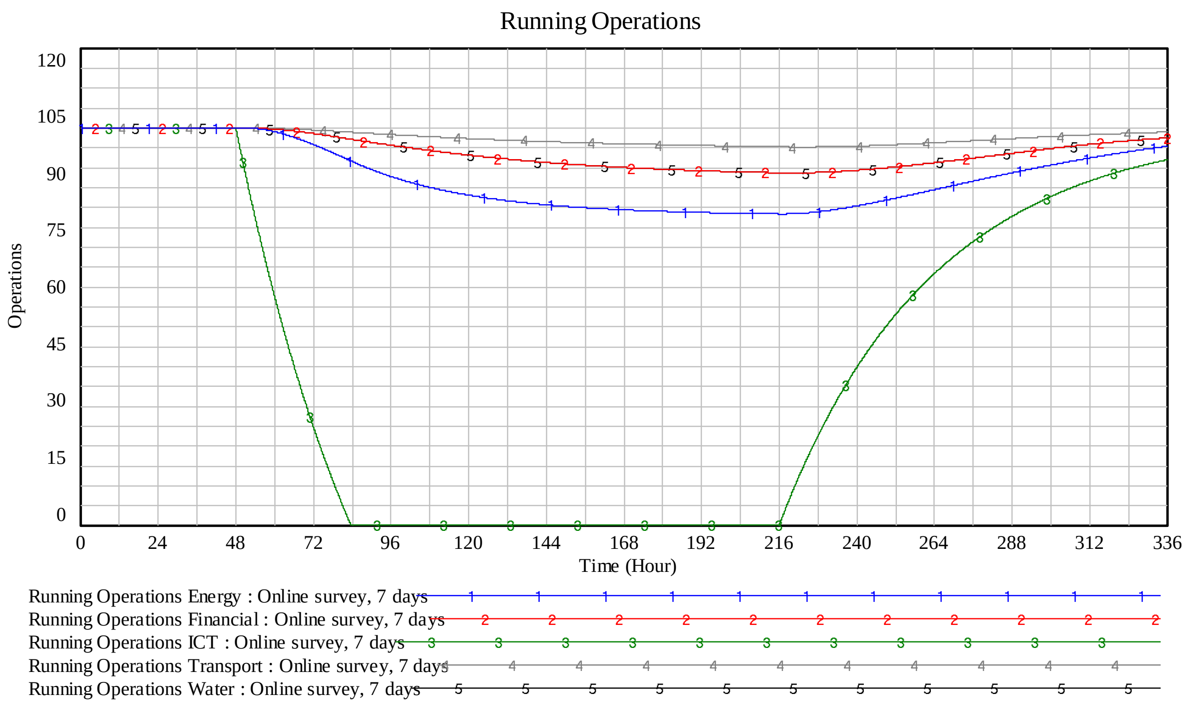

Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Online survey, 24 hours
Service Provided Financial : Online survey, 24 hours
Service Provided ICT : Online survey, 24 hours
Service Provided Transport : Online survey, 24 hours
Service Provided Water : Online survey, 24 hours

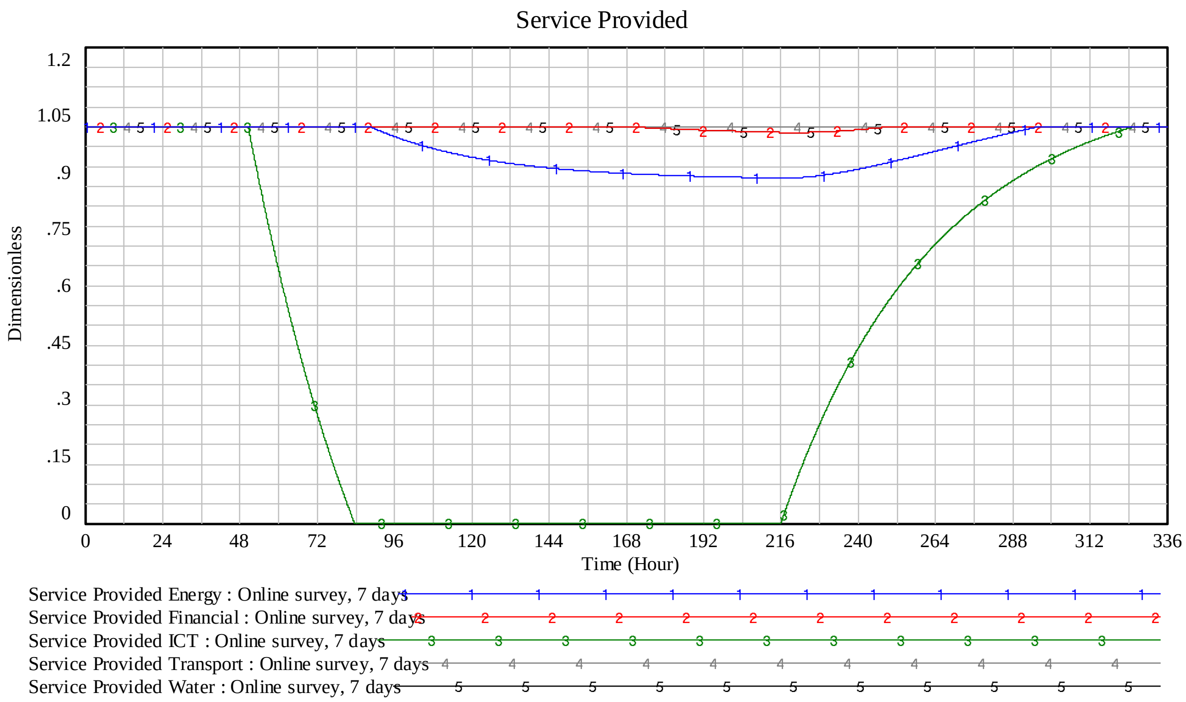


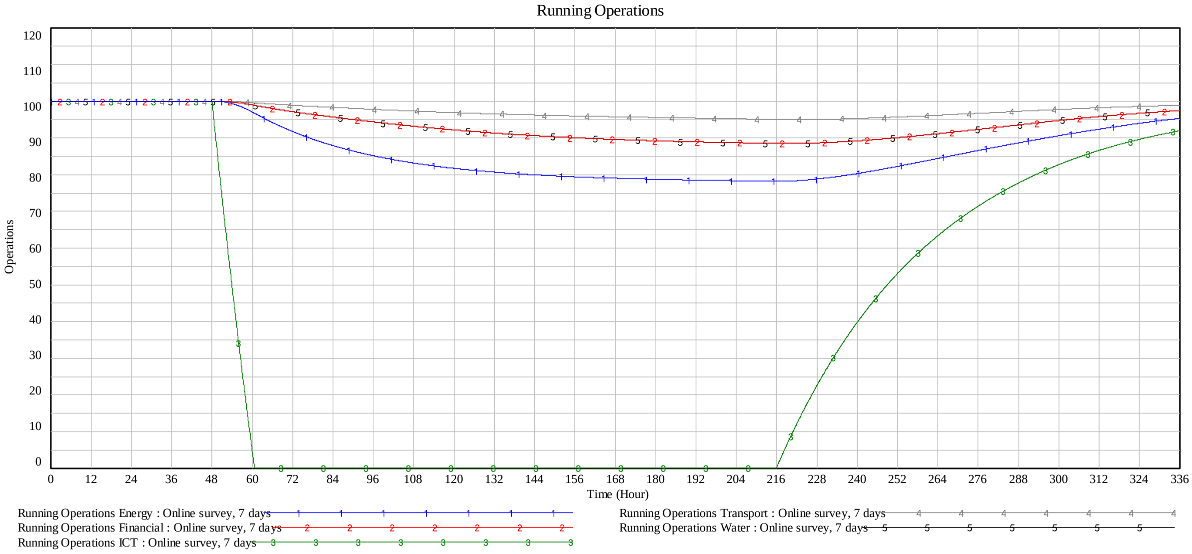
Running Operations
Operations
120
105
90
75
60
45
30
15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 7 days
Running Operations Financial : Online survey, 7 days
Running Operations ICT : Online survey, 7 days
Running Operations Transport : Online survey, 7 days
Running Operations Water : Online survey, 7 days



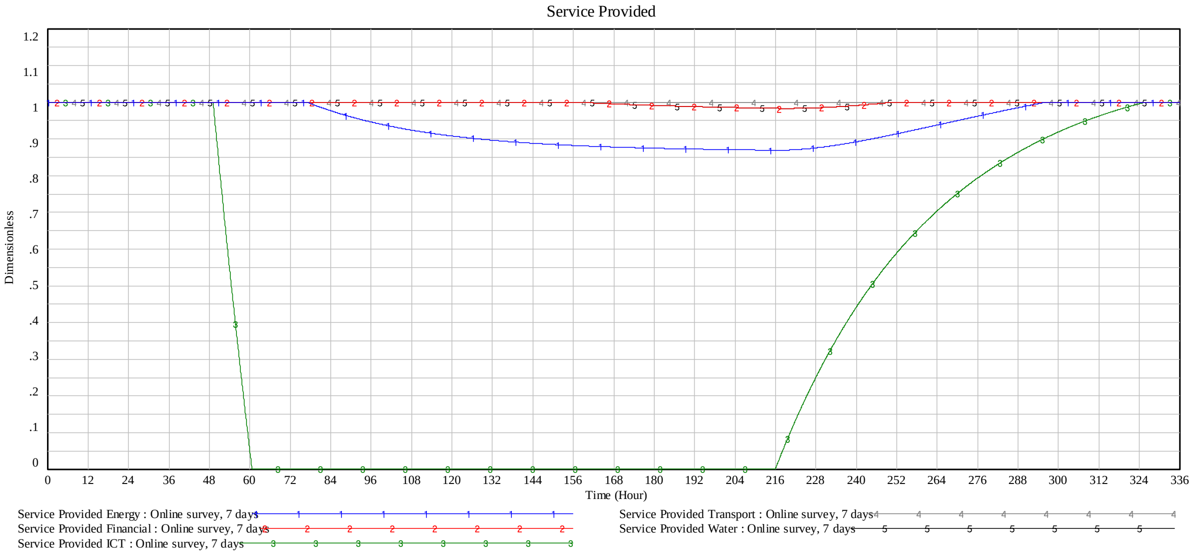
Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 7 days
Service Provided Financial : Online survey, 7 days
Service Provided ICT : Online survey, 7 days
Service Provided Transport : Online survey, 7 days
Service Provided Water : Online survey, 7 days


Running Operations
120
105
90
75
60
45
30
15
0
Operations
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Running Operations Energy : Online survey, 7 days
Running Operations Financial : Online survey, 7 days
Running Operations ICT : Online survey, 7 days
Running Operations Transport : Online survey, 7 days
Running Operations Water : Online survey, 7 days


Service Provided
1.2
1.05
.9
.75
.6
.45
.3
.15
0
Dimensionless
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
Time (Hour)
Service Provided Energy : Online survey, 7 days
Service Provided Financial : Online survey, 7 days
Service Provided ICT : Online survey, 7 days
Service Provided Transport : Online survey, 7 days
Service Provided Water : Online survey, 7 days

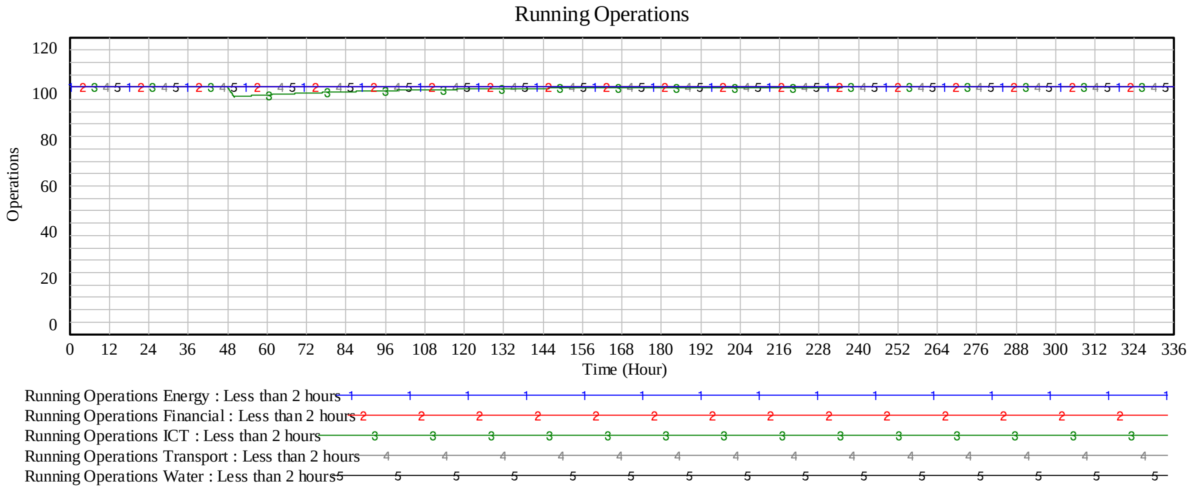


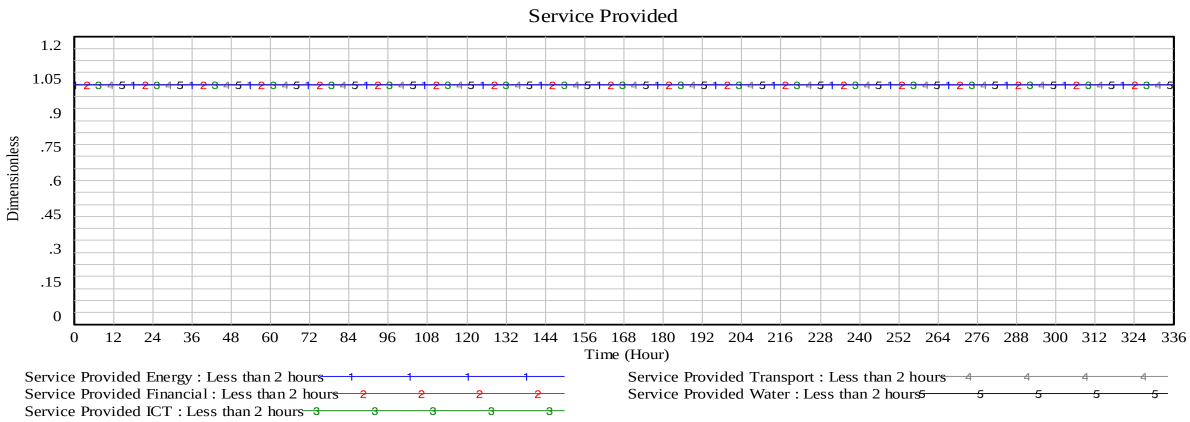
Running Operations
Operations
Time (Hour)
Running Operations Energy : Online survey, 7 days
Running Operations Financial : Online survey, 7 days
Running Operations ICT : Online survey, 7 days
Running Operations Transport : Online survey, 7 days
Running Operations Water : Online survey, 7 days

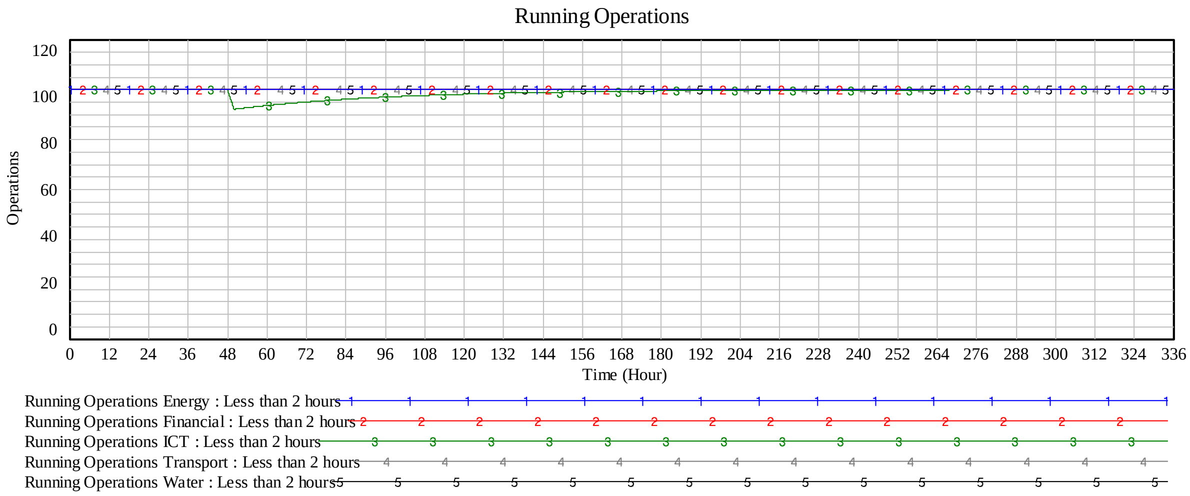


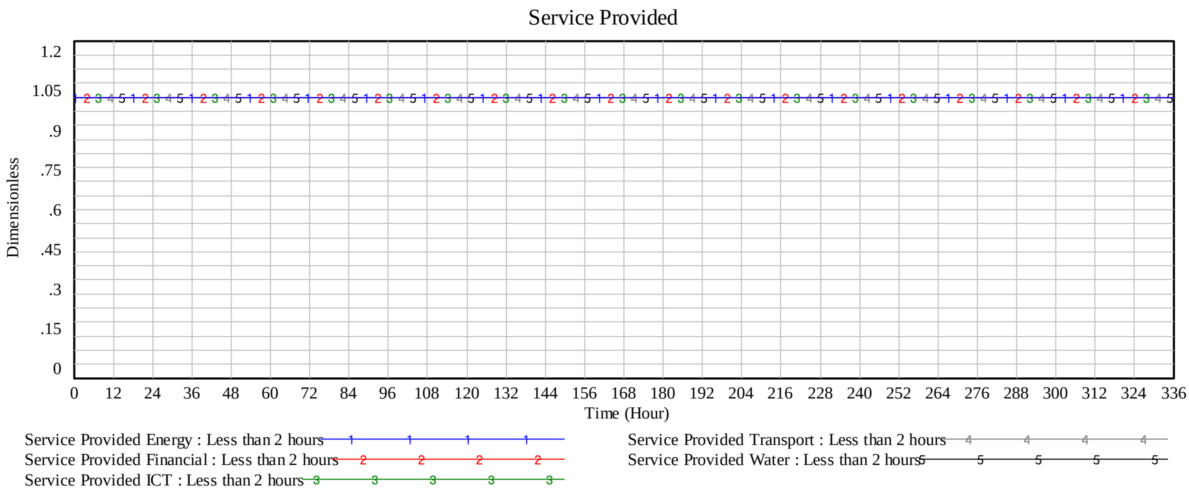
Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Online survey, 7 days
Service Provided Financial : Online survey, 7 days
Service Provided ICT : Online survey, 7 days
Service Provided Transport : Online survey, 7 days
Service Provided Water : Online survey, 7 days

Appendix H – Results from the single disruption scenario simulations with correct e_{ij}-parameters, pairwise according to disruption length and magnitude

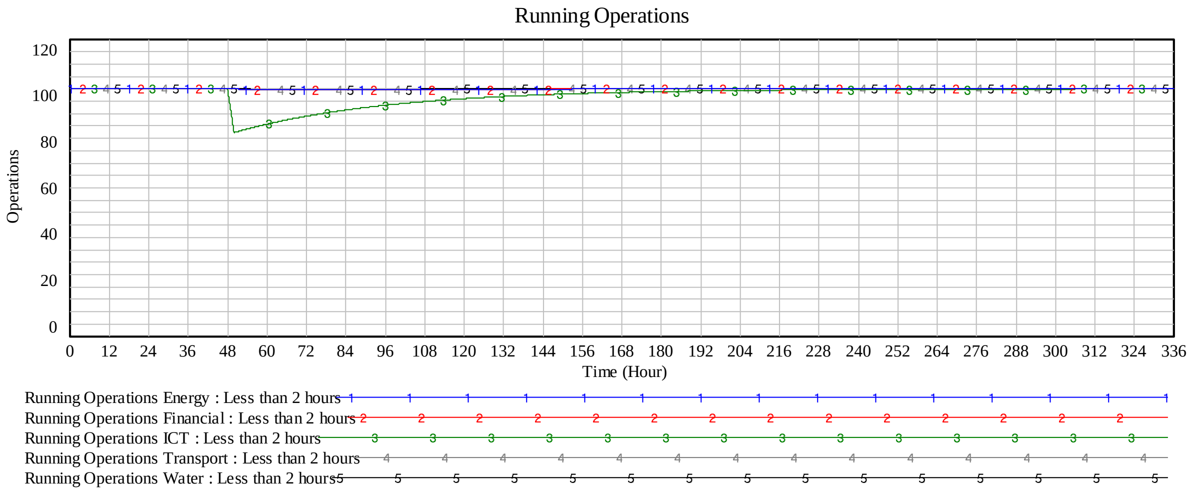




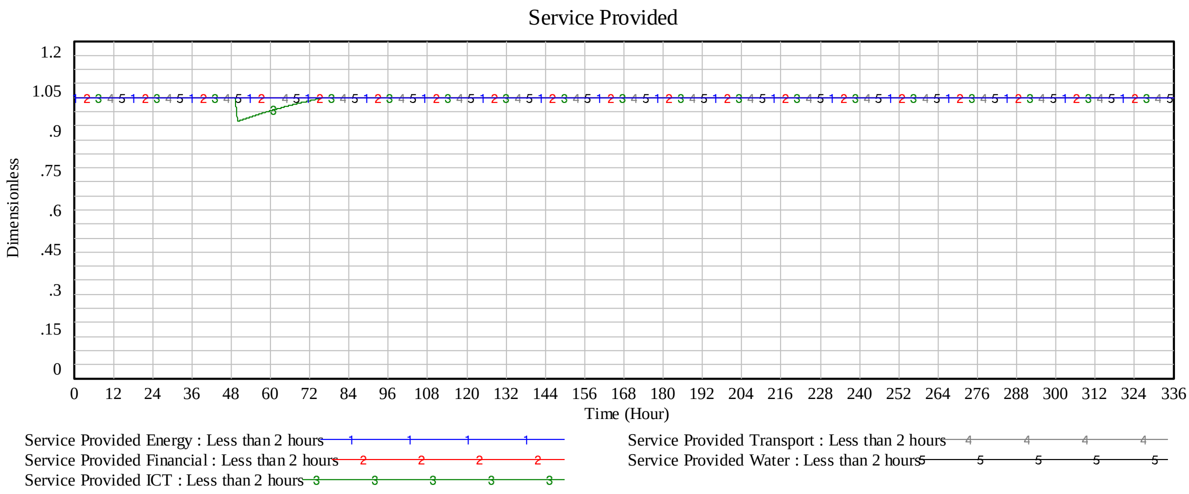




Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192 204 216 228 240 252 264 276 288 300 312 324 336
Time (Hour)
Service Provided Energy : Less than 2 hours
Service Provided Financial : Less than 2 hours
Service Provided ICT : Less than 2 hours
Service Provided Transport : Less than 2 hours
Service Provided Water : Less than 2 hours

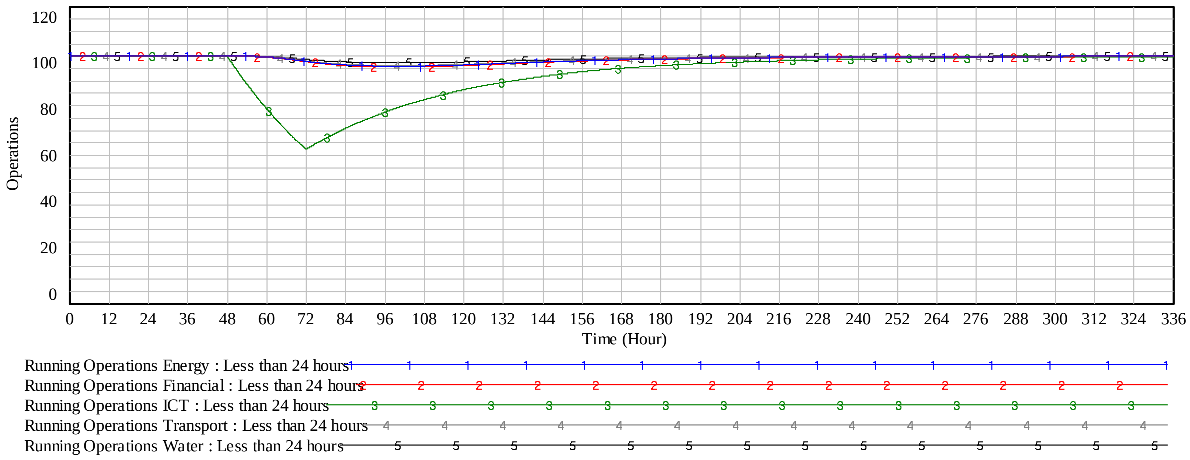


Running Operations
Operations
120
100
80
60
40
20
0
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192 204 216 228 240 252 264 276 288 300 312 324 336
Time (Hour)
Running Operations Energy : Less than 2 hours
Running Operations Financial : Less than 2 hours
Running Operations ICT : Less than 2 hours
Running Operations Transport : Less than 2 hours
Running Operations Water : Less than 2 hours

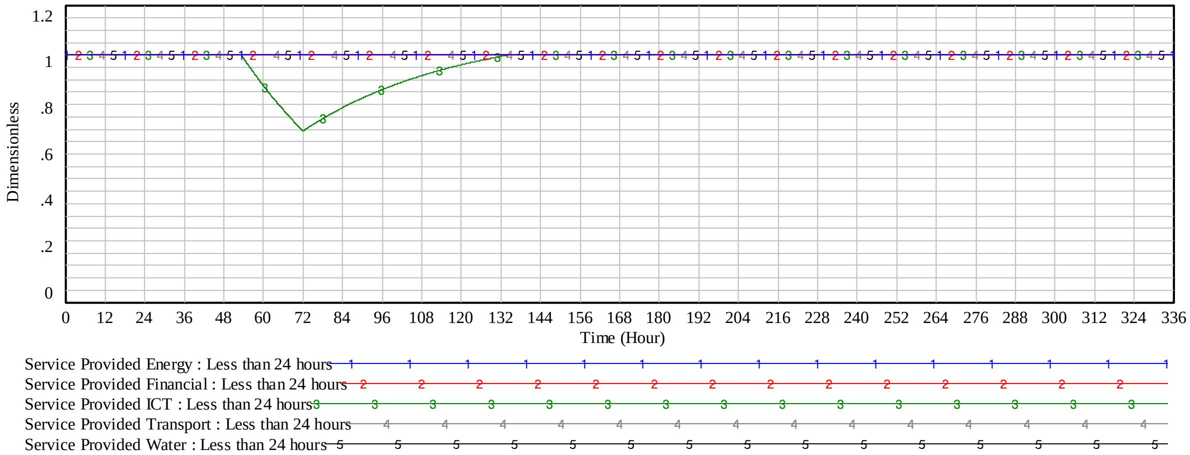


Service Provided
Dimensionless
1.2
1.05
.9
.75
.6
.45
.3
.15
0
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192 204 216 228 240 252 264 276 288 300 312 324 336
Time (Hour)
Service Provided Energy : Less than 2 hours
Service Provided Financial : Less than 2 hours
Service Provided ICT : Less than 2 hours
Service Provided Transport : Less than 2 hours
Service Provided Water : Less than 2 hours

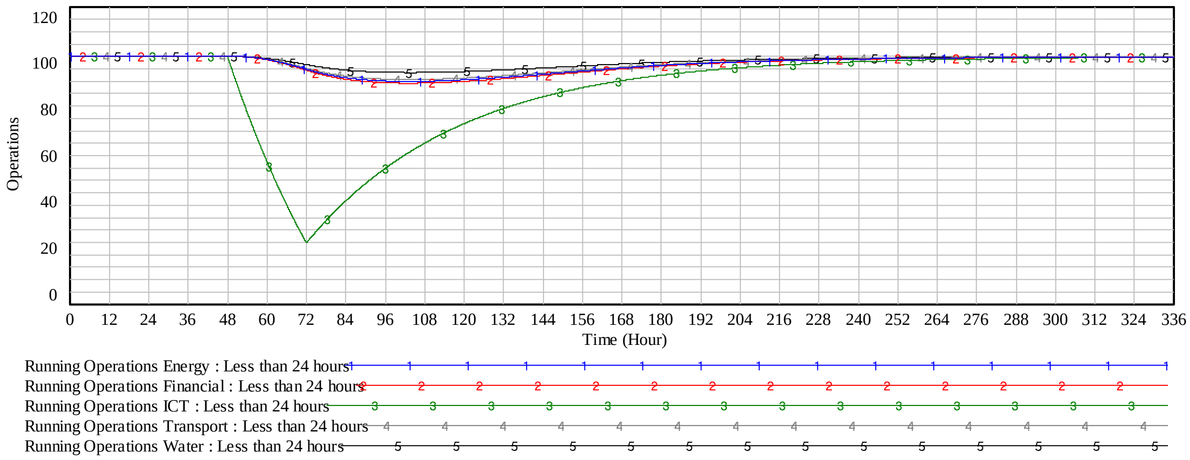
Running Operations

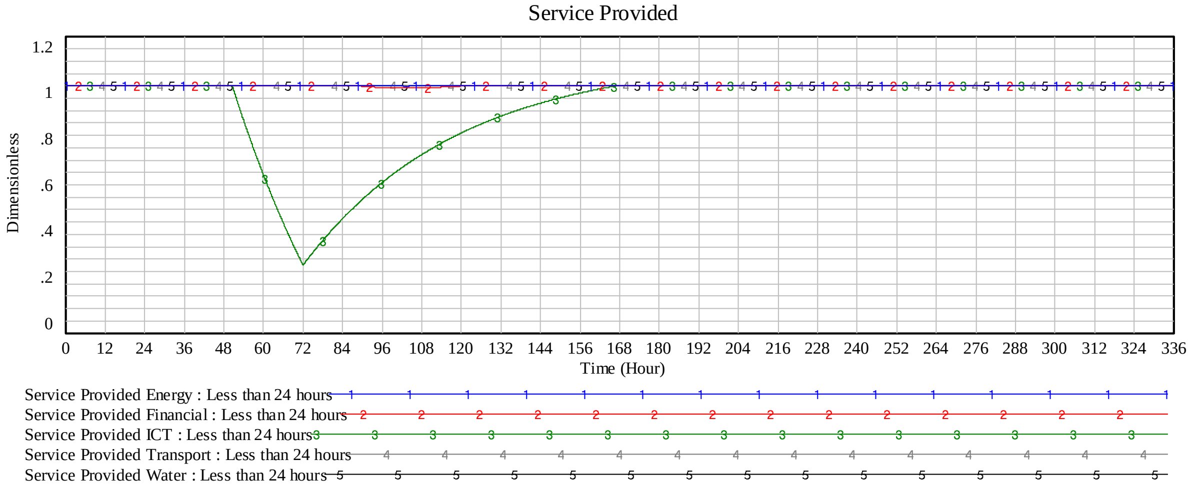


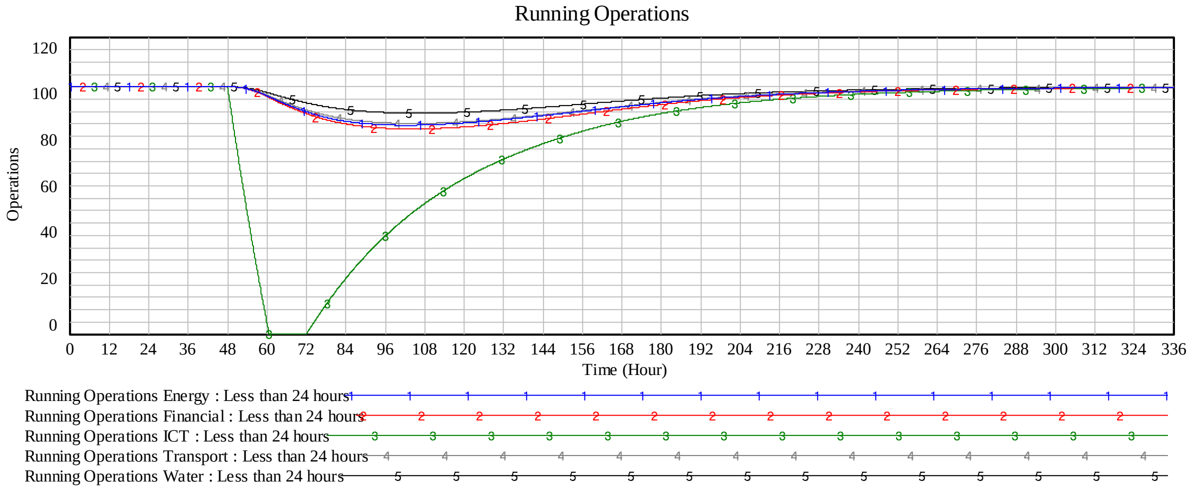
Service Provided

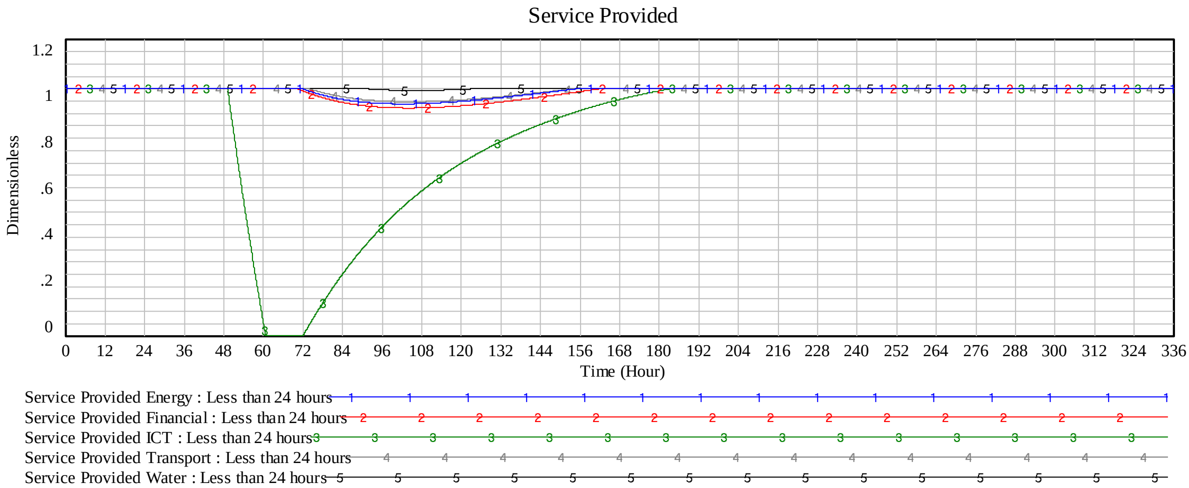


Running Operations

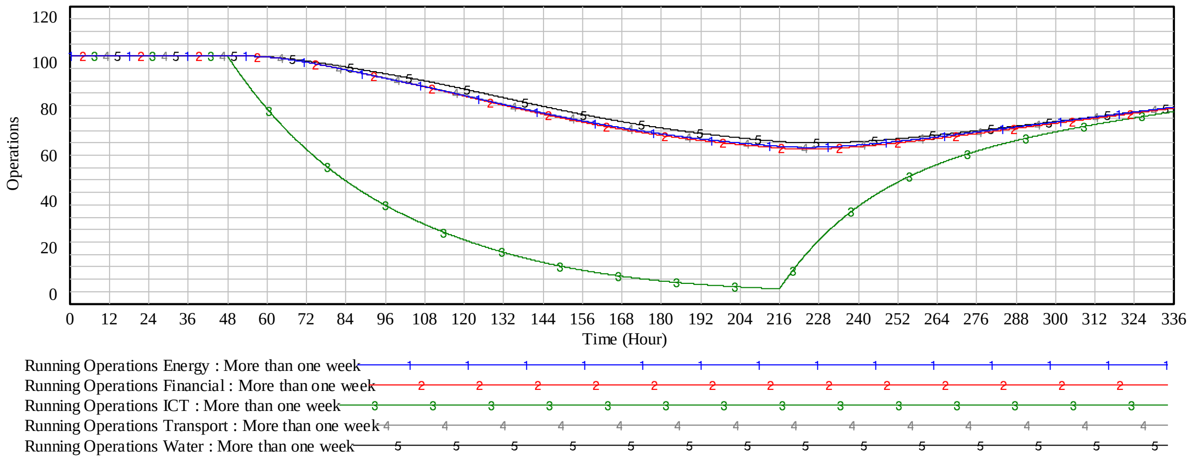



Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Less than 24 hours
Service Provided Financial : Less than 24 hours
Service Provided ICT : Less than 24 hours
Service Provided Transport : Less than 24 hours
Service Provided Water : Less than 24 hours

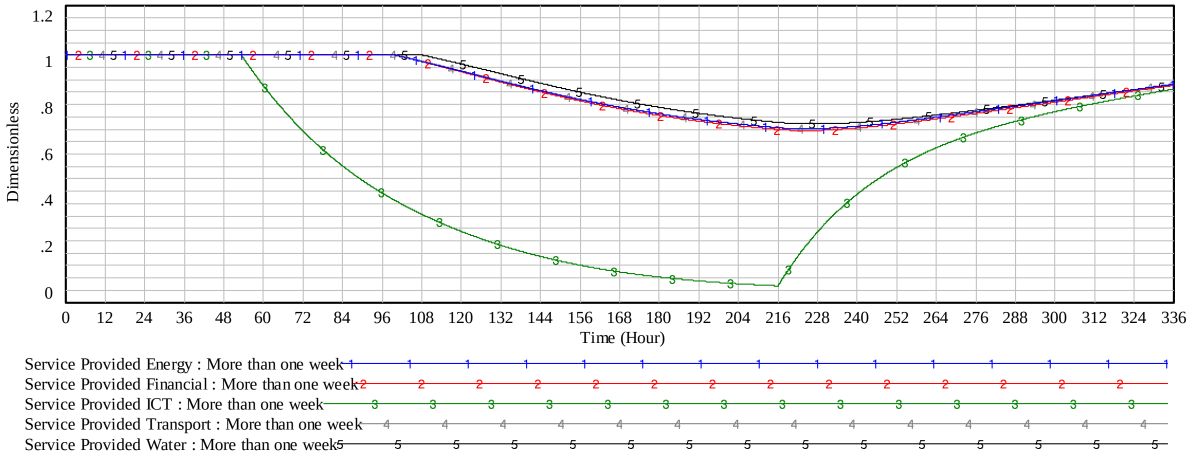

Running Operations
Operations
Time (Hour)
Running Operations Energy : Less than 24 hours
Running Operations Financial : Less than 24 hours
Running Operations ICT : Less than 24 hours
Running Operations Transport : Less than 24 hours
Running Operations Water : Less than 24 hours


Service Provided
Dimensionless
Time (Hour)
Service Provided Energy : Less than 24 hours
Service Provided Financial : Less than 24 hours
Service Provided ICT : Less than 24 hours
Service Provided Transport : Less than 24 hours
Service Provided Water : Less than 24 hours

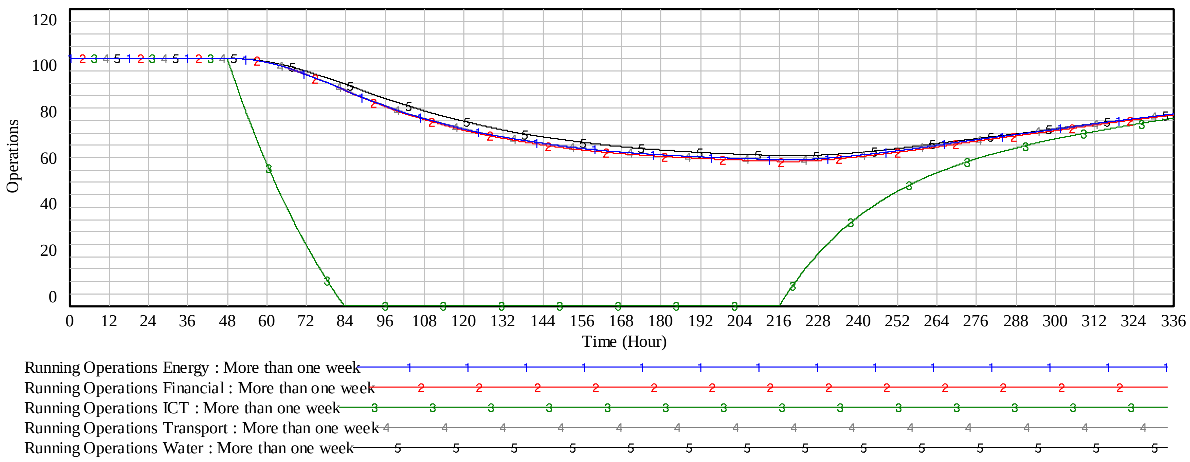
Running Operations



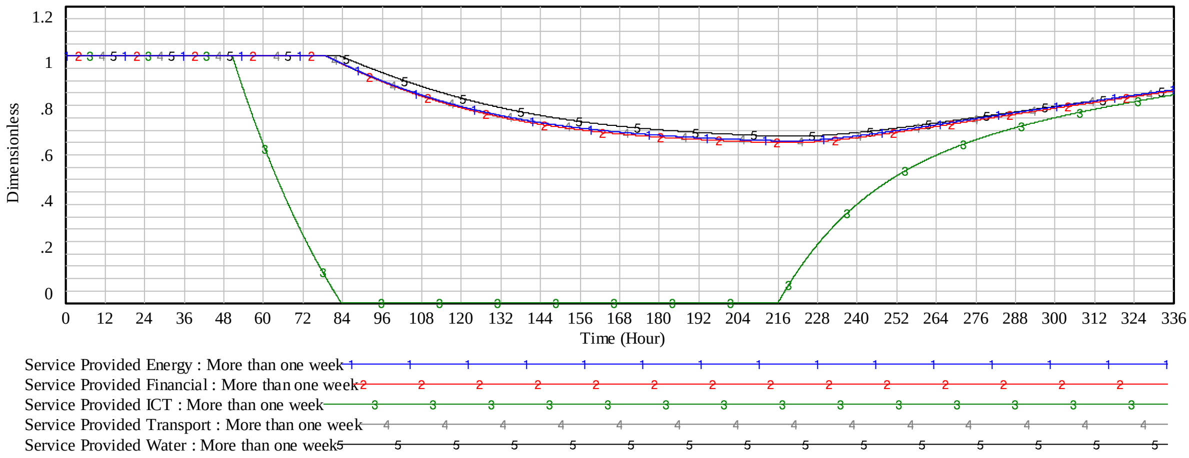
Service Provided



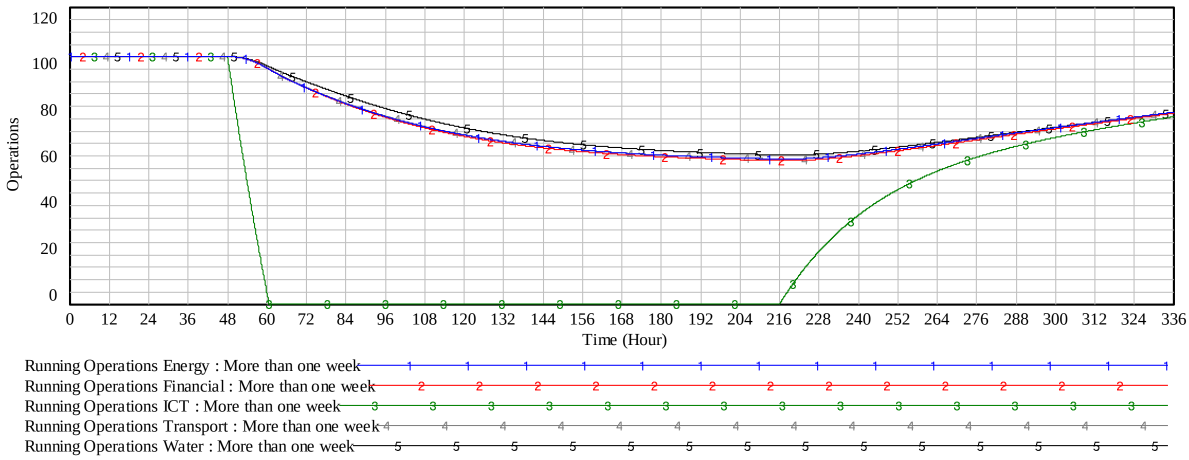
Running Operations



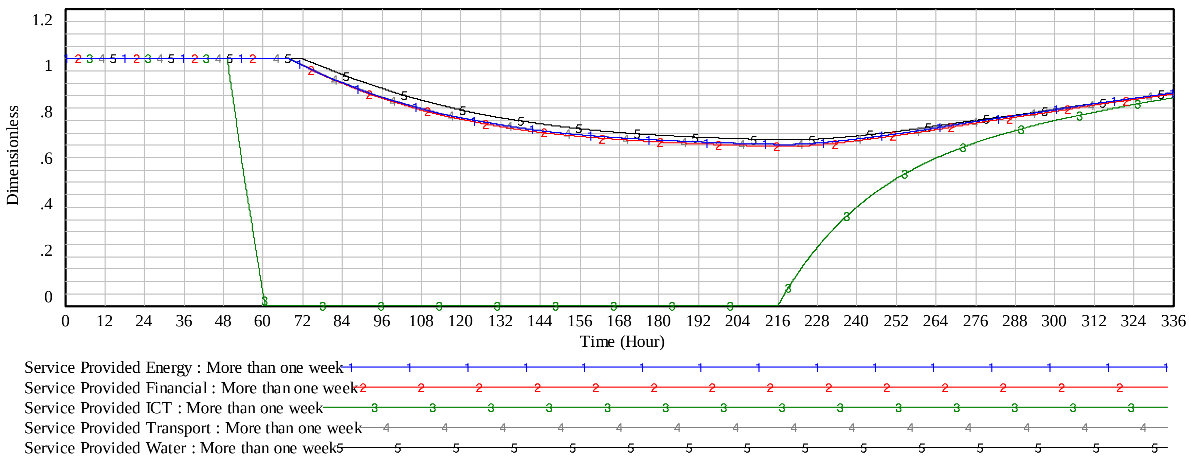
Service Provided



Running Operations



Service Provided



Appendix I – Replicated model

Average Demand Energy = 0.9

Units: Dmnl

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Demand Financial = 0.9

Units: Dmnl

An assumption is made that all CI performs on average at 90 percent of full capacity at any given time to render their demand to each other.

Average demand ICT = 0.9

Units: Dmnl

An assumption is made that all CI performs on average at 90 percent of full capacity at any given time to render their demand to each other.

Average demand Transport = 0.9

Units: Dmnl

An assumption is made that all CI performs on average at 90 percent of full capacity at any given time to render their demand to each other.

Average demand Water = 0.9

Units: Dmnl

An assumption is made that all CI performs on average at 90 percent of full capacity at any given time to render their demand to each other.

Average repair time Financial = 33

Units: Hour

The average time it takes to repair the Financial CI, measured in hours. The value was given by Canzani herself.¨

Average repair time Transport = 33

Units: Hour

The average time it takes to repair the Energy CI, measured in hours. The value was given by Canzani herself.

Average repair time Water = 33

Units: Hour

The average time it takes to repair the Water CI, measured in hours. The value was given by Canzani herself.

Average time to repair Energy = 33

Units: Hour

The average time it takes to repair the Energy CI, measured in hours. The value was given by Canzani herself.

Average time to repair ICT = 33

Units: Hour

The average time it takes to repair the ICT CI, measured in hours. The value was given by Canzani herself.

Average unit time to restore Energy = 14

Units: Hour

The return to service average time unit, measure in hours. Provided by Canzani.

Average unit time to restore Financial = 14

Units: Hour

The return to service average time unit, measure in hours. Provided by Canzani.

Average unit time to restore ICT = 14

Units: Hour

The return to service average time unit, measure in hours. Provided by Canzani.

Average unit time to restore Transport = 14

Units: Hour

The return to service average time unit, measure in hours. Provided by Canzani.

Average Unit time to restore Water = 14

Units: Hour

The return to service average time unit, measure in hours. Provided by Canzani.

Breakdown rate Energy=

IF THEN ELSE (Running Operations Energy > 0, Disruption Energy + (Running Operations Energy / Max Capability Energy) * ((effect on CI1 from CI2[Energy,ICT] * (1 - Service provided ICT)) + (effect on CI1 from CI2[Energy,Water]* (1 - Service provided Water)) + (effect on CI1 from CI2[Energy,Financial] * (1 - Service provided Financial)) + (effect on CI1 from CI2[Energy,Transport] * (1 - Service provided Transport))) / 5, 0)

Units: Operations/Hour

The breakdown rate from running operations to down operations with and added specific Disruption, to simulate multiple disruption-scenarios. The rate is also influenced by 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.

Breakdown rate Financial=

IF THEN ELSE (Running Operations Financial > 0, (Running Operations Financial / Max Capacity Financial) * ((effect on CI1 from CI2[Financial,Energy] * (1 - Service Provided Energy)) + (effect on CI1 from CI2[FinancialICT] * (1 - Service provided ICT)) + (effect on CI1 from CI2[Financial,Water] * (1 - Service provided Water)) + (effect on CI1 from CI2[Financial,Transport] * (1 - Service provided Transport))) / 5, 0)

Units: Operations/Hour

The breakdown rate from running operations to down operations with and added specific Disruption, to simulate multiple disruption-scenarios. The rate is influenced by 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.

Breakdown rate ICT=

IF THEN ELSE (Running Operations ICT > 0, Disruption ICT + (Running Operations ICT/ Max capability ICT) * ((effect on CI1 from CI2[ICT,Energy] * (1 - Service Provided Energy)) + (effect on CI1 from CI2[ICT,Water] * (1 - Service provided Water)) + (effect on CI1 from CI2[ICT,Financial] * (1 - Service provided Financial)) + (effect on CI1 from CI2[ICT,Transport] * (1 - Service provided Transport))) / 5, 0)

Units: Operations/Hour

The breakdown rate from running operations to down operations with an added specific Disruption. The rate is influenced by 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.

Breakdown rate Transport=

IF THEN ELSE (Running Operations Transport > 0, (Running Operations Transport/ Max capacity Transport) * ((effect on CI1 from CI2[Transport,Energy] * (1 - Service Provided Energy)) + (effect on CI1 from CI2[Transport,ICT] * (1 - Service provided ICT)) + (effect on CI1 from CI2[Transport,Water] * (1 - Service provided Water)) + (effect on CI1 from CI2[Transport,Financial] * (1 - Service provided Financial))) / 5, 0)

Units: Operations/Hour

The breakdown rate from running operations to down operations with and added specific Disruption, to simulate multiple disruption-scenarios. The rate is influenced by 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.

Breakdown rate Water=

IF THEN ELSE (Running Operations Water > 0, (Running Operations Water / Max Capability Water) * ((effect on CI1 from CI2[Water,Energy] * (1 - Service Provided Energy)) + (effect on CI1 from CI2[Water,ICT] * (1 - Service provided ICT)) + (effect on CI1 from CI2[Water,Financial] * (1 - Service provided Financial)) + (effect on CI1 from CI2[Water,Transport]* (1 - Service provided Transport))) / 5, 0)

Units: Operations/Hour

The breakdown rate from running operations to down operations with and added specific Disruption, to simulate multiple disruption-scenarios. The rate is influenced by 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.

CI1:

Energy, ICT, Water, Financial, Transport

The subset of the elements in the two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The populated values range from 0 to 5.

CI2:

Energy, ICT, Water, Financial, Transport

The elements in the two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The populated values range from 0 to 5.

Current Capability Energy = Running Operations Energy / Max Capability Energy

Units: 1

The current capability of the Energy CI, defined as the ratio between the running operations stock and the maximum capacity of the Energy CI.

Current Capability ICT = Running Operations ICT / Max capability ICT

Units: Dmnl

The current capability of the ICT CI, defined as the ratio between the running operations stock and the maximum capacity of the ICT CI.

Current capability Water = Running Operations Water / Max Capability Water

Units: 1

The current capability of the Water CI, defined as the ratio between the running operations stock and the maximum capacity of the Water CI.

Current Capacity Financial = Running Operations Financial / Max Capacity Financial

Units: 1

The current capability of the Financial CI, defined as the ratio between the running operations stock and the maximum capacity of the Financial CI.

Current capacity Transport = Running Operations Transport / Max capacity Transport

Units: 1

The current capability of the Transport CI, defined as the ratio between the running operations stock and the maximum capacity of the Transport CI.

Disruption duration = 24

Units: Hour

The duration of the disruption measured in hours.

Disruption duration Energy = 36

Units: Hour

The duration of the pulse disruption measured in hours.

Disruption Energy = Disruption Magnitude Energy * PULSE (Disruption Time Energy, Disruption duration Energy)

Units: Operations/Hour

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.

Disruption ICT = PULSE (Disruption Time , Disruption duration) * Disruption Magnitude

Units: Operations/Hour

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.

Disruption Magnitude=2

Units: Operations/Hour

The dimensionless magnitude of the disruption, ranging from 0 (no disruption), to 10 (complete breakdown).

Disruption Magnitude Energy = 0

Units: Operations/Hour

The dimensionless magnitude of the disruption, ranging from 0 (no disruption), to 10 (complete breakdown).

Disruption Time = 24

Units: Hour

The time during the simulation in which the disruption occurs.

Disruption Time Energy = 96

Units: Hour

The time of the simulation in which the Energy CI disruption occurs.

Down Operations Energy = INTEG(Breakdown rate Energy - Repair rate Energy, 0)

Units: Operations

The down-state, where the Energy CI has a lack of output in production. Depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations Financial = INTEG(Breakdown rate Financial - Repair rate Financial, 0)

Units: Operations

The down-state, where the Financial CI has a lack of output in production. Depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations ICT = INTEG(Breakdown rate ICT - Repair rate ICT , 0)

Units: Operations

The down-state, where the ICT CI has a lack of output in production. Depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations Transport = INTEG(Breakdown rate Transport - Repair rate Transport, 0)

Units: Operations

The down-state, where the Transport CI has a lack of output in production. Depending on the breakdown rate, disruption and cascading factors.The assumption is made that at t=0 the level is empty.

Down Operations Water = INTEG(Breakdown rate Water - Repair rate water , 0)

Units: Operations

The down-state, where the Water CI has a lack of output in production. Depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

effect on CI1 from CI2[CI1,CI2]=

0, 2.67, 0.83, 0.17, 1.17;

0.86, 0, 0.57, 0.71, 1;

1.33, 1, 0, 0, 0;

2.67, 2.33, 0, 0, 1;

2.4, 2.4, 0.2, 0.6, 0;

Units: Operations/Hour

The two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The values can range from 0 to 5 and are taken from Canzani's (2016, p. 7)

FINAL TIME = 336

Units: Hour

The final time for the simulation.

INITIAL TIME = 0

Units: Hour

The initial time for the simulation.

Max Capability Energy = 100

Units: Operations

The maximum capability of the Energy CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max capability ICT = 100

Units: Operations

The maximum capability of the ICT CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capability Water = 100

Units: Operations

The maximum capability of the Water CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capacity Financial = 100

Units: Operations

The maximum capability of the Financial CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max capacity Transport = 100

Units: Operations

The maximum capability of the Transport CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Operations recovered ICT = INTEG(Repair rate ICT - Return to service ICT ,0)

Units: Operations

The recovering phase in which the infrastructure attempts to return to previous service levels.

Recovering Operations Energy = INTEG(Repair rate Energy - Return to service Energy, 0)

Units: Operations

The recovering phase in which the infrastructure attempts to return to previous service levels.

Recovering Operations Financial = INTEG(Repair rate Financial - Return to service Financial, 0)

Units: Operations

The recovering phase in which the infrastructure attempts to return to previous service levels.

Recovering Operations Transport = INTEG(Repair rate Transport - Return to service Transport, 0)

Units: Operations

The recovering phase in which the infrastructure attempts to return to previous service levels.

Recovering Operations Water = INTEG(Repair rate water - Return to service Water, 0)

Units: Operations

The recovering phase in which the infrastructure attempts to return to previous service levels.

Repair rate Energy = Down Operations Energy / Average time to repair Energy

Units: Operations/Hour

The rate at which the Energy CI is repaired and enters the recovery state.

Repair rate Financial = Down Operations Financial / Average repair time Financial

Units: Operations/Hour

The rate at which the Financial CI is repaired and enters the recovery state.

Repair rate ICT = Down Operations ICT / Average time to repair ICT

Units: Operations/Hour

The rate at which the ICT CI is repaired and enters the recovery state.

Repair rate Transport = Down Operations Transport / Average repair time Transport

Units: Operations/Hour

The rate at which the Transport CI is repaired and enters the recovery state.

Repair rate water = Down Operations Water / Average repair time Water

Units: Operations/Hour

The rate at which the Water CI is repaired and enters the recovery state.

Return to service Energy = Recovering Operations Energy / Average unit time to restore Energy

Units: Operations/Hour

The rate at which the Energy CI returns to full service.

Return to service Financial = Recovering Operations Financial / Average unit time to restore Financial

Units: Operations/Hour

The rate at which the Financial CI returns to full service.

Return to service ICT = Operations recovered ICT / Average unit time to restore ICT

Units: Operations/Hour

The rate at which the ICT CI returns to full service.

Return to service Transport = Recovering Operations Transport / Average unit time to restore Transport

Units: Operations/Hour

The rate at which the Transport CI returns to full service.

Return to service Water = Recovering Operations Water / Average Unit time to restore Water

Units: Operations/Hour

The rate at which the Water CI returns to full service.

Running Operations Energy = INTEG(- Breakdown rate Energy + Return to service Energy, 100)

Units: Operations

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.

Running Operations Financial = INTEG(Return to service Financial - Breakdown rate Financial, 100)

Units: Operations

Running operations represents the day-to-day functions of the Financial CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations ICT = INTEG(Return to service ICT - Breakdown rate ICT , 100)

Units: Operations

Running operations represents the day-to-day functions of the ICT CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations Transport = INTEG(Return to service Transport - Breakdown rate Transport, 100)

Units: Operations

Running operations represents the day-to-day functions of the Transport CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations Water = INTEG(- Breakdown rate Water + Return to service Water, 100)

Units: Operations

Running operations represents the day-to-day functions of the Water CI. It is assumed that the CI operates at 100% capacity at time t=0.

SAVEPER = TIME STEP

Units: Hour [0,?]

The frequency with which output is stored.

Service Provided Energy=

IF THEN ELSE (Current Capability Energy >= Average Demand Energy , 1,Current Capability Energy / Average Demand Energy)

Units: 1

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.

Service provided Financial = IF THEN ELSE (Current Capacity Financial >= Average Demand Financial , 1, Current Capacity Financial / Average Demand Financial)

Units: 1

The control variable which assesses over time the service provided by the Financial CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service provided ICT = IF THEN ELSE (Current Capability ICT >= Average demand ICT, 1, Current Capability ICT / Average demand ICT)

Units: 1

The control variable which assesses over time the service provided by the ICT CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service provided Transport = IF THEN ELSE (Current capacity Transport >= Average demand Transport, 1, Current capacity Transport / Average demand Transport)

Units: 1

The control variable which assesses over time the service provided by the Transport CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service provided Water = IF THEN ELSE (Current capability Water >= Average demand Water, 1, Current capability Water / Average demand Water)

Units: 1

The control variable which assesses over time the service provided by the ICT CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

TIME STEP = 0.0078125

Units: Hour [0,?]

The time step for the simulation.

Appendix J – Thesis model

Average Demand Energy = 0.9

Units: Dimensionless

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Demand Financial = 0.9

Units: Dimensionless

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Demand ICT=0.9

Units: Dimensionless

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Demand Transport = 0.9

Units: Dmnl

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Demand Water = 0.9

Units: Dimensionless

An assumption is made that all CI perform on average at 90 percent of full capacity at any given time to supply their demand to each other.

Average Repair and Restore Time Energy=47

Units: Hours

The sum of the total average repair and restore time variables from Canzanis article, measured in hours.

Average Repair and Restore Time Financial=47

Units: Hours

The sum of the total average repair and restore time variables from Canzanis article, measured in hours.

Average Repair and Restore Time ICT=47

Units: Hours

The sum of the total average repair and restore time variables from Canzanis article, measured in hours.

Average Repair and Restore Time Transport=47

Units: Hours

The sum of the average repair and restore time variables from Canzanis article, measured in hours.

Average Repair and Restore Time Water=47

Units: Hours

The sum of the total average repair and restore time variables from Canzanis article, measured in hours.

Breakdown Rate Energy=

IF THEN ELSE(Running Operations Energy>0 :AND: Max Capability Energy<>0, MIN(Unit normalization*(Running Operations Energy / Max Capability Energy) * (((Effect on CI1 from CI2[Energy,ICT] * (1 -Service Provided ICT)) + (Effect on CI1 from CI2[Energy,Water]* (1 - Service Provided Water)) + (Effect on CI1 from CI2[Energy,Financial] * (1 - Service Provided Financial)) + (Effect on CI1 from CI2[Energy,Transport] * (1 - Service Provided Transport))) / 5), Running Operations Energy/TIME STEP),0)

Units: Operations/Hour

The breakdown rate from running operations to down operations. The rate is affected by cascading effects from the other CI's (Service Provided). The IF THEN ELSE with the nested MIN-function ensures the Running operations never goes below zero. The equation uses the respective e(ij) values from the subscript array.

Breakdown Rate Financial=

IF THEN ELSE(Running Operations Financial>0 :AND: Max Capability Financial <>0, MIN(Unit normalization*(Running Operations Financial / Max Capability Financial) * (((Effect on CI1 from CI2[Financial,Energy]* (1 - Service Provided Energy)) + (Effect on CI1 from CI2[Financial,ICT]* (1 - Service Provided ICT)) + (Effect on CI1 from CI2[Financial,Water] * (1 - Service Provided Water)) + (Effect on CI1 from CI2[Financial,Transport] * (1 - Service Provided Transport))) / 5), Running Operations Financial/TIME STEP),0)

Units: Operations/Hour

The breakdown rate from running operations to down operations. The rate is affected by cascading effects from the other CI's (Service Provided). The IF THEN ELSE with the nested MIN-function ensures the Running operations never goes below zero. The equation uses the respective e(ij) values from the subscript array.

Breakdown Rate ICT=

IF THEN ELSE(Running Operations ICT>0 :AND: Max Capability ICT <>0, MIN(Disruption +Unit normalization*(Running Operations ICT / Max Capability ICT) * (((Effect on CI1 from CI2[ICT,Energy] * (1 - Service Provided Energy)) + (Effect on CI1 from CI2[ICT,Water]* (1 - Service Provided Water)) + (Effect on CI1 from CI2[ICT,Financial] * (1 - Service Provided Financial)) + (Effect on CI1 from CI2[ICT,Transport]* (1 - Service Provided Transport))) / 5),Running Operations ICT/TIME STEP),0)

Units: Operations/Hour

The breakdown rate from running operations to down operations. The rate is affected by cascading effects from the other CI's (Service Provided). The IF THEN ELSE with the nested MIN-function ensures the Running operations never goes below zero. The equation uses the respective e(ij) values from the subscript array.

Breakdown Rate Transport=

IF THEN ELSE(Running Operations Transport>0 :AND: Max Capability<>0, MIN(Unit normalization*(Running Operations Transport / Max Capability Transport) * (((Effect on CI1 from CI2[Transport,Energy] * (1 - Service Provided Energy)) + (Effect on CI1 from CI2[Transport,ICT] * (1 - Service Provided ICT)) + (Effect on CI1 from CI2[Transport,Water] * (1 - Service Provided Water)) + (Effect on CI1 from CI2[Transport,Financial] * (1 - Service Provided Financial))) / 5), Running Operations Transport/TIME STEP),0)

Units: Operations/Hour

The breakdown rate from running operations to down operations. The rate is affected by cascading effects from the other CI's (Service Provided). The IF THEN ELSE with the nested MIN-function ensures the Running operations never goes below zero. The equation uses the respective e(ij) values from the subscript array.

Breakdown Rate Water=

IF THEN ELSE(Running Operations Water>0 :AND: Max Capability Water<>0, MIN(Unit normalization*(Running Operations Water / Max Capability Water)* (((Effect on CI1 from CI2[Water,Energy] * (1 - Service Provided Energy)) + (Effect on CI1 from CI2[Water,ICT] * (1 - Service Provided ICT))+ (Effect on CI1 from CI2[Water,Financial] * (1 - Service Provided Financial)) + (Effect on CI1 from CI2[Water,Transport] * (1 - Service Provided Transport))) / 5), Running Operations Water/TIME STEP),0)

Units: Operations/Hour

The breakdown rate from running operations to down operations. The rate is affected by cascading effects from the other CI's (Service Provided). The IF THEN ELSE with the nested MIN-function ensures the Running operations never goes below zero. The equation uses the respective e(ij) values from the subscript array.

CI1:

Energy, ICT, Water, Financial, Transport

The subset of the elements in the two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The populated values range from 0 to 5, depending on which table they are collected from, either Lauge or the online survey.

CI2:

Energy, ICT, Water, Financial, Transport

The elements in the two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The populated values range from 0 to 5, depending on which table they are collected from, either Lauge or the online survey.

Current Capability Energy=

IF THEN ELSE (Max Capability Energy > 0, Running Operations Energy / Max Capability Energy, 0)

Units: Dimensionless

The current capability of the Energy CI, defined as the ratio between the running operations stock and the maximum capacity of the Energy CI.

Current Capability Financial =

IF THEN ELSE (Max Capability Financial > 0, Running Operations Financial / Max Capability Financial, 0)

Units: Dimensionless

The current capability of the Financial CI, defined as the ratio between the running operations stock and the maximum capacity of the Financial CI.

Current Capability ICT =

IF THEN ELSE (Max Capability ICT > 0, Running Operations ICT / Max Capability ICT, 0)

Units: Dimensionless

The current capability of the ICT CI, defined as the ratio between the running operations stock and the maximum capacity of the ICT CI.

Current Capability Transport =

IF THEN ELSE (Max Capability Transport > 0, Running Operations Transport / Max Capability Transport, 0)

Units: Dmnl

The current capability of the Transport CI, defined as the ratio between the running operations stock and the maximum capacity of the Transport CI.

Current Capability Water =

IF THEN ELSE (Max Capability Water> 0, Running Operations Water / Max Capability Water

Units: Dimensionless

The current capability of the Water CI, defined as the ratio between the running operations stock and the maximum capacity of the Water CI.

Disruption = PULSE (Disruption Time, Disruption Duration) * Disruption Magnitude

Units: Operations/Hour

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.

Disruption Duration = 24

Units: Hours

The duration of the disruption.

Disruption Magnitude=9

Units: Operations/Hour

The dimensionless magnitude of the disruption, ranging from 0 (no disruption), to 10 (complete breakdown).

Disruption Time=21

Units: Hours

The time during the simulation in which the disruption occurs.

Down Operations Energy = INTEG (Breakdown Rate Energy - Return to Service Energy, 0)

Units: Operations

The down-state of the Energy CI, where the Energy CI has a lack of output in production, depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations Financial = INTEG (Breakdown Rate Financial - Return to Service Financial, 0)

Units: Operations

The down-state of the Financial CI, where the Financial CI has a lack of output in production, depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations ICT = INTEG (Breakdown Rate ICT - Return to Service ICT, 0)

Units: Operations

The down-state of the ICT CI, where the ICT CI has a lack of output in production, depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations Transport = INTEG (Breakdown Rate Transport - Return to Service Transport, 0)

Units: Operations

The down-state of the Transport CI, where the Transport CI has a lack of output in production, depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Down Operations Water = INTEG (Breakdown Rate Water - Return to Service Water, 0)

Units: Operations

The down-state of the Water CI, where the Water CI has a lack of output in production, depending on the breakdown rate, disruption and cascading factors. The assumption is made that at t=0 the level is empty.

Effect on CI1 from CI2[CI1,CI2]=

0, 4.67, 3.43, 2.43, 3;

4.57, 0, 3.5, 3, 3.83;

4.57, 3.67, 0, 2, 3.67;

4.67, 4.67, 1, 0, 3.67;

4.2, 4.6, 2.6, 2.2, 0;

Units: Dmnl

The two-dimensional subscript array which contains all the values in the e(ij)-table, corresponding to the effect each CI has on the other. The populated values range from 0 to 5, depending on which table they are collected from, either Lauge or the online survey.

FINAL TIME = 168

Units: Hour

The final time for the simulation.

INITIAL TIME = 0

Units: Hour

The initial time for the simulation.

Max Capability Energy = 100

Units: Operations

The maximum capability of the Energy CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capability Financial = 100

Units: Operations

The maximum capability of the Financial CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capability ICT = 100

Units: Operations

The maximum capability of the ICT CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capability Transport=100

Units: Operations

The maximum capability of the Transport CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Max Capability Water = 100

Units: Operations

The maximum capability of the Water CI measured in the number of operations it can perform. 0 being no operations at all and 100 representing full performance.

Return to Service Energy = IF THEN ELSE (Average Repair and Restore Time Energy >0, Down Operations Energy / Average Repair and Restore Time Energy, 0)

Units: Operations/Hour

The rate at which the Energy CI returns to full service.

Return to Service Financial = IF THEN ELSE (Average Repair and Restore Time Financial >0, Down Operations Financial / Average Repair and Restore Time Financial, 0)

Units: Operations/Hour

The rate at which the Financial CI returns to full service.

Return to Service ICT = IF THEN ELSE (Average Repair and Restore Time ICT>0, Down Operations ICT / Average Repair and Restore Time ICT, 0)

Units: Operations/Hour

The rate at which the ICT CI returns to full service.

Return to Service Transport = IF THEN ELSE (Average Repair and Restore Time Transport>0, Down Operations Transport / Average Repair and Restore Time Transport, 0)

Units: Operations/Hour

The rate at which the Transport CI returns to full service.

Return to Service Water = IF THEN ELSE (Average Repair and Restore Time Water>0, Down Operations Water / Average Repair and Restore Time Water, 0)

Units: Operations/Hour

The rate at which the Water CI returns to full service.

Running Operations Energy= INTEG (Return to Service Energy - Breakdown Rate Energy,100)

Units: Operations

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.

Running Operations Financial = INTEG (Return to Service Financial - Breakdown Rate Financial, 100)

Units: Operations

Running operations represents the day-to-day functions of the Financial CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations ICT = INTEG (Return to Service ICT - Breakdown Rate ICT , 100)

Units: Operations

Running operations represents the day-to-day functions of the ICT CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations Transport = INTEG (Return to Service Transport - Breakdown Rate Transport, 100)

Units: Operations

Running operations represents the day-to-day functions of the Transport CI. It is assumed that the CI operates at 100% capacity at time t=0.

Running Operations Water = INTEG (Return to Service Water - Breakdown Rate Water, 100)

Units: Operations

Running operations represents the day-to-day functions of the Water CI. It is assumed that the CI operates at 100% capacity at time t=0.

SAVEPER = TIME STEP

Units: Hour [0,?]

The frequency with which output is stored.

Service Provided Energy = IF THEN ELSE (Current Capability Energy >= Average Demand Energy, 1, Current Capability Energy / Average Demand Energy)

Units: Dimensionless

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.

Service Provided Financial=

IF THEN ELSE (Current Capability Financial >= Average Demand Financial, 1, Current Capability Financial / Average Demand Financial)

Units: Dimensionless

The control variable which assesses over time the service provided by the Financial CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service Provided ICT =IF THEN ELSE (Current Capability ICT >= Average Demand ICT, 1, Current Capability ICT / Average Demand ICT)

Units: Dimensionless

The control variable which assesses over time the service provided by the ICT CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service Provided Transport=IF THEN ELSE (Current Capability Transport >= Average Demand Transport, 1, Current Capability Transport / Average Demand Transport)

Units: Dimensionless

The control variable which assesses over time the service provided by the Transport CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

Service Provided Water=IF THEN ELSE (Current Capability Water >= Average Demand Water, 1, Current Capability Water / Average Demand Water)

Units: Dimensionless

The control variable which assesses over time the service provided by the Water CI. Measured between 0 and 1. 0 Being no service provided and 1 representing full service provided.

TIME STEP = 0.0625

Units: Hour [0,?]

The time step for the simulation.

Unit normalization=1

Units: Operations/Hour

The normalizing factor which ensures the units for the e(ij)-factors are coherently operations/hour.