# Supply-at-Risk: Resilience Metric for Infrastructure Systems: Framework for assessing and comparing resilience of infrastructure systems in urban areas



**Author(s):**
Dubaniowski, Mateusz Iwo; Heinimann, Hans Rudolf

**Publication date:**
2019

**Permanent link:**
https://doi.org/10.3929/ethz-b-000403795



**Originally published in:**
https://doi.org/10.1109/ICSRS48664.2019.8987665

# Supply-at-risk: resilience metric for infrastructure systems

Framework for assessing and comparing resilience of infrastructure systems in urban areas


Mateusz Iwo Dubaniowski
Future Resilient Systems at Singapore-ETH Centre (SEC)
ETH Zurich
Singapore, Singapore
iwo.dubaniowski@frs.ethz.ch

Hans R. Heinimann
Future Resilient Systems at Singapore-ETH Centre (SEC)
ETH Zurich
Singapore, Singapore



***Abstract*—Urban systems, composed of households, businesses, and infrastructures, are continuously evolving and expanding. This has several implications because the impacts of disruptions, and the complexity and interdependence of systems, are rapidly increasing. Hence, we face a challenge in how to assess resilience of infrastructure systems in these urban areas. This issue has significant implications on infrastructure systems design and development.**

**The aims of this study were to: (1) to apply a framework for modeling interdependencies between infrastructure systems, businesses and households to a certain urban area; (2) develop a suite of disruption scenarios for the model; and (3) to devise a metric for resilience of infrastructure systems in an urban area that could be derived from the simulation model.**

**Our study resulted in the development of a model that mimics infrastructure systems, businesses, and households in an urban area. Subsequently, a metric for resilience of infrastructure systems was proposed and applied. The metric – supply-at-risk – was shown to be useful in comparing developments to infrastructure systems in terms of resilience. Our simulation experiment has shown that the supply-at-risk curve moves down after beneficial change is made to the system. We concluded that the supply-at-risk is a useful metric for resilience assessment allowing comparison of various infrastructure developments. Ideas for future research were also identified centered around assessing the metric under a wider range of disruptions and modifications to infrastructure systems.**



***Keywords-resilience assessment, resilience metric, infrastructure modeling, infrastructure resilience, infrastructure reliability, systems safety, systems resilience.***


## I. INTRODUCTION

Throughout past years urban areas have grown to become more and more dependent on technology. As cities grow, complex infrastructures that are required for delivery of modern technologies but also vital urban services become more and more interdependent. This process is constantly progressing and will increase even more in the future as urbanization advances. Interdependencies in these systems have influenced how disruptions emerging in one system propagate to other systems and what impact they have on urban areas in general. Moreover, disruptions to urban areas are becoming more frequent and more impactful. This is because: (1) cities grow larger and denser, so more people are affected by a disruption of similar magnitude; (2) cities become more dependent on technology; and (3) infrastructures providing these technologies form an ever-growing complex, intertwined mesh of services and resources [1].

Consequently, it becomes crucial to model how interdependencies between various organisms and systems of a city impact disruptions happening in the city. Specifically, it becomes crucial to evaluate resilience i.e. resistance, response and recovery to and from disruptions of urban areas or future developments in these areas. It is especially important to provide a robust metric that can be used to assess resilience of infrastructure systems and how constant developments of systems affect their resilience. Several authors and streams of research have attempted this challenge [2][3][4]. Haimes [5] has defined resilience of systems and shown its growing importance to various systems. Hosseini et al. [6] expanded on this by providing a range of definitions of resilience and measures of resilience as applied to systems engineering. However, approaches that provide a metric for assessing resilience of interdependent infrastructure systems are rare. Francis and Bekera [7] propose a metric and framework for resilience analysis of infrastructure systems. Likewise, infrastructure systems have been modeled to understand their response to disruptions [8][9][10]. Ouyang, Duenas-Osorio, and Min [11] have presented a framework for analyzing resilience of infrastructures. These approaches, however, focus primarily on infrastructure systems and do not consider socioeconomic effects of disruptions on businesses and households and wider society. To tackle this challenge, we aim to apply a framework for modelling interdependencies between infrastructure systems, businesses and households to a certain urban area; and subsequently, using this model, we aim to propose a metric for assessment of resilience of the area. This would enable us to assess how the urban organism in the area is prepared for a wide range of disruptions and what impact these might have on the system. Furthermore, it could help to compare different improvements to a system that might be proposed for the area in terms of resilience.

## II. MODEL SPECIFICATION

In this study, we utilize the model developed by Dubaniowski and Heinimann [2] to describe interdependencies between infrastructure systems, businesses and households. The model represents an urban area and allows for introduction of disruptions into the model. The model can evaluate the impact of disruptions being introduced into the system. The modeling framework consists of these elements: (1) a self-organizing network of agents representing metabolism of individual businesses or households (2) an agent representing behavior of a business or household unit (3) disruption generators allowing for introduction of disruptions into the system. A diagram of the conceptual framework of the model is presented on Figure 1.

A business or a household is represented as an agent that consists primarily of an input-output technology matrix that defines the agent in terms of what resources it can produce and what resources it uses in its production process. The input-output model [12] is employed to represent the production capability of the agent. The technology matrix describes the production processes of the agent, while the agent is also connected to raw material suppliers and includes a final consumer demand that allows for representation of final consumption happening at the agent. The agents primarily represent businesses and households in the model, however, they also represent infrastructure systems. This is achieved through business agents that correspond to infrastructure providing businesses. Consequently, infrastructure systems are represented in two ways in the model (1) as business unit agents that provide infrastructure products into the networks i.e. by business agents that correspond to an infrastructure provider business, and (2) as infrastructure system links that provide connections allowing transfer of resources between the agents. These two representations are complementary and allow for an adequate representation of interdependencies of socioeconomic units within an urban area. The links between agents allow for transportation of resources from an agent to another agent, while production of resources, understood as transformation of a set of input resources into another resource happens within an agent.

The exchange of resources takes place through infrastructure system links between the agents. An agent can obtain resources from any agent that is preceding the agent in the network. Similarly, it notifies all the following agents of resources that it can produce, and what is the cost of these resources at the agent. A price mechanism is subsequently used on agent by agent basis to decide on where to supply resources from to each particular agent.

The agents are connected together with infrastructure systems links to form a network of businesses and households that represents an urban area accurately. A separate network for each infrastructure system is implemented. The nodes of the networks correspond to agents mimicking household or business metabolism. The links correspond to links allowing transfer of resources between the agents. Each agent produces resources attempting to satisfy the agents following it in each resource's infrastructure network. Each agent receives resources from preceding agents. The allocation of resources and selection of sources is self-organizing and depends on the cost of obtaining the resources. The lowest cost is selected. The cost of a resource incoming to an agent is the transportation cost and production cost, where production cost is defined as cost of resources involved in producing the resource at preceding agent. A change in price means that the allocation of resources in model has changed. Hence, with dynamic changes in the system, the model is self-organizing due to the price mechanism of resource allocation.

Disruptions in the model are manifested through: (1) changes to the agent's production process, and (2) changes to the network topology i.e. transportation links. In agents the changes can happen to all components of the agent including technology matrix, raw material suppliers, or final consumer demand vectors. In the network topology, the changes can affect links by varying their cost or removing links altogether. The disruptions attempt to mimic real world events that might affect the urban area modeled.

Disruptions are introduced into the model through disruption generators. These generators follow certain stochastic processes to develop a disruption and subsequently deploy the disruption into the system. The range of disruption generators is carefully generated to match the real-world events happening to the urban area. A suite of disruption generators can be created to test response of a system to these disruptions.

## III. RESILIENCE METRIC – SUPPLY-AT-RISK

In this work, we introduce a new metric that can be utilized to assess the resilience of urban infrastructure systems. The metric follows the concept of a notion widely spread in the finance domain: value-at-risk. The value-at-risk describes possible loss of value of a portfolio with given threshold probability i.e. maximum loss with a given probabilistic confidence level. Similarly, the metric we utilize in this study to measure the resilience of systems is supply-at-risk. The supply-at-risk metric is the worst-case supply curve of resources with a certain threshold probability of adverse events that could occur to the systems. This means it is the worst-case supply curve for the area with a certain probabilistic confidence level. This metric can be used to evaluate the impact and magnitude of certain disruptions on an urban area. Furthermore, it can help in estimating which parts of the area considered will be especially affected by a disruption, and will suffer the largest change in costs of resources. In turn, supply-at-risk metric can help infrastructure planners to better design infrastructure systems in the area.

The metric used here is the cost of resources averaged across all these resources for total aggregated quantity for each agent. This allows us to obtain a single curve for the model in the system under analysis. The single curve helps to simplify the presentation of results, and furthermore allows for easier comparison of certain different systems. For example, it can be easily used to compare two areas, or to compare the impact of an infrastructure investment.

To obtain the metric, the stochastic disruption generators are run multiple times, in our case they are run so that a total of 100 distinct runs is achieved. This allows us to obtain 100 supply curves, subsequently we obtain the supply curve at 5% to obtain the supply-at-risk for the area at 5%. To obtain the supply curve we utilize values from the 5th worst curve (out of a 100) at each point of the supply graph.

## IV. Experiment design

To present an example of the metric, we used an abstract urban area. The urban area is transformed into the model described here. It consists of 21 business/household agents, and 5 types of resources are exchanged by these agents: water, power, consumer goods, capital goods, and human capital. One of the resource transportation networks – water supply - is shown on Figure 2. This system is then evaluated with a normal performance level, without any disruptions. A disruption generator is subsequently applied to the model to estimate the impact of disruptions. This step allows us to deliver a supply-at-risk metric for the system. This supply-at-risk curve is generated from a wide range of 100 randomly generated disruptions to the networks considered.

To show the impact of changes to the modeled urban area on the resilience of systems in the area, we include a modification to the model, a possible infrastructure investment project, and apply the disruption generators again to this modified system to understand how supply-at-risk curve changes as a result of the developments to the system. The applied modification to the network can be seen on Figure 2, where before and after modification topology is presented. This process allows us to exhibit the usefulness of the model and the metric introduced in our study for assessing the impact of potential infrastructure developments on the system.

A disruption generator was designed that affected nodes of the network and links with a certain probability and to a certain degree. This generator was used to obtain supply-at-risk curves of the system. To obtain the supply-at-risk curves here, we gathered results of 100 runs under the disruption generator, and we used the supply-at-risk curve at 5%. The 5th worst case pieces of supply curves from the 100 runs were joined to arrive with the supply-at-risk curve as shown on Figure 3. This process allowed us to obtain the 5% supply-at-risk curve of the system before the modification, and after the modification.

## V. Experiment results

The result of running the simulation is presented on Figure 3. The x-axis represents total aggregate amount of resources in the system supplied at each agent, while the y-axis represents the price averaged across resources for each agent. Therefore, the curves represent aggregate supply of resources across all 21 agents. The supply-at-risk curves are estimated by obtaining the supply-at-risk at 5% from 100 runs of a disruption generator. Thus, such supply-at-risk curves signify that with 95% confidence the supply under a disruption should be better than the supply-at-risk curve.

From Figure 3, we can see that as a result of introducing the modification into the system, the supply-at-risk curve moved down. The move down of a supply-at-risk curve and closing the gap between the supply-at-risk curve and the no disruption curve is a good outcome. As supply-at-risk curve moves down, it signifies the drop in overall risk of the system as the same amount of resources can be supplied at a lower price. Such behavior is desirable under a disruption. We can see from the figure that in our experiment the supply-at-risk curve moved down after introducing the modification to the system. Especially, it moved down for the region to the right of the graph, where the extra cost due to disruption had been the highest.

Results of the experiment indicate that the development introduced into the system helps to decrease the impact of disruptions on the system and the modification results in the system becoming more resilient. In such case, we can postulate that the impact of the development is positive on the resilience of the system. If we attempt to compare two or more prospective developments in such way, we can compare such three or more results and based on the supply-at-risk profile decide what development to include in the system, and which would be the most beneficial to the system.

This approach could help in infrastructure investment decisions. Comparing several infrastructure investment options and assessing them to arrive with the approach that improves resilience the most, as measured by supply-at-risk curve, can provide valuable input to decision-makers, urban planners, and infrastructure asset managers.

## VI. Conclusions

The aim of this study was to describe and apply a framework for modelling interdependencies between infrastructure systems, businesses and households to a certain urban area; and subsequently using this model to propose a metric for assessment of resilience of the urban area. The outcome of the study was an application of the model to an abstract urban area. Several infrastructure systems were modelled together with businesses and households in an abstract urban area. Disruption generators were then devised and applied to the model.

Furthermore, the above model has allowed us to establish a new metric for modeling resilience of infrastructures in urban areas. The new metric uses supply-at-risk curve to assess the system in terms of resilience. The supply-at-risk curve is obtained through applying a suite of disruption generators to a model of an urban area. It can be stated at different probabilistic confidence levels. The conducted experiment shows how the supply-at-risk metric can be used to assess resilience of system's potential future developments. This outcome and the metric presented herein is novel, as thus far assessment of resilience and reliability of infrastructure systems has not been done by looking at how supply of resources is impacted in a socioeconomic context.

The chief implication of the supply-at-risk approach is that it allows us to compare resilience impacts of different potential developments of infrastructure systems. Thus, the metric presented in this study can be used by scientists to better compare resilience of systems. Moreover, policymakers and decision-makers can use the metric to evaluate different proposals for investments into infrastructure projects, and professionals, such as urban and infrastructure planners, can utilize the model to design more resilient cities.

The limitations to this study include a limited number of urban areas and modification to the systems attempted.

Moreover, only one set of disruption generators was used in running the experiment. To address these challenges, a wider range of disruption generators could be used in the simulations in the future. Similarly, a wider range of modifications to the systems could be attempted to see how supply-at-risk metric changes under various different disruptions. Finally, a complex validation of the model against data obtained from a real-world system could be attempted.

## ACKNOWLEDGMENT

This work is an outcome of the Future Resilient Systems project at the Singapore-ETH Centre (SEC), which is funded by the National Research Foundation of Singapore (NRF) under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

## REFERENCES

[1] H. R. Heinimann and K. Hatfield, "Infrastructure Resilience Assessment, Management and Governance – State and Perspectives," in *Resilience and Risk*, Springer, Dordrecht, 2017, pp. 147–187.

[2] M. I. Dubaniowski and H. R. Heinimann, "A framework modeling flows of goods and services between businesses, households, and infrastructure systems," in *Resilience The 2nd International Workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment : 14-16 December 2017, Ispra*, Ispra, Italy, 2017, vol. I, pp. 182–190.

[3] I. Eusgeld, C. Nan, and S. Dietz, "'System-of-systems' approach for interdependent critical infrastructures," *Reliability Engineering & System Safety*, vol. 96, no. 6, pp. 679–686, Jun. 2011.

[4] M. I. Dubaniowski and H. R. Heinimann, "Time Granularity in System-of-Systems Simulation of Infrastructure Networks," in *Complex Networks and Their Applications VII*, 2019, pp. 482–490.

[5] Y. Y. Haimes, "On the Definition of Resilience in Systems," *Risk Analysis*, vol. 29, no. 4, pp. 498–501, 2009.

[6] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, "A review of definitions and measures of system resilience," *Reliability Engineering & System Safety*, vol. 145, pp. 47–61, Jan. 2016.

[7] R. Francis and B. Bekera, "A metric and frameworks for resilience analysis of engineered and infrastructure systems," *Reliability Engineering & System Safety*, vol. 121, pp. 90–103, Jan. 2014.

[8] S. E. Chang, "Infrastructure Resilience to Disasters," *The Bridge*, vol. 44, no. 3, pp. 36–41, 2014.

[9] D. Dudenhoeffer, P. Pederson, S. Hartley, and M. Permann, "Critical infrastructure interdependency modeling: a survey of U.S. research," presented at the CRIS, Third International Conference on Critical Infrastructures, 2006.

[10] D. L. Alderson, G. G. Brown, and W. M. Carlyle, "Operational Models of Infrastructure Resilience," *Risk Analysis*, vol. 35, no. 4, pp. 562–586, 2015.

[11] M. Ouyang, L. Dueñas-Osorio, and X. Min, "A three-stage resilience analysis framework for urban infrastructure systems," *Structural Safety*, vol. 36–37, pp. 23–31, May 2012.

[12] Leontief, Wassily W., *Input-output Economics*. Oxford University Press, 1986.

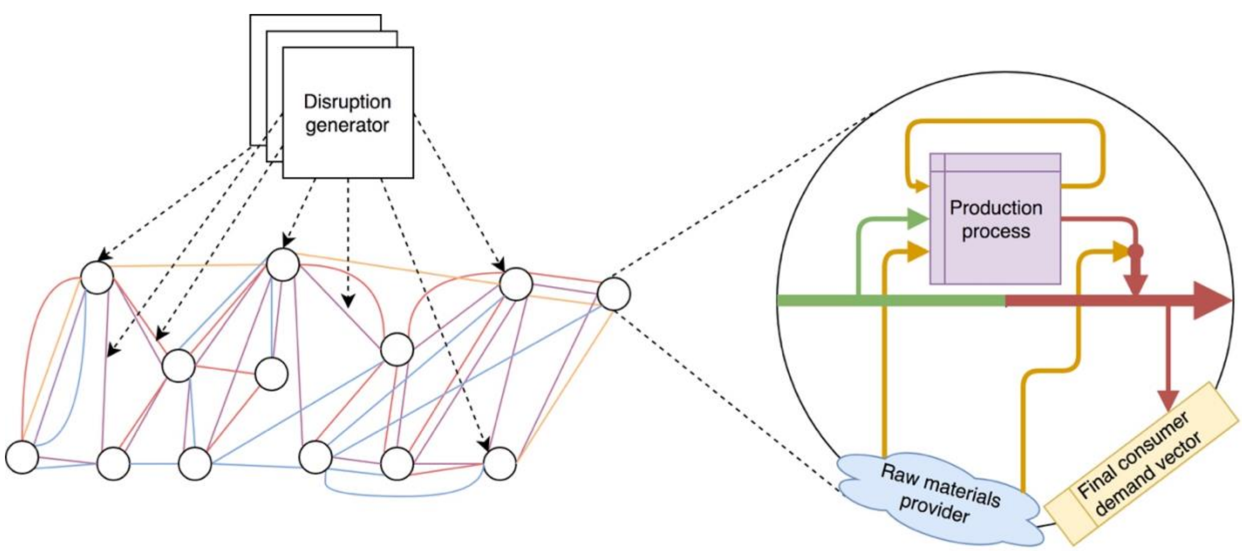


**Figure 1: Conceptual model of business/household unit agents joined together to form a network. Internal mechanism of each individual agent is presented on the right. The agent performs production processes based on inputs from other agents or from its raw materials provider. It also consumes resources as defined in the final consumer demand vector. Disruption generators are present to disrupt the system at various points within agents and infrastructure system links.**

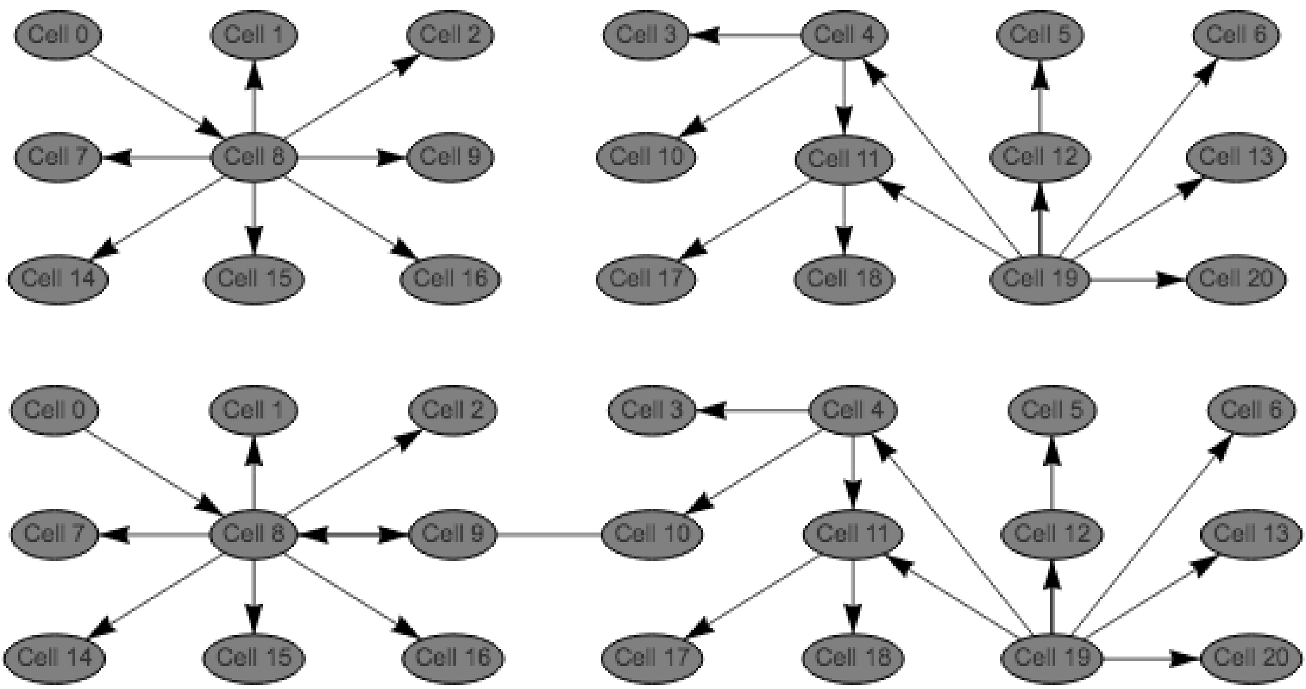


**Figure 2: Simulation experiment model. One of infrastructure system networks – water supply – before (top) and after (bottom) introduction of the modification into the system. The modification – link between agent 8 and 10 – can be clearly seen. The links correspond to water supply network. Cells correspond to agents conducting production, introducing raw resources, and performing final consumption. There are 5 similar networks in the experiment, one for each resource included in the model, however, their topologies differ.**

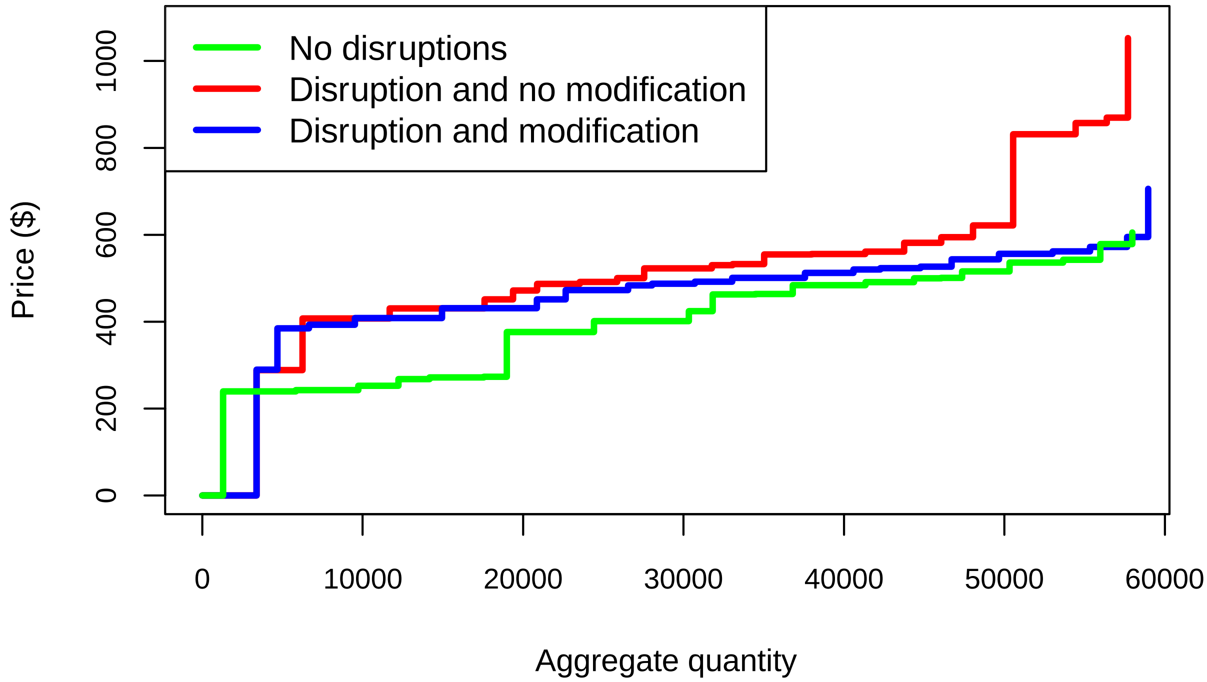


**Figure 3: Simulation experiment results. Supply curve of the original system with no disruption is shown (green), and compared with supply-at-risk at 5% curves of the original system (red) and of the modified system (blue). The aggregate quantity corresponds to the aggregated total of all 5 resources produced in an agent. From the figure, we see that introduction of the modification results in an improvement in resilience of the system by moving the supply-at-risk curve downwards and decreasing the huge jump in supply-at-risk curve on the right side of the graph.**