# Impact of a disruption in a supply chain: an assessment model

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**Abstract**: This paper aims to propose a model for the evaluation of the economic impact caused by a disruption of a supply chain. The model evaluates the impact on companies (nodes) upstream and downstream after identifying disrupted nodes. The impact on individual nodes is calculated in terms of Business Interruption (representing the number of days that the node does not generate value) and the turnover produced by the node. The paper describes the main operating logics of the model and the method used for their verification and validation. The work was developed using the anylogic simulation tool.

**Keywords**: Supply Chain, Losses Evaluation, Simulation

## 1. Introduction

In the current situation due to globalization, technological change and the emergence of financial markets, supply chains have expanded. For this reason, business objectives and business risks may not individually be sustained by the companies. Risk sharing through joint ventures, supply chain and other organizational structures has justified the trend towards ever larger supply chains, but also raised some issues regarding the risks and their control (Bruzzone et al. 2000). In fact, companies face with new problems such as political unrest, acts of terrorism, strikes, etc.

At odds with the traditional focus on the internal and external risks in operations and logistics, the supply chain is now much more exposed to risks "totally" external, that are not controllable by the individual company (Briano, E. et al. 2009).

Moreover, the current trend to reduce waste, primarly inventories, and production just in time further contributed to improving the efficiency of companies (Giribone, P et al. 2007).

Risk management in the supply chain consists mainly in control, risk prevention and the use of financial instruments to reduce and eliminate the effects of the financial consequences.

Mainly the application of the risk management process within the supply chain (SC) does not only have to orient themselves to the goal of crisis management disruptions of business cases. It needs to try to implement a systematic management of all the risks to daily management, effective and efficient supply chain (Pettit, Croxton and Fiksel, 2013).

Since a SC is a complex system in which it is not possible to isolate the effects in a static way, it is necessary to adopt an integrated and systemic approach that allows to perceive and understand how a change in one part of the system inevitably produces effects on other parts (Santillo et al., 2013). To optimize the performance of a supply chain is necessary to identify all the variables at the same time being able to formalize any such risks could alter the performance of the latter (Revetria, 2008).

Generally a risk management process involves four steps, in this order: 1) identification of the risks; 2) evaluation of the risks; 3) choice and implementation of actions to reduce the likelihood of risks and minimize the effects if they occur; and 4) monitoring of risks (Hallikas et al., 2004).
Tuncel and Alpan discuss the purpose of each of these four steps, as follows:

- The first step is aimed to identify risks in order to develop a common understanding of future uncertainties by assessing future risks, and to be ready to face them effectively.
- The second step is known as risk assessment, focusing to identify events probabilities connected with their consequences.
- The third step is to define the risk management actions to be implemented. These actions can be both reactive (when a pre-identified event really occurs) or proactive (actions to mitigate risk by

reducing the probability of occurrence or the degree of the consequences).

- The fourth step is to monitor the risk in order to detect the impacts of risks that occur and the effectiveness of the countermeasures taken.

The aim of this work is to propose a modeling diagram of a supply chain and evaluate the impact of any disruption to the system as a whole. Regarding the steps outlined above, this model proposes a solution (step 2) based on the assessment of the consequences of a disruption. This model may be used to evaluate any risk mitigation policies and even to evaluate the resilience of the supply chain (Murino et al., 2011). Supply Chain resiliency has been an interesting research topic in the last years however despite many proposed approaches only a few have defined a quantitative method for assessing the risk.

Rébula de Oliveira et al. (2017) propose a review classifying 27 papers. In these papers only 8 papers face the measurement of the consequences of risks. In particular Harland el al. (2003) classify the possible consequences of different types of risks, but does not provide an evaluation model.

Roshan Gaonkar et al. (2007) propose an integer quadratic programming model for partner selection that tries to minimize the overall cost impact from the deviation in supplier costs as long with another mixed integer-programming model for partner selection that tries to minimize the overall impact on the supply shortfall consequential from the failure of a supplier (i.e. poor performance).

Swierczek (2016) shows that there is a relationship between the intensity and span of supply chain integration and the "snowball effect" in the transmission of disruptions. The obtained findings show that the span of supply chain integration is negatively associated with the strength of the "snowball effect" in the transmission of disruptions. In addition, the results suggest that higher supply chain integration contributes to the "snowball effect" in material flows in the forward and backward transmission of disruptions.

The proposed model, using a hybrid approach (simulation and linear programming), allows to evaluate the trend of losses as well as to measure how long and on which nodes the effect of a disruption will propagate. It also takes into account the effect of a possible backup plants or a different supply strategy that may be activated in case disruption (i.e. backup products).

## 2. Problem Formulation

To implement risk mitigation actions in a supply chain, it is important to define a model for losses assessment: such task is generally considered tough due to the high number of factors connected each other.

many authors in literature suggest the use of different modeling techniques: mixed integer linear program, agent-based, system dynamics and event driven (Damiani, L., Giribone, P., Guizzi, G., 2016).

The model proposed is a hybrid modeling - Agent-based and linear programming: it allows to make an evaluation of expected losses due to disruption occurred at one of the several levels of the supply chain.

The supply chain has been defined, from an ontological point of view, through the formalization of different layers:

- location of the nodes in the supply chain
- association of the plants and related products in output to the nodes of the supply chain
- identification of materials flows between the plants

These layers allow representing the supply chain by a directed acyclic graph.

For each layer, several properties have been defined with respect to the supply chain (SC) as presented in table 1.

**Table 1: Supply Chain Properties**

| Layer | Property | Description |
|---|---|---|
| Location of the nodes | Node-ID | Identifier of the node in the SC |
| | GeoReference | City where is located the site |
| | Turnover | Annual turnover produced by the site |
| Association of the plants and related products in output to the nodes of the supply chain | Node-ID | The SC node to which the plant belongs |
| | Plant-ID | Identifier of the plant |
| | Plant-Name | Name of the plant |
| | Product | Product in output of the plant |
| | Turnover | Percentage of turnover of the site carried out by the plant |
| | WIP | Work in progress (in days) |
| | Inventory | Days in inventory (days) |
| | Product Replacement | Percentage of demand covered with alternative products in the case of the system fail |
| | Product Replacement Time | Days it takes for the product replacement activation |
| | Alternative Plant | Percentage of demand covered by a partial restoration of the plant or on an alternative plant |
| | Alternative Plant Recovery Time | Days it takes for the activation of Alternative Plant |
| | Plant-IDUp | Plant ID upstream |

| | | |
|---|---|---|
| identification of the material flows between the plants | Impact on Upstream | Percentage of production of the Plant CodeUp required by Plant CodeDown |
| | Plant-ID Downstream | Plant ID downstream |
| | Impact on Downstream | Percentage of production of the Plant CodeDown that is impacted if Plant CodeUp fail |

To demonstrate the attitude of the proposed ontology to represent a supply chain, a simple example could be used as in tables 2 to 4.

**Table 2: Example of Supply Chain: Localization of nodes**

| Node-ID | GeoReference | Turnover |
|---|---|---|
| Node A | Naples | 10.000k€ |
| Node B | Genoa | 15.000k€ |
| Node C | Caserta | 13.000k€ |

**Table 3.1: Example of Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 6 |
| Site B | GE001 | Plant GE | ProdB | 100% | 3 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |

**Table 3.2: Example of Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product-Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 5 | 30% | 3 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

**Table 4: Example of Supply Chain: identification of the materials flows between the plants**

| Plant IDUp | Impact on Upstream | Plant ID Downstream | Impact on Downstream |
|---|---|---|---|
| NA001 | 70% | GE001 | 100% |
| NA001 | 30% | CE001 | 100% |

The proposed simplified supply chain may be represented as in the following figure 1:

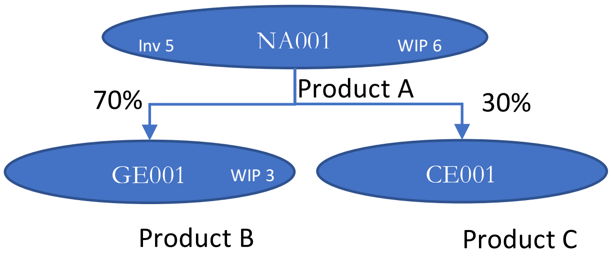


**Figure 1: Example of supply chain**

Any failure of a node in the supply chain model should impact in both the downstream and upstream supply chain. In this simple example, we can understand that, in the case of failure of NA001 node, the nodes CE001 and GE001 stop. In particular, they will stop after 5 days of the disruption since the NA001 node has an inventory of 5 days of the finished product. If the fail of GE001 node (CE001) occurs, it has no impact on CE001 (GE001). Of course, NA001 will suffer losses as a client node does not request the product. The aim of this study is to formulate a model to provide information such as:

- the trend over time of the losses in the supply chain in the case of disruption of one or more nodes / plant.

- nodes / plant impacted and after how many days from the disruption it has an effect on the node i.

To solve this problem, a hybrid model has been proposed based on agents based simulation and linear programming (Damiani, L., Giribone, P., Mzoughi et al. 2016 built using AnyLogic simulation tool with the support of Apache commons math4 optim library chosen for its attitude in solving mixed integer linear programming problems.

A Plant agent contains the parameters indicated in the above tables and in particular: ID, Name, GeoReference, WIP, Inventory, Product, ProductReplacement, ProductReplacementTime, AlternativePlant, AlternativePlantRecoveryTime, Turnover (daily).

For each agent the variables indicated in the table 5 were used do capture the agent current simulated statuses.

**Table 5: Plant agent variables**

| Variable | Description |
|---|---|
| Broken | It is a boolean value. True means that the plant is broken, False means that it is operating |
| WIPLeft | It is a counter of time to evaluate the time needed to have the first product available after a restart of the production (WIP) |
| CurrentInv | It is the current stock available. The initial value is Inventory |
| Power | It is a float value [0;1]. 0 means that the plant is stopped. 1 means that the plant is operating at 100% |
| ProductReplacement | It is a float value [0;ProductReplacement]. 0 means that the plant can't supply the product to the downstream. ProductReplacement means that downstream will be |

| | |
|---|---|
| | supplied at ProductReplacement % if plant is stopped. |
| AlternativePower | It is a float value [0;AlternativePlant]. 0 means that the plant is stopped. AlterativePlant means that the plant may be operating at AlternativePlant% if plant is stopped. |

During the simulation, each time step (one day), the model performs the following actions:

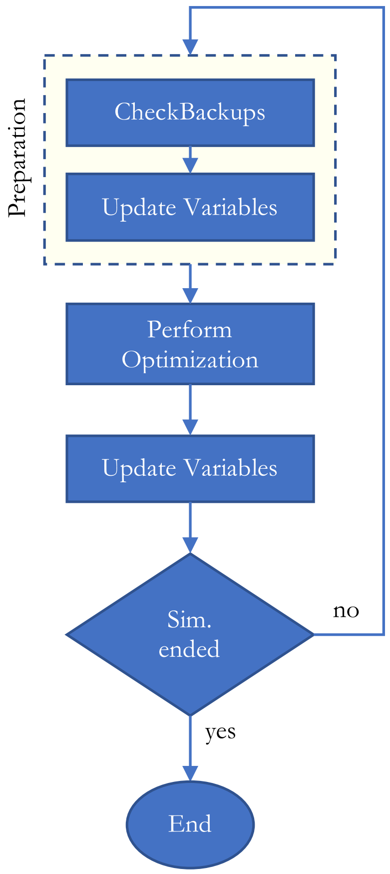


**Figure 2: Simulation Steps.**

During the preparation phase are performed the following activities:

- CheckBackups
- Update Variables

The CheckUpdate activity monitors, for each Plant of the population, whether it is stopped (due to a disruption or because they stopped other tools connected), if it is available an alternative (of the plant output or product) and if it is spent the time required for the activation of replacement (Alternative Plant Recovery Time or ProductReplacementTime). If these conditions are met Replacement (Alternative Plant and / or Product Replacement) can be operational.

The Update Variables activities perform the setting of the variables for the linear programming model.

In particular, the following variables are set each Plant:

- power.setUpperBound(capacity)

  where capacity is the maximum rate at which the plant can operate.

- AlternativePower.setUpperBound(AlternativePlant)

  where AlternativePlant is the maximum rate at which the plant can operate after a failure (if available AlternativePlant for that plant.usedInventory.setUpperBound(currentInventory) where currentInventory is the inventory available at simulation time now.

- usedProductReplacement.setUpperBound(productReplacement)
  where ProductReplacement is the maximum percentage of product available in the case failure of the plant.
- usedWIP.setUpperBound(WIPLeft) where WIPLeft is the time elapsed since of the plant restart (after a failure of the plant and consequent start if a AlternativePlant) is available.

The Perform Optimization activities perform the optimization of the flows between nodes.

The objective function is:

$$Max\ \sum_i power_i \tag{1}$$

where i are the plants of the supply chain.

The constraints on the model, for each plant, are:

$$power_i + alternative\_power_i \leq 1 \tag{2}$$

$$power_i + alternative\_power_i + usedInventory + usedProductReplacement \leq 1 \tag{3}$$

$$-power_i - alternative\_power_i + \sum_k impactdownstream_{ki} = 0 \tag{4}$$

$$-power_i - alternative\_power_i - usedInventory_i - usedProductReplacement_i - usedWIP_i + \sum_k impactupstream_{ik} + flowOutside_i = 0 \tag{5}$$

In constraint (4) refers to impactdownstream flows relating to products coming from upstream (k is an upstream node). In constraint (5) impactupstream refers to the flows towards the downstream. The sum of flows could not be less than plantpower + alternative_power. The objective function (1) is aimed at maximizing the flows in the supply chain.

At the end of the activity, Perform Optimization has carried out the Update Variables activities by the choices made. In particular, this activity consists of a series of tasks:

1) Plant check impact: for each plant (not affected) if is true this condition at simulation time now:

   $$power + alternativepower + usedWIP < 1$$

   it means that the node is affected directly or indirectly by the supply chain.

2) Plant update Inventory: if, after optimization, usedInventory>0 it implies that

$$\text{currentInventory} = \text{currentInventory} - 1.$$

Inoltre se usedWIP>0 it implies that

$$\text{WIPLeft} = \text{WIPLeft} - 1$$

3) Plant update Turnover:

$$\text{addTurnover} = \text{dailyExpectedTurnover} \cdot (power + alternativepower)$$

$$\text{currentTurnover} = \text{currentTurnover} + \text{addTurnover}$$

$$TotalExpectedTurnove = TotalExpectedTurnover + dailyExpectedTurnover$$

$$TotalCurrentLosses = TotalExpectedTurnover - currentTurnover$$

$$TotalTurnoverLosses = TotalTurnoverLosses + TotalCurrentLosses$$

### 3. Verification & Validation of the model

Validation is the process of determining whether the conceptual model is an accurate representation of the actual system being analyzed. Validation deals with building the right model.

Verification is the process of determining whether a simulation computer program works as intended (i.e., debugging the computer program). Verification deals with building the model right.

A three-step approach for developing a valid and credible model:

1. Develop a model with high face validity:
   - The objective of this step is to develop a model that, on the surface, seems reasonable to people who are familiar with the system under study.
   - This step may be achieved through discussions with system experts, observing the system, or the use of intuition.
   - It is important for the modeler to interact with the client on a regular basis throughout the process.
   - It is important for the modeler to perform a structured walk-through of the conceptual model before key people to ensure the correctness of model's assumptions .
2. Test the assumptions of the model empirically:
   - In this step, the assumptions made in the initial stages of model development are tested quantitatively. For example, if a theoretical distribution has been fitted to some observed data, graphical methods and goodness of fit tests are used to test the adequacy of the fit.
   - Sensitivity analysis can be used to determine if the output of the model significantly changes when an input distribution or when the value of an input variable is changed. If the output is sensitive to some aspect of the model, that aspect of the model must be modeled very carefully.
3. Determine how representative the simulation output data are:
   - The most definitive test of a model's validity is determining how closely the simulation output resembles the output from the real system.
   - The *Turing test* can be used to compare the simulation output with the output from the real system. The output data from the simulation can be presented to people knowledgeable about the system in the same exact format as the system data. If the experts can differentiate between the simulation and the system outputs, their explanation of how they did that should improve the model.
   - Statistical methods are available for comparing the output from the simulation model with those from the real-world system.

Therefore, for the validation of the model it was carried out with the evaluation of some test cases the result of which is known and has been carried out an assessment of any discrepancies.

### 4. Discussion and future development

The work shows how from an ontological point of view, the proposed representation can represent many supply chain. In fact, the representation of the supply chain - through nodes (representing Transport Tools or System) and streams that link the nodes - allows a simple but effective representation of the network. It also allows you to represent scenarios where backup Tool or Transportation System are present. This allows to evaluate the effect of any actions of risk mitigation as the presence of Tool or alternative transport systems having potentially different performance compared to previous Tool or Transport Systems. Moreover, thanks to a hybrid approach - simulation based on agents and linear programming - it is possible to evaluate the trend of losses (over time) depending on the number of business interruption days. Indeed, the simulation approach, unlike the exclusive use of linear programming, shows how the state (i. flows between nodes, stock level, work in progress) of the supply network changes over time. For this reason, the model can be used - during the analysis - to estimate losses in case of disruption in the AS IS supply network. Furthermore, this model can also be used during the proposed risk mitigation actions to evaluate the effect of Tool / Alternative Transportation System, the use of alternative materials or the inclusion of additional supplier in the network in order to diversify risks.

As a future development, the authors believe that other objective functions can be used in the linear programming model to be able to assign the flow of material by other criteria. The current objective function aims to maximize the overall flows in the supply chain to calculate the losses resulting a disruption, but it could be interesting to evaluate an assignment of flows - for example - as a function of minimization of the overall losses in the supply chain. The evaluation done using this objective functions can be considered as benchmark. In fact the result obtained in this way represents the best allocation of possible flows for the considered supply chain subject to a given disruption. The value of losses obtained with the previous objective function (maximization of flows) can be compared with the value of losses obtained with the new objective function (minimization of the overall losses). This will provide an indication to the risk manager about how the current assignment of the flows is far from the best possible (subject to the same disruption).

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## Appendix A. Test Cases

### A.1 Test case 1

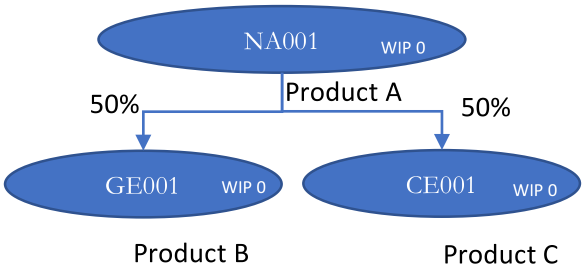


**Figure A.1: Test Case 1 of Supply chain.**

**Table A.1: Test Case 1 Supply Chain: Localization of nodes**

| Node-ID | GeoReference | Turnover |
|---|---|---|
| Site A | Naples | 10.000k€ |
| Site B | Genoa | 10.000k€ |
| Site C | Caserta | 10.000k€ |

**Table A.2.1: Test Case 1 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 0 |
| Site B | GE001 | Plant GE | ProdB | 100% | 0 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |

**Table A.2.2: Test Case 1 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

**Table A.3: Test Case 1 Supply Chain: identification of the materials flows between the plants**

| Plant IDUp | Impact on Upstream | Plant ID Downstream | Impact on Downstream |
|---|---|---|---|
| NA001 | 60% | GE001 | 100% |
| NA001 | 40% | CE001 | 100% |

If the disruption occurs at site NA001, the losses chart is shown in figure A.2.

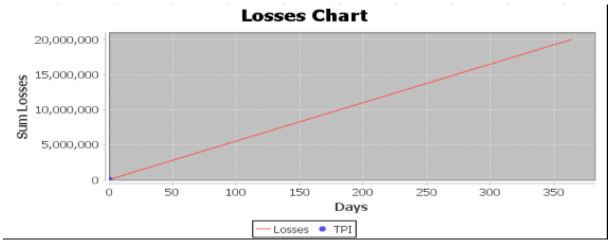


**Figure A.2: Test Case 1 of Supply chain.**

The losses result for each day (of the first 10 days) are shown in the table B.1 (see Appendix B).

In this case, as expected, the disruption of NA001 node affects immediately (day 0) all nodes. Therefore the losses for each plant are proportional to the relative daily turnover and the days of business interruption.

### A.2 Test Case 2

This test case is similar to the Test Case 1. The difference is the inventory available at the plant NA001 (10 days of inventory) as shown in the table 9.1 and 9.2.

**Table A.4.1: Test Case 2 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 0 |
| Site B | GE001 | Plant GE | ProdB | 100% | 0 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |

**Table A.4.2: Test Case 2 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 10 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

If the disruption occurs at site NA001, the losses chart is shown in figure A.3.

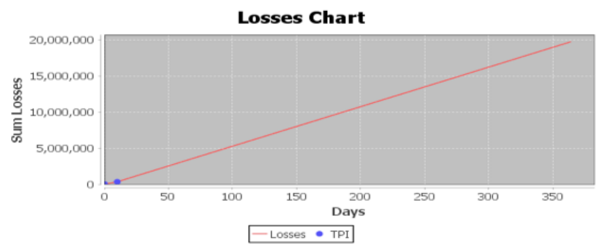


**Figure A.3: Test Case 2 of Supply chain.**

The losses result for each day (of the first 15 days) are shown in the table B.2 (See Appendix B).

In this case, as expected, the disruption of NA001 node influences, after 10 Days of Business Interruption, all nodes downstream. Therefore the losses, in a first phase are relative only to the system NA001, after 10 days are added to the losses of this plant those that are generated on the plant GE001 and CE001. These nodes are impacted after 10 days of Business Interruption.

### A.3 Test Case 3

This test case is similar to the Test Case 1. The difference is the WIP at the plant NA001 (9 days), alternative plant 40% after 3 days as shown in the table A.5.1 and A.5.2.

**Table A.5.1: Test Case 3 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 9 |
| Site B | GE001 | Plant GE | ProdB | 100% | 0 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |

**Table A.5.2: Test Case 3 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 0 | 0% | 0 | 40% | 3 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

If the disruption occurs at site NA001, the losses chart is shown in figure A.4.

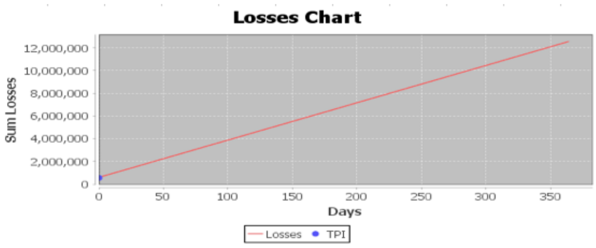


**Figure A.4: Test Case 3 of Supply chain.**

The losses result for each day (of the first 10 days) are shown in the table B.3 (see Appendix B).

In this case, as expected, the disruption of NA001 node due to the WIP causes a translation of the loss curve upwards equal to the sum of WIP * Turnover of each plant. Besides, after 3 days (alternative plant recovery time) the system starts again to 40% (power).

### A.4 Test Case 4.

This test case is similar to the Test Case 1. The difference is the WIP at the plant NA001 (9 days), product replacement 40% at the same time of the disruption as shown in the table A.6.1 and A.6.2.

**Table A.6.1: Test Case 4 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 9 |
| Site B | GE001 | Plant GE | ProdB | 100% | 0 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |

**Table A.6.2: Test Case 4 Supply Chain association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 0 | 40% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

If the disruption occurs at site NA001, the losses chart is shown in figure A.5.

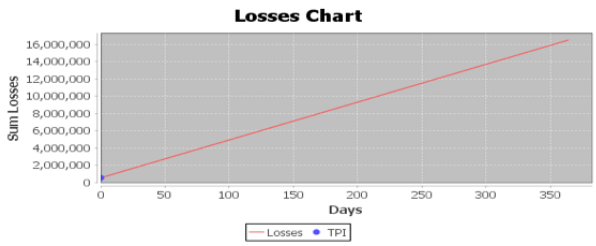


**Figure A.5: Test Case 4 of Supply chain.**

The losses result for each day (of the first 10 days) are shown in the table B.4 (see Appendix B).

In this case, as expected, the disruption of NA001 node due to the WIP causes a translation of the loss curve upwards equal to the sum of WIP * Turnover of each plant. Besides, immediately (Product Replacement Time), the system feeds the downstream node to 40% (power). Note how the NA001 plant, in this case, continues not to be operating and generate losses due to the plant downtime (power = 0).

### A.5 Test Case 5.

This test case is much more complex then the previous.

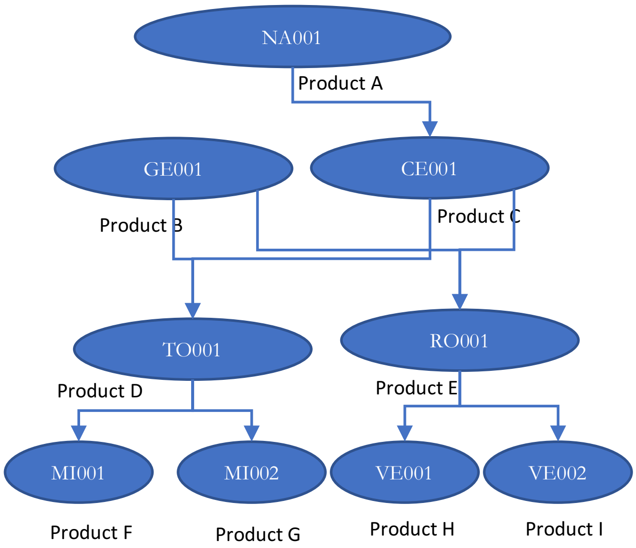


**Figure A.6: Test Case 5 of Supply Chain**

**Table A.7: Test Case 5 Supply Chain: Localization of nodes**

| Node-ID | GeoReference | Turnover |
|---|---|---|
| Site A | Naples | 10.000k€ |
| Site B | Genoa | 0k€ |
| Site C | Caserta | 10.000k€ |
| Site D | Turin | 10.000k€ |
| Site E | Rome | 10.000k€ |
| Site F | Milan | 10.000k€ |
| Site G | Venice | 10.000k€ |

**Table A.8.1: Test Case 5 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part I)**

| Node-ID | Plant ID | Plant Name | Product | Turnover | WIP |
|---|---|---|---|---|---|
| Site A | NA001 | Plant NA | ProdA | 100% | 0 |
| Site B | GE001 | Plant GE | ProdB | 100% | 0 |
| Site C | CE001 | Plant CE | ProdC | 100% | 0 |
| Site D | TO001 | Plant TO | ProdD | 100% | 0 |
| Site E | RO001 | Plant RO | ProdE | 100% | 0 |
| Site F | MI001 | Plant MI1 | Prod F | 50% | 2 |
| Site F | MI002 | Plant MI2 | ProdG | 50% | 0 |
| Site G | VE001 | Plant VE1 | ProdH | 50% | 0 |
| Site G | VE002 | Plant VE2 | ProdI | 50% | 0 |

**Table A.8.2: Test Case 5 Supply Chain: association of the plants and related products in output to the nodes of the supply chain (part II)**

| Inventory | Product Replacement | Product-Replacement Time | Alternative Plant | Alternative Plant Recovery Time |
|---|---|---|---|---|
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 10 | 0% | 0 | 0% | 0 |
| 6 | 0% | 0 | 40% | 5 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |
| 0 | 0% | 0 | 0% | 0 |

**Table A.9: Test Case 5 Supply Chain: identification of the materials flows between the plants**

| Plant IDUp | Impact on Upstream | Plant ID Downstream | Impact on Downstream |
|---|---|---|---|
| NA001 | 100% | CE001 | 100% |
| CE001 | 50% | RO001 | 100% |
| CE001 | 50% | TO001 | 100% |
| RO001 | 50% | VE001 | 100% |
| RO001 | 50% | VE001 | 100% |
| TO001 | 10% | MI001 | 100% |
| TO002 | 70% | MI002 | 100% |
| GE001 | 50% | TO001 | 100% |
| GE001 | 50% | RO001 | 100% |

If the disruption occurs at site MI001, the losses chart is shown in figure A.7.


**Figure A.7: Test Case 5 of Supply chain**

The losses result for each day (of the first 170 days) are shown in the table B.5 (see Appendix B).

In this case, as expected, the disruption of the MI001 node the presence of a WIP on affected plant causes a translation of the loss curve upwards equal to the sum of WIP * Turnover of each plant. I t shows how the disruption of MI001 determine the effects on upstream and consequently on the downstream of the other nodes of the supply chain. In fact, the plant CE001, GE001, NA001, RO001, TO001 are affected at the time of disruption. Instead, the plant VE001 and VE002 are affected by disruption only after 163 days of interruption due to the available stock on the plant TO001. Lastly, it follows that the MI002 plant is not affected by the disruption occurred on MI001.

## Appendix B. Results of Test Cases

**Table B.1: Test Case 1 Supply Chain Losses for each day**

| Business Interruption (days) | Plant | Losses |
|---|---|---|

| | | |
|---|---|---|
| 0 | NA001 | 27397,26 |
| 0 | GE001 | 13698,63 |
| 0 | CE001 | 13698,63 |
| 1 | NA001 | 27397,26 |
| 1 | GE001 | 13698,63 |
| 1 | CE001 | 13698,63 |
| 2 | NA001 | 27397,26 |
| 2 | GE001 | 13698,63 |
| 2 | CE001 | 13698,63 |
| 3 | NA001 | 27397,26 |
| 3 | GE001 | 13698,63 |
| 3 | CE001 | 13698,63 |
| 4 | NA001 | 27397,26 |
| 4 | GE001 | 13698,63 |
| 4 | CE001 | 13698,63 |
| 5 | NA001 | 27397,26 |
| 5 | GE001 | 13698,63 |
| 5 | CE001 | 13698,63 |
| 6 | NA001 | 27397,26 |
| 6 | GE001 | 13698,63 |
| 6 | CE001 | 13698,63 |
| 7 | NA001 | 27397,26 |
| 7 | GE001 | 13698,63 |
| 7 | CE001 | 13698,63 |
| 8 | NA001 | 27397,26 |
| 8 | GE001 | 13698,63 |
| 8 | CE001 | 13698,63 |
| 9 | NA001 | 27397,26 |
| 9 | GE001 | 13698,63 |
| 9 | CE001 | 13698,63 |
| 10 | NA001 | 27397,26 |
| 10 | GE001 | 13698,63 |
| 10 | CE001 | 13698,63 |

**Table B.2: Test Case 2 Supply Chain Losses for each day**

| Business Interruption (days) | Plant | Current Inventory | Losses |
|---|---|---|---|
| 0 | NA001 | 9.0 | 27397,26 |
| 0 | GE001 | 0.0 | 0,00 |
| 0 | CE001 | 0.0 | 0,00 |
| 1 | NA001 | 8.0 | 27397,26 |
| 1 | GE001 | 0.0 | 0,00 |
| 1 | CE001 | 0.0 | 0,00 |
| … | … | … | … |
| 9 | NA001 | 0.0 | 27397,26 |
| 9 | GE001 | 0.0 | 0,00 |
| 9 | CE001 | 0.0 | 0,00 |
| 10 | NA001 | 0.0 | 27397,26 |
| 10 | GE001 | 0.0 | 13698,63 |
| 10 | CE001 | 0.0 | 13698,63 |
| 11 | NA001 | 0.0 | 27397,26 |
| 11 | GE001 | 0.0 | 13698,63 |
| 11 | CE001 | 0.0 | 13698,63 |
| 12 | NA001 | 0.0 | 27397,26 |
| 12 | GE001 | 0.0 | 13698,63 |
| 12 | CE001 | 0.0 | 13698,63 |
| 13 | NA001 | 0.0 | 27397,26 |
| 13 | GE001 | 0.0 | 13698,63 |
| 13 | CE001 | 0.0 | 13698,63 |
| 14 | NA001 | 0.0 | 27397,26 |
| 14 | GE001 | 0.0 | 13698,63 |
| 14 | CE001 | 0.0 | 13698,63 |
| 15 | NA001 | 0.0 | 27397,26 |
| 15 | GE001 | 0.0 | 13698,63 |
| 15 | CE001 | 0.0 | 13698,63 |

**Table B.3: Test Case 3 Supply Chain Losses for each day**

| Business Interruption (days) | Plant | Power | Losses |
|---|---|---|---|
| 0 | NA001 | 0 | 273972,60 |
| 0 | GE001 | 0 | 136986,30 |
| 0 | CE001 | 0 | 136986,30 |
| 1 | NA001 | 0 | 273972,60 |
| 1 | GE001 | 0 | 136986,30 |
| 1 | CE001 | 0 | 136986,30 |
| 2 | NA001 | 0 | 273972,60 |
| 2 | GE001 | 0 | 136986,30 |
| 2 | CE001 | 0 | 136986,30 |
| 3 | NA001 | 0.4 | 16438,36 |
| 3 | GE001 | 0.4 | 8219,18 |
| 3 | CE001 | 0.4 | 8219,18 |
| 4 | NA001 | 0.4 | 16438,36 |
| 4 | GE001 | 0.4 | 8219,18 |
| 4 | CE001 | 0.4 | 8219,18 |
| 5 | NA001 | 0.4 | 16438,36 |
| 5 | GE001 | 0.4 | 8219,18 |
| 5 | CE001 | 0.4 | 8219,18 |
| 6 | NA001 | 0.4 | 16438,36 |
| 6 | GE001 | 0.4 | 8219,18 |
| 6 | CE001 | 0.4 | 8219,18 |
| 7 | NA001 | 0.4 | 16438,36 |

| | | | |
|---|---|---|---|
| 7 | GE001 | 0.4 | 8219,18 |
| 7 | CE001 | 0.4 | 8219,18 |
| 8 | NA001 | 0.4 | 16438,36 |
| 8 | GE001 | 0.4 | 8219,18 |
| 8 | CE001 | 0.4 | 8219,18 |
| 9 | NA001 | 0.4 | 16438,36 |
| 9 | GE001 | 0.4 | 8219,18 |
| 9 | CE001 | 0.4 | 8219,18 |
| 10 | NA001 | 0.4 | 16438,36 |
| 10 | GE001 | 0.4 | 8219,18 |
| 10 | CE001 | 0.4 | 8219,18 |

**Table B.4: Test Case 4 Supply Chain Losses for each day**

| Business Interruption (days) | Plant | Current Inventory | Losses |
|---|---|---|---|
| 0 | NA001 | 0.0 | 273972,60 |
| 0 | GE001 | 0.4 | 131506,85 |
| 0 | CE001 | 0.4 | 131506,85 |
| 1 | NA001 | 0.0 | 27397,26 |
| 1 | GE001 | 0.4 | 8219,18 |
| 1 | CE001 | 0.4 | 8219,18 |
| 2 | NA001 | 0.0 | 27397,26 |
| 2 | GE001 | 0.4 | 8219,18 |
| 2 | CE001 | 0.4 | 8219,18 |
| 3 | NA001 | 0.0 | 27397,26 |
| 3 | GE001 | 0.4 | 8219,18 |
| 3 | CE001 | 0.4 | 8219,18 |
| 4 | NA001 | 0.0 | 27397,26 |
| 4 | GE001 | 0.4 | 8219,18 |
| 4 | CE001 | 0.4 | 8219,18 |
| 5 | NA001 | 0.0 | 27397,26 |
| 5 | GE001 | 0.4 | 8219,18 |
| 5 | CE001 | 0.4 | 8219,18 |
| 6 | NA001 | 0.0 | 27397,26 |
| 6 | GE001 | 0.4 | 8219,18 |
| 6 | CE001 | 0.4 | 8219,18 |
| 7 | NA001 | 0.0 | 27397,26 |
| 7 | GE001 | 0.4 | 8219,18 |
| 7 | CE001 | 0.4 | 8219,18 |
| 8 | NA001 | 0.0 | 27397,26 |
| 8 | GE001 | 0.4 | 8219,18 |
| 8 | CE001 | 0.4 | 8219,18 |
| 9 | NA001 | 0.0 | 27397,26 |
| 9 | GE001 | 0.4 | 8219,18 |
| 9 | CE001 | 0.4 | 8219,18 |
| 10 | NA001 | 0.0 | 27397,26 |
| 10 | GE001 | 0.4 | 8219,18 |
| 10 | CE001 | 0.4 | 8219,18 |

**Table B.5: Test Case 5 Supply Chain Losses for each day**

| Business Inter. (days) | Plant | Curr. Inven-tory | Power | Losses |
|---|---|---|---|---|
| 0 | CE001 | 0 | 0,9 | 8219,18 |
| 0 | GE001 | 0 | 0,9 | 0 |
| 0 | MI001 | 5 | 0 | 41095,89 |
| 0 | MI002 | 0 | 1 | 0 |
| 0 | NA001 | 0 | 0,9 | 8219,18 |
| 0 | RO001 | 9,9 | 0,9 | 8219,18 |
| 0 | TO001 | 0 | 0,9 | 8219,18 |
| 0 | VE001 | 0 | 1 | 2739,73 |
| 0 | VE002 | 0 | 1 | 2739,73 |
| 1 | CE001 | 0 | 0,9 | 2739,73 |
| 1 | GE001 | 0 | 0,9 | 0 |
| 1 | MI001 | 4 | 0 | 13698,63 |
| 1 | MI002 | 0 | 1 | 0 |
| 1 | NA001 | 0 | 0,9 | 2739,73 |
| 1 | RO001 | 9,8 | 0,9 | 2739,73 |
| 1 | TO001 | 0 | 0,9 | 2739,73 |
| 1 | VE001 | 0 | 1 | 0 |
| 1 | VE002 | 0 | 1 | 0 |
| 2 | CE001 | 0 | 0,9 | 2739,73 |
| 2 | GE001 | 0 | 0,9 | 0 |
| 2 | MI001 | 3 | 0 | 13698,63 |
| 2 | MI002 | 0 | 1 | 0 |
| 2 | NA001 | 0 | 0,9 | 2739,73 |
| 2 | RO001 | 9,7 | 0,9 | 2739,73 |
| 2 | TO001 | 0 | 0,9 | 2739,73 |
| 2 | VE001 | 0 | 1 | 0 |
| 2 | VE002 | 0 | 1 | 0 |
| 3 | CE001 | 0 | 0,9 | 2739,73 |
| 3 | GE001 | 0 | 0,9 | 0 |
| 3 | MI001 | 2 | 0 | 13698,63 |
| 3 | MI002 | 0 | 1 | 0 |
| 3 | NA001 | 0 | 0,9 | 2739,73 |
| 3 | RO001 | 9,6 | 0,9 | 2739,73 |
| 3 | TO001 | 0 | 0,9 | 2739,73 |
| 3 | VE001 | 0 | 1 | 0 |
| 3 | VE002 | 0 | 1 | 0 |
| 4 | CE001 | 0 | 0,9 | 2739,73 |
| 4 | GE001 | 0 | 0,9 | 0 |
| 4 | MI001 | 1 | 0 | 13698,63 |
| 4 | MI002 | 0 | 1 | 0 |
| 4 | NA001 | 0 | 0,9 | 2739,73 |
| 4 | RO001 | 9,5 | 0,9 | 2739,73 |
| 4 | TO001 | 0 | 0,9 | 2739,73 |
| 4 | VE001 | 0 | 1 | 0 |
| 4 | VE002 | 0 | 1 | 0 |
| 5 | CE001 | 0 | 0,94 | 1643,84 |
| 5 | GE001 | 0 | 0,94 | 0 |
| 5 | MI001 | 0,4 | 0,4 | 8219,18 |

| | | | | |
|---|---|---|---|---|
| 5 | MI002 | 0 | 1 | 0 |
| 5 | NA001 | 0 | 0,94 | 1643,84 |
| 5 | RO001 | 9,44 | 0,94 | 1643,84 |
| 5 | TO001 | 0 | 0,94 | 1643,84 |
| 5 | VE001 | 0 | 1 | 0 |
| 5 | VE002 | 0 | 1 | 0 |
| … | … | … | … | … |
| 161 | CE001 | 0 | 0,94 | 1643,84 |
| 161 | GE001 | 0 | 0,94 | 0 |
| 161 | MI001 | 0 | 0,4 | 8219,18 |
| 161 | MI002 | 0 | 1 | 0 |
| 161 | NA001 | 0 | 0,94 | 1643,84 |
| 161 | RO001 | 0,08 | 0,94 | 1643,84 |
| 161 | TO001 | 0 | 0,94 | 1643,84 |
| 161 | VE001 | 0 | 1 | 0 |
| 161 | VE002 | 0 | 1 | 0 |
| 162 | CE001 | 0 | 0,94 | 1643,84 |
| 162 | GE001 | 0 | 0,94 | 0 |
| 162 | MI001 | 0 | 0,4 | 8219,18 |
| 162 | MI002 | 0 | 1 | 0 |
| 162 | NA001 | 0 | 0,94 | 1643,84 |
| 162 | RO001 | 0,02 | 0,94 | 1643,84 |
| 162 | TO001 | 0 | 0,94 | 1643,84 |
| 162 | VE001 | 0 | 1 | 0 |
| 162 | VE002 | 0 | 1 | 0 |
| 163 | CE001 | 0 | 0,94 | 1643,84 |
| 163 | GE001 | 0 | 0,94 | 0 |
| 163 | MI001 | 0 | 0,4 | 8219,18 |
| 163 | MI002 | 0 | 1 | 0 |
| 163 | NA001 | 0 | 0,94 | 1643,84 |
| 163 | RO001 | 0 | 0,94 | 1643,84 |
| 163 | TO001 | 0 | 0,94 | 1643,84 |
| 163 | VE001 | 0 | 0,96 | 547,95 |
| 163 | VE002 | 0 | 0,96 | 547,95 |
| 164 | CE001 | 0 | 0,94 | 1643,84 |
| 164 | GE001 | 0 | 0,94 | 0 |
| 164 | MI001 | 0 | 0,4 | 8219,18 |
| 164 | MI002 | 0 | 1 | 0 |
| 164 | NA001 | 0 | 0,94 | 1643,84 |
| 164 | RO001 | 0 | 0,94 | 1643,84 |
| 164 | TO001 | 0 | 0,94 | 1643,84 |
| 164 | VE001 | 0 | 0,94 | 821,92 |
| 164 | VE002 | 0 | 0,94 | 821,92 |
| 165 | CE001 | 0 | 0,94 | 1643,84 |
| 165 | GE001 | 0 | 0,94 | 0 |
| 165 | MI001 | 0 | 0,4 | 8219,18 |
| 165 | MI002 | 0 | 1 | 0 |
| 165 | NA001 | 0 | 0,94 | 1643,84 |
| 165 | RO001 | 0 | 0,94 | 1643,84 |
| 165 | TO001 | 0 | 0,94 | 1643,84 |
| 165 | VE001 | 0 | 0,94 | 821,92 |
| 165 | VE002 | 0 | 0,94 | 821,92 |
| 166 | CE001 | 0 | 0,94 | 1643,84 |
| 166 | GE001 | 0 | 0,94 | 0 |
| 166 | MI001 | 0 | 0,4 | 8219,18 |
| 166 | MI002 | 0 | 1 | 0 |
| 166 | NA001 | 0 | 0,94 | 1643,84 |
| 166 | RO001 | 0 | 0,94 | 1643,84 |
| 166 | TO001 | 0 | 0,94 | 1643,84 |
| 166 | VE001 | 0 | 0,94 | 821,92 |
| 166 | VE002 | 0 | 0,94 | 821,92 |
| 167 | CE001 | 0 | 0,94 | 1643,84 |
| 167 | GE001 | 0 | 0,94 | 0 |
| 167 | MI001 | 0 | 0,4 | 8219,18 |
| 167 | MI002 | 0 | 1 | 0 |
| 167 | NA001 | 0 | 0,94 | 1643,84 |
| 167 | RO001 | 0 | 0,94 | 1643,84 |
| 167 | TO001 | 0 | 0,94 | 1643,84 |
| 167 | VE001 | 0 | 0,94 | 821,92 |
| 167 | VE002 | 0 | 0,94 | 821,92 |
| 168 | CE001 | 0 | 0,94 | 1643,84 |
| 168 | GE001 | 0 | 0,94 | 0 |
| 168 | MI001 | 0 | 0,4 | 8219,18 |
| 168 | MI002 | 0 | 1 | 0 |
| 168 | NA001 | 0 | 0,94 | 1643,84 |
| 168 | RO001 | 0 | 0,94 | 1643,84 |
| 168 | TO001 | 0 | 0,94 | 1643,84 |
| 168 | VE001 | 0 | 0,94 | 821,92 |
| 168 | VE002 | 0 | 0,94 | 821,92 |
| 169 | CE001 | 0 | 0,94 | 1643,84 |
| 169 | GE001 | 0 | 0,94 | 0 |
| 169 | MI001 | 0 | 0,4 | 8219,18 |
| 169 | MI002 | 0 | 1 | 0 |
| 169 | NA001 | 0 | 0,94 | 1643,84 |
| 169 | RO001 | 0 | 0,94 | 1643,84 |
| 169 | TO001 | 0 | 0,94 | 1643,84 |
| 169 | VE001 | 0 | 0,94 | 821,92 |
| 169 | VE002 | 0 | 0,94 | 821,92 |
| 170 | CE001 | 0 | 0,94 | 1643,84 |
| 170 | GE001 | 0 | 0,94 | 0 |
| 170 | MI001 | 0 | 0,4 | 8219,18 |
| 170 | MI002 | 0 | 1 | 0 |
| 170 | NA001 | 0 | 0,94 | 1643,84 |
| 170 | RO001 | 0 | 0,94 | 1643,84 |
| 170 | TO001 | 0 | 0,94 | 1643,84 |
| 170 | VE001 | 0 | 0,94 | 821,92 |
| 170 | VE002 | 0 | 0,94 | 821,92 |