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A New Framework for Strategic Risk Analysis in a Global Pump Manufacturing Network

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Abstract. This paper presents a new risk analysis framework applied to a global production network for pump manufacturing considering strategic decisions regarding alternative suppliers and markets. External and internal risk scenarios are defined and alternative network configurations are evaluated considering the constructed risk scenarios. Inoperability of individual nodes in the global production networks caused by identified risks are determined by taking into account propagation of risks due to the interdependencies between nodes. Fuzzy arithmetic is applied to track the level of uncertainty inherent in the model parameters and the outcomes. It is demonstrated how recommendations can be made with regard to the network configuration and handling of the uncertainty in the results.

Keywords: Resilient Production Netowkrs, Collaborative Supply Networks Modelling, Risk Management, Global Production Networks, Inoperability Input Output Model, Fuzzy Arithmetic

1.1 Introduction

Global Production Networks (GPNs) are networks of globally interconnected actors, such as suppliers, production facilities, logistics providers and customers that facilitate the provision of products and services [1]. Due to the diversity in global conditions and the inherent complexity of these networks, they are subject to different risks, such as political risks, economic risks, insolvencies, accidents, delays and so on. Risks affect certain nodes or regions of the network directly, while other nodes are affected through the interdependencies within the network and as a result of risk propagation. These risks and their propagation need to be taken into account when strategic decisions, such as choosing the key partners, are being made. In this paper, we consider a real world pump manufacturing network and consider three alternative GPN configurations. These GPN configurations are then investigated and analysed with regard to risks.

In Section 1.2, the relevant literature, and the Interoperability Input Output Model used in this research, are briefly introduced. In Section 1.3, the framework for the strategic risk evaluation in GPNs is proposed, while, in Section 1.4 the three alternative GPN configurations for the pump manufacturing network are presented. Furthermore, in Section 1.5 a number of external and internal risk scenarios are introduced by providing the relevant details such as risk likelihood and its impact. Section 1.6 provides the results of the inoperability model and the expected loss of risk, defined here as the expected reduction of financial revenue arising from the anticipated risk. Finally, section 1.7 provides concluding remarks and future directions.

1.2 Literature Review

Supply chain risk has been extensively studied in recent years. We review some of the relevant literature. [2] considers the processes for risk management in complex supply networks with strategic collaborations. [3] provides a classification of supply chain risk by conducting a comprehensive survey of the literature. Furthermore, [4] conceptually examines the levels and dimensions of risk propagation. Additionally, [5] uses both network theory and Monte Carlo simulation to investigate bottleneck identification in supply networks. Also, in an interesting study about project management risks, [6] describes a real case of utilising causal maps to engage with the stakeholders to develop a comprehensive risk profile. We refer interested readers to [7] for a comprehensive review of supply chain risks literature.

Our analysis of impact of risk and its propagation is based on Inoperability Input Output Model (IIM) [8]. IIM examines risks and inoperability, i.e. deviation from the planned productivity level, within the economic sectors. Among the IIM literature, [9] introduces a dynamic variation of the IIM while others incorporate fuzzy uncertainties [10–13]. To the best of our knowledge, [14] is the only other application of IIM on supply networks, where the effect of disruptions on an example network is investigated using the IIM model and a multi-criteria method for interdependencies. However, uncertainties in the GPN and dynamism in the disruptions have not been considered.

In this paper, a pump manufacturing network is studied by considering the strategic decisions that need to be made with regard to its suppliers and customers. We apply a fuzzy dynamic variation of the IIM to analyse the impact of risks described in the risk scenarios on the alternative GPN configurations.

1.3 Strategic Risk Evaluation in Global Production Networks

The purpose of strategic risk evaluation of GPNs is to determine the suitability of alternative GPN configurations with respect to the identified risk criteria. The risk criteria that can potentially affect the company are defined in a set of risk scenarios. The analysis is done using all risk scenarios imposed on each of the GPN configurations and the results obtained for each scenario are aggregated to determine risk indicators including average inoperability and expected loss of risk, of each of the GPN configurations.

The framework of this evaluation is shown in Fig. 1.1.

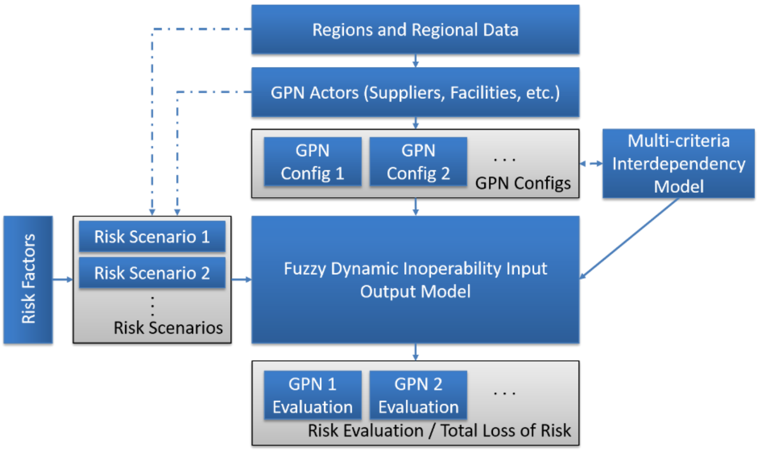

Fig. 1.1. Framework of the Risk Evaluation of GPNs

The framework requires inputs including the interdependency values of all GPNs, perturbation impact and timings for all scenarios, the intended revenue of each node, resilience of the nodes to risk, regions and locations of each node within regions and also likelihood of each scenario. Furthermore, the framework evaluates each GPN by determining the inoperability value of nodes for each risk scenario as well as the loss of risk due to the inoperability. We will discuss each of these inputs and outputs further in the following sections.

Most inputs and outputs of the framework, such as interdependencies, perturbation impact, intended revenue, resilience, likelihood, inoperability and loss of risk, are assumed to be uncertain. To model these uncertainties, we utilise triangular fuzzy numbers in the form of [a, b, c] where ‘a’ represents the lowest possible value, ‘b’ identifies the most likely value and ‘c’ is the highest possible value. It is possible to use linguistic terms, such as low, medium and high, to describe the inputs which are then translated into triangular fuzzy numbers.

GPN configurations rely on GPN actors data (such as suppliers, production facilities, etc.) that is, in turn, dependent on regional data on various actors’ locations. In addition, a multi-criteria interdependency model is used to determine the rate of dependency between GPN actors. The criteria included in the method include trade volume, inventory, substitutability of the product or supplier, distance and collaboration agreement. Risk scenarios are based on risk factors that represent the conceptual categories of risk, and are defined over either regions or actors.

A novel Fuzzy Dynamic Inoperability Input Output Model (FDIIM) is developed that uses fuzzy arithmetic to track uncertainty, from inputs to derived outcomes. It determines the inoperability of individual nodes in a GPN by considering the initial perturbations as well as the propagation of the perturbations to the related nodes. The level of inoperability shows the deviation of the node operation from its intended operation level, and is also used to estimate the financial loss of risk. FDIIM is presented in Appendix.

1.4 Alternative Configurations for the GPN

The framework for the risk evaluation is described using as an example a pump manufacturing GPN and considering three possible configurations. The first configuration includes four suppliers for base constituents, hydraulic components, control unit and electric motor in Europe and an additional supplier for electric motors in Asia. All the supplies are delivered to the main assembly plant in Europe, either directly or through a delivery company for electric motors. Then, the finished products in the assembly plant can be delivered to customers in either Asia or Europe. See Fig. 1.2. for a visualisation of the network configuration.

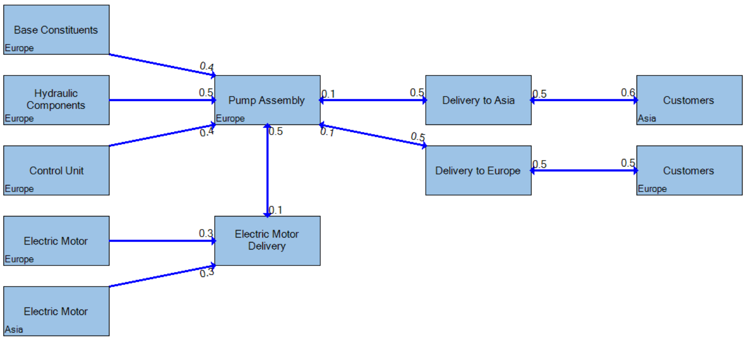

Fig. 1.2. Configuration 1 for the pump GPN

Configuration 2 has a single difference compared to Configuration 1 where the electric motor supplier in Asia is being excluded from the network and only the supplier in Europe is being utilized for sourcing electric motors. The network configuration is presented in Fig. 1.3.

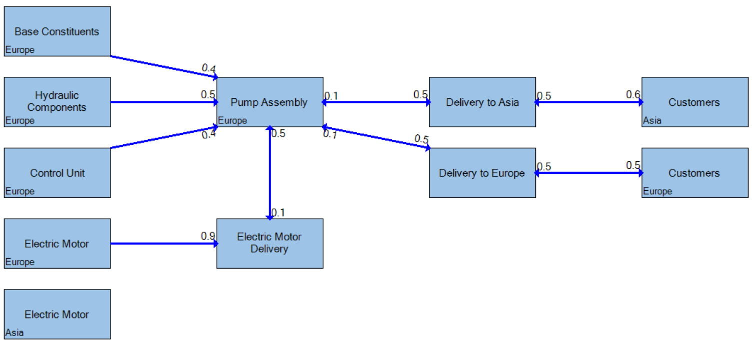

Fig. 1.3. Configuration 2 for the pump GPN

Configuration 3 considers the case that the products are only sold in the European market. This configuration is shown in Fig. 1.4.

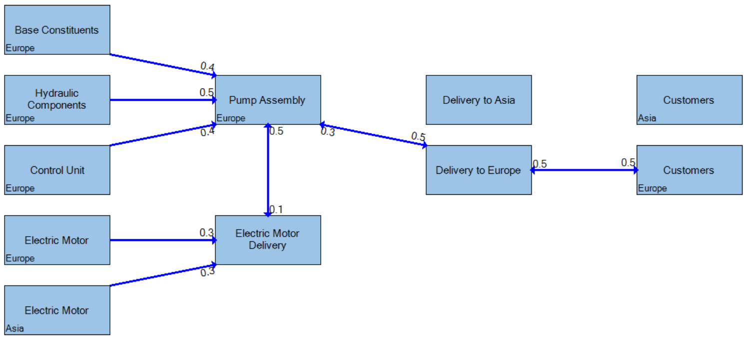

Fig. 1.4. Configuration 3 for the pump GPN

1.4.1 Regions

Regions play an important role in determining the impact of external risks on the GPNs. Nodes can be differently affected based on their region and this is identified in the configurations described above.

In the proposed case, two main regions are considered: Europe and Asia. Nodes within each region will be affected by the risks relevant to that particular region.

1.4.2 Interdependencies

The interdependencies measure the dependency of the dependent nodes on the supporting nodes. The numbers on the actors' links in Fig. 1.2., 1.3. and 1.4. show the relative percentage of the dependent node operation that can be affected per unit of inoperability in the supporting node. Calculating this information directly through statistical methods is extremely difficult, if not impossible. Instead, we use a fuzzy multi criteria method that allows the experts to use their judgements to determine the interdependency values and their confidence in the estimated values. Both estimated values and confidence are described using linguistic terms, including very low, low, fairly low, medium, fairly high, high and very high, and modelled using fuzzy sets. The fuzzy values and the corresponding confidence are aggregated and defuzzified into scalar values which best represent obtained aggregated fuzzy values. These defuzzified results are shown as labels on the arrows in Fig. 1.2., 1.3., and 1.4.

It is interesting to point out that value of interdependency has an inverse relationship with the substitutability of the supplier. In the provided example, in Configuration 1 where both electric motor suppliers in Europe and Asia are present, the interdependency between them and the electric motor delivery is set to 0.3, while, in Configuration 2, when the electric motor supplier in Europe is the only option, the interdependency rate is 0.9. A similar issue can be observed in Configuration 1 and 3, in the interdependency rate of the pump assembly and the two markets.

1.5 Risk Scenarios

Two types of risks are considered: those directly affecting the individual actors and those that are due to regional issues that can have an equal impact on all actors within the region. For each of these two types of risks, a set of risk scenarios are constructed. These scenarios are introduced in the following sections.

1.5.1 External Risks

With regard to Europe, two risk scenarios are constructed:

1) Economic Issues: the risk of Europe being hit with economic issues, such as recession or inflation is considered. It is estimated that each company operating in Europe will have a perturbation with an impact of [0.7, 0.8, 0.9] (triangular fuzzy number) for 40 periods with a likelihood of [0.02, 0.03, 0.04]. As mentioned earlier, user estimates the parameters of the model by entering triangular fuzzy numbers which determine the lowest possible value, the most likely value and the highest possible value of the parameter.
2) Compliance Risk: The risk of a new legislation which can significantly affect the operation of partners in Europe is considered. A perturbation impact is estimated as [0.3, 0.4, 0.5] for 10 periods with a likelihood of [0.05, 0.1, 0.15].

Also, two risk scenarios relevant to Asia are defined:

1) Social Unrest: This risk is related to possible social unrest as a result of political conflicts or economic problems. The scenario includes a perturbation with an impact of [0.7, 0.8, 0.9] for 20 periods with a likelihood of [0.05, 0.1, 0.15].
2) Embargo: this is risk of countries within Asia to be put under embargo. It includes a perturbation with an impact of [0.8, 0.9, 1] for 30 periods with a likelihood of [0.01, 0.02, 0.03].

1.5.2 Internal Risks

Internal risks affect individual nodes within the network. These could be related to individual suppliers, production facilities, logistics providers or customer markets. The following internal risk scenarios are considered:

1) Strike in the supplier of Electric Motor in Asia: It includes a perturbation with an impact of [0.9, 1, 1] for 20 periods on the electric motor supplier in Asia with a likelihood of [0.05, 0.1, 0.15].
2) Transport accident in delivery to Asia: It includes a perturbation with an impact of [1, 1, 1] for 10 periods on 'Delivery to Asia' with a likelihood of [0.1, 0.2, 0.3].
3) Temporary unavailability of pump's base constituents: It includes a perturbation with an impact of [0.7, 0.8, 0.9] for 20 periods on 'Base Constituents' with a likelihood of [0.1, 0.2, 0.3].
4) Custom issue in Asia affecting Delivery to Asia: where the deliveries to Asia are delayed or impounded by customs. It includes a perturbation with an

impact of [0.1, 0.2, 0.3] for 10 periods on 'Delivery to Asia' with a likelihood of [0.1, 0.15, 0.2].

5) Insolvency of European customers: It includes a perturbation with an impact of [0.8, 0.9, 1] for 10 periods on 'Customers – Europe' with a likelihood of [0.005, 0.01, 0.015].

1.6 Analysis of Results

As mentioned earlier, the FDIIM is applied to each of the network configurations for all risk scenarios. This results in determining the inoperability of each node within the network for each of the risk scenarios over the time horizon. These results are aggregated in two ways: first, the average inoperability of nodes for all scenarios and over the time horizon is calculated, which gives an indication of the average susceptibility of the node in the configuration under consideration to the risks. In the second, the expected loss of risk in each GPN configuration is determined. Loss of risk is the financial impact of the risks that is calculated in the inoperability model as the product of the intended revenue of the operations of a node and the calculated inoperability of the node (presented in Appendix).

1.6.1 Nodes Inoperability

In Table 1.1. the average value of inoperability of all nodes and the configurations aggregated over the time horizon and all the risk scenarios are presented. It can be noted that in all the three configurations, pump assembly, delivery to Europe and customers (Europe) are among the most affected. However, in the first two configurations that include supply of pumps to customers in Asia, customers (Asia) and Delivery to Asia have had a higher inoperability, while, in Configuration 3, customers (Asia) and delivery to Asia have very little inoperability which is due to isolated impact of risk scenarios that directly affect Asia and Asian customers. Additionally, suppliers of base constituents, hydraulic components, control unit and electric motor have the same inoperability values across the GPN configurations. This is due to the fact that these suppliers are assumed to have no dependency on the other nodes in the configurations and they are only affected by direct perturbations, which is the same for all configurations.

Table 1.1. Average inoperability of nodes for all three GPN configurations

Node	**Configuration 1**	**Configuration 2**	**Configuration 3**
Base Const. (Europe)	[0.09, **0.1**, 0.11]	[0.09, **0.1**, 0.11]	[0.09, **0.1**, 0.11]
Hydraulic Comp. (Europe)	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]
Control Unit (Europe)	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]
Electric Motor (Europe)	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]	[0.06, **0.07**, 0.08]

Electric Motor Delivery	[0.03, **0.07**, 0.13]	[0.05, **0.08**, 0.11]	[0.03, **0.07**, 0.13]
Electric Motor (Asia)	[0.11, **0.12**, 0.13]	[0.11, **0.12**, 0.13]	[0.11, **0.12**, 0.13]
Pump Assembly (Europe)	[0.11, **0.15**, 0.24]	[0.1, **0.13**, 0.19]	[0.11, **0.15**, 0.22]
Customers (Europe)	[0.11, **0.13**, 0.2]	[0.11, **0.13**, 0.17]	[0.11, **0.13**, 0.19]
Customers (Asia)	[0.13, **0.17**, 0.26]	[0.13, **0.17**, 0.24]	[0.07, **0.08**, 0.09]
Delivery to Asia	[0.11, **0.18**, 0.32]	[0.11, **0.16**, 0.27]	[0.02, **0.02**, 0.02]
Delivery to Europe	[0.09, **0.14**, 0.25]	[0.08, **0.13**, 0.2]	[0.09, **0.14**, 0.22]

1.6.2 Expected Loss of Risk

For the purpose of identifying financial loss, only nodes that are adding value to the company will be considered. In this example, only electric motor supplier in Europe and pump assembly that are subsidiaries of the main company are considered to be generating revenue. Using experts opinion, intended revenues for electric motor supplier in Europe and pump assembly are estimated as [190000 €, 200000 €, 210000 €] and [990000 €, 1000000 €, 1010000 €] respectively. Table 1.2. shows the expected loss of risk, aggregated considering all the risk scenarios for each of the configurations.

Table 1.2. Expected loss of risks for all three configurations

GPN	Expected Loss of Risk
Configuration 1	[1,723,488 €, **5,110,298 €**, 14,796,154 €]
Configuration 2	[1,623,458 €, **4,428,031 €**, 11,924,483 €]
Configuration 3	[1,836,773 €, **4,947,313 €**, 12,288,945 €]

The expected loss of risk is lower for Configuration 2 in comparison with Configuration 1. So, the use of both suppliers in Europe and Asia for electric motors is not justified as it increases the risk. This is especially unacceptable, as having two suppliers in comparison with just one is usually done at a financial cost, mainly with the goal of significantly reducing risks.

Also, we see a lower loss in Configuration 3 in comparison with Configuration 1, which means focusing on European Customers only reduced the risk. However, it is important to point out that this analysis only considers the risk perspective while other criteria, such as revenue, could compensate for the increased risks.

Furthermore, as it can be observed from both Table 1.1. and Table 1.2., the uncertainty levels are quite high in the analysis. For example, the highest possible value of inoperability for pump assembly in Configuration 1 is almost 70% higher than the most likely value. This problem is even more obvious in the loss of risks, as the highest possible loss of risk for the Configuration 1 is near three times as much as the most likely value. This uncertainty is due to the uncertainty in the inputs of the model, including the interdependency values, impact, likelihood and intended revenue. More precise data would generate results with smaller uncertainty associated with them!

1.7 Conclusions

In this paper, strategic risk analysis for a pump manufacturing network has been investigated. The analysis is based on the FDIIM we developed, which determines the propagation of risks due to interdependencies between nodes, and uses fuzzy arithmetic to track uncertainty levels in the parameter values. To illustrate the framework for strategic risk analysis proposed, three GPN configurations are defined and analysed with respect to a set of external and internal risk scenarios. The configurations differ in using an alternative supplier for electric motors and also in the market they supply. It is demonstrated how the framework can be used to decide by GPN configuration with respect to risk, for example, which suppliers to use, which market to target and so on. In addition to risk analysis, GPN configurations should be analysed considering an economic aspect. This is a direction of our current research.

Appendix: Fuzzy Dynamic Inoperability Input Output Model

A vector representation of the fuzzy dynamic inoperabiltiy input output model function is as follows:

$$\tilde{q}(t+1) = \tilde{K}\widetilde{A^*}\tilde{q}(t) + \tilde{K}\widetilde{c^*}(t) + \left(I - \tilde{K}\right)\tilde{q}(t) \tag{1.1}$$

where $\tilde{q}(t+1)$ is the vector of fuzzy inoperability of nodes at time period $t+1$, $\tilde{K}$ is the fuzzy diagonal matrix of resilience, $\widetilde{A^*}$ is the fuzzy interdependency matrix and $\widetilde{c^*}(t)$ is the fuzzy perturbation of nodes for the risk scenario under consideration at time period t. Resilience represents the speed that the node can recover from disruptions.

The expected loss of risk for all risk scenarios is calculated as follows:

$$\tilde{Q} = \widetilde{x^T} \sum_{s=1}^{S} \widetilde{p_s} \sum_{t=1}^{T} \widetilde{q_s}(t) \tag{1.2}$$

where $\tilde{Q}$ is the fuzzy loss of risk for the GPN configuration, $\widetilde{x^T}$ is the transposed vector of the fuzzy intended revenues of the nodes, S is the number of risk scenarios, $\widetilde{p_s}$ is the fuzzy likelihood of risk scenario s, T is the number of time periods in the time horizon and $\widetilde{q_s}(t)$ is the fuzzy inoperability vector of nodes in scenario s at time period t.

The FDDIM method have been described in more details in [15].

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