Improving the Supply Chain Efficiency Based on Reliability Analysis

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***Abstract*—One of the objectives of every company is to minimize disruption to its operation. It is an axiom of business that no business stands alone. The reliability of any business depends in part on the reliability of its upstream business partners. As a consequence, the level of disruption to a company's operations depends in part on the reliability of its upstream business partners. Every supply chain is composed of a network of businesses where each depends on upstream business for supplies and services. A reliability chain exists along supply chains. This paper models for improving supply chains efficiency by designing SC that is robust (i.e., perform well with respect to uncertainties in the data, such as demand) and reliable (i.e., perform well when parts of the system fail).**

Keywords—Supply chains and networks; robustness; reliability analysis; risk management.

I. INTRODUCTION

Modern supply chains face various challenges caused by uncertainty. On one hand, customers are more demanding than ever on service and product qualities. On the other hand, in light of highly volatile demands, many supply chain decisions involve a high degree of risk and channel members will suffer if the supply chain is not sufficiently robust.

Today's business environment has become an international playing field in which companies have to exceed logistics performance, i.e. markets require full responsiveness, high quality products and high reliability of supply chains in small time period and with the lowest cost. As a consequence, supply chains have excluded most non-value adding activities and have become leaner. However, lean supply chains without much inventory are more vulnerable to disturbances in logistic processes, which mean that they might be less consistent in their performance, i.e. are less [1]. Therefore, the competitive power of vulnerable supply chains in the market may diminish. In practice, in recent years there have been reported many events that have led to disturbances in supply chains processes (e.g. supplier failures caused by natural disasters or fires in the warehouses, delivery delays due to traffic accidents, product recalls due to lack of fulfillment of quality or safety requirements, etc.). Because of that, there is increasing interest by practitioners and academics to reduce supply chain vulnerability and design robust supply chains.

In supply chain literature robustness is mainly considered as the ability of a system to continue to function well in the event of a disruption, i.e. an unexpected event that severely impacts performance. A literature review on supply chain robustness shows that there is a lack of an integral methodology that guides companies in managing disturbances and designing robust supply chains. With this paper we aim to contribute to supply chain management theory by developing such an integrated methodology for the design robust supply chain.

In this paper we consider supply chain system as a typical complex system, which is characterized by its components. The importance reliability analysis allows to estimate the influence of each supply chain system component to the system reliability, its functioning and failure.

The paper is organized as follows. Section 2 discusses what supply chain risk management and robustness is in the state of the art. Section 3 presents the model for designing robust supply chain, and here we focus on the following elements: supply chain disturbances, sources of vulnerability and redesign strategies. Section 4 presents a mathematical model that allows for the estimation of the influence of each supply chain system component to the system efficiency and reliability, its functioning and failure. Section 5 presents the application of the research methodology in the case study. Section 6 concludes the paper with limitations and future research opportunities.

II. LITERATURE REVIEW

Recent papers show increasing interest in decision-oriented approaches to financial performance and risk management. Guillen optimize change in equity as a financial performance metric in their approach for integrated supply chain planning and scheduling in the chemical industry. Comelli combine supply chain master planning with activity-based costing for aggregated supply chain processes. Bertel maximize average cash position in their decision model for operational supply chain planning based on a flow shop scheduling formulation [2,3].

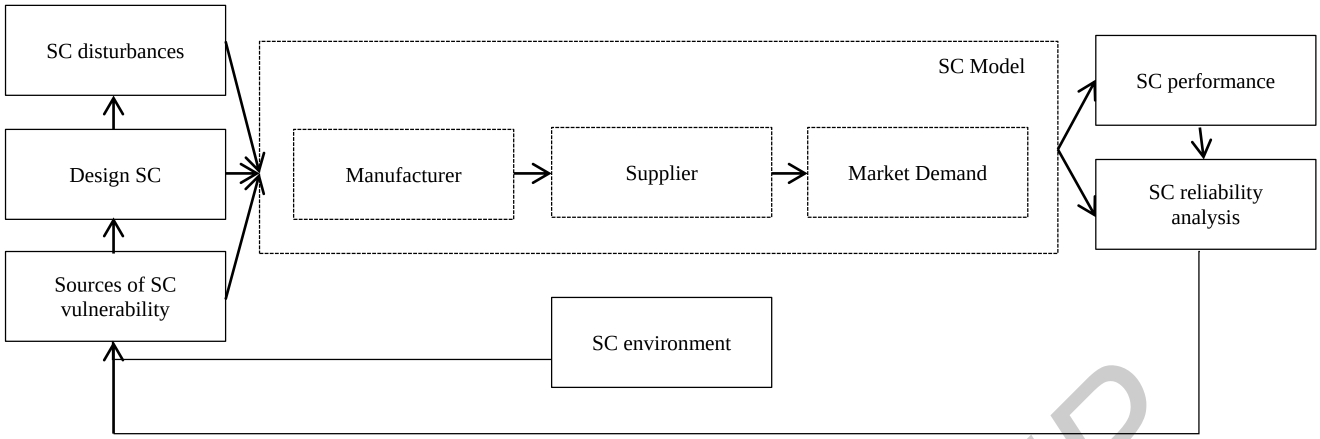

Fig. 1. Model for designing robust supply chain

OR-based approaches to risk management mainly focus on the physical domain of supply chain management and omit financial implications [3]. Pongsakdi and You provide two-stage stochastic programming approaches to risk management in chemical supply chains. Pongsakdi investigate a case study in refinery operations planning and utilize risk curves as well as the sample average approximation method to reduce risk impact. You evaluate different risk metrics and their implications for global supply chain planning [4]. Multi-stage frameworks for risk management are provided in Goh and Sodhi and Tang. However, only Sodhi and Tang consider material and financial flows simultaneously in their approach to supply chain risk management motivated by asset–liability management [4].

A large body of literature deals with stochastic production and supply chain planning to cover different sources of risk. Robust optimization methods according to the aforementioned concepts are applied to problems in supply chain master planning at the mid-term level in Yu and Li and Leung. Eppen, Bok, and Aghezzaf investigate robust approaches to capacity expansion and facility location planning at the long-term level [5,6].

In summary, stochastic programming and robust optimization methods are prevalent in physical supply chain planning as well as financial performance and risk management. However, current decision frameworks only consider selected aspects and do not provide a comprehensive robust approach to value-based performance and risk optimization. Therefore, we extend the value-based optimization approach towards a robust framework for integrated performance and risk management. Implications for scenario generation are considered to account for robustness from both the data and the decision model perspective.

III. SUPPLY CHAIN RESEARCH MODEL

SC risk can include a variety of factors with potential impact on any organization’s activities, processes, and resources. External factors can result from economic change, financial market developments, and dangers arising in political, legal, technological, and demographic environments. Most of these are beyond the control of a given organization, although organisations can prepare and protect themselves in time-honoured ways. Internal risks include human error, fraud, systems failure, disrupted production, and other risks. Often systems are assumed to be in place to detect and control risk, but inaccurate numbers are sometimes generated for various reasons. Organizations of all types need robust, reliable systems to control risks that arise in all facets of life. Differences between SC risk management and traditional risk management were compared by Banham as shown in Table 1 [6].

I. DIFFERENCES BETWEEN SC RISK MANAGEMENT AND TRADITIONAL RISK MANAGEMENT

Traditional risk management	**SC risk management**
Risk as individual hazards	Risk viewed in context of business strategy
Risk identification and assessment	Risk portfolio development
Focus on discrete risks	Focus on critical risks
Risk mitigation	Risk optimisation
Risk limits	Risk strategy
Risks with no owners	Defined risk responsibilities
Haphazard risk quantification	Monitoring and measurement of risks
‘Risk is not my responsibility’	‘Risk is everyone’s responsibility’

Tools of risk management can include creative risk financing solutions, blending financial, insurance and capital market strategies [7]. Capital market instruments include catastrophe bonds, risk exchange swaps, derivatives/ options, catastrophe equity puts (cat-e-puts), contingent surplus notes, collateralised debt obligations, and weather derivatives. In this paper we consider supply chain reliability as the degree to which a supply chain shows an acceptable performance in its Key Performance Indicators (KPIs) during and after an unexpected event that caused disturbances in one or more logistics processes. To operationalize this definition, a supply chain is robust with respect to a KPI if the value of that KPI, adequately measured over an observation period, is sustained in a predefined desired range, even in the presence of disturbances. We call this predefined desired range the Robustness Range, and it is characterized by a lower and/or upper level. If a KPI performs above or below the robustness range, the supply chain is considered vulnerable. The stronger and longer the negative impact to performances is, the more vulnerable supply chain is to that disturbance.

The literature provides many definitions of supply chains, but in general it can be said that a supply chain is a group of actors that perform specific roles and processes linked to each other via goods, information and money flows, using specific infrastructures aiming to fulfill consumer wishes at lowest cost [3]. Based on this definition we use the term supply chain scenario to describe the supply chain instance at hand. A supply chain scenario is an internally consistent view of a possible instance of the logistics supply chain concept.

“Fig. 1” presents the research model for increasing robust supply chain efficiency. According to Viswanadham and Gaonkar, an increased awareness of the existence of supply chain disturbances and their causes may enable better preparedness for handling or preventing them. In other words, the sources of vulnerability and related disturbances are the base for determining appropriate redesign strategies, i.e. strategic as well as tactical plans and operational actions that should increase the robustness level [8]. The implementation of an appropriate redesign strategy implies a change in one or more elements of the supply chain scenario. As a result either the vulnerability source is eliminated (and therefore the frequency of disturbance is reduced) or the system becomes less vulnerable as the domino effect is disabled (and therefore the impact of disturbances in the supply chain is reduced). For example, the impact of a disturbance in the delivery of raw materials is reduced either by having buffer stocks or one eliminates or reduces the occurrence of such a disturbance by sourcing from multiple suppliers and having timely information that could trigger emergency actions. Alternatively the impact of a raw material delivery disturbance to a shortage of final products can be reduced by keeping a higher inventory level of final products.

In the supply chain management literature, there are only a few papers that focus on a definition and characterization of disturbances. Svensson introduced a conceptual definition of disturbance. He defined disturbance as “a deviation that causes negative consequences for the firm involved in the supply chain”. Melnyk on the other hand defined supply chain disturbance from an operational viewpoint as the output of a chain of events triggered by an unexpected event at one point in the supply chain that adversely affect the performance of one or more components located elsewhere in the supply chain. In line with Melnyk we define supply chain disturbance as a minor or major deviation, or failure of one or more logistics processes triggered by unexpected events in the supply chain or its environment resulting in poor performance of the process itself, company and potentially along the supply chain in a given time period [9].

In line with work of Scipioni, disturbances can be characterized by a number of elements, i.e. the frequency of occurrence, the possibility of detection and the impact on supply chain performance. According to Svensson causes of disturbances are related to volume and quality [9]. Causes of disturbances in volumes are related to a lack of materials for downstream activities in the chain, and we refer to it as the quantitative dimension of disturbances as it considers unexpected changes in quantity of materials. Causes of disturbances in product quality are related to deficiencies in materials in the supply chain, and we refer to it as the qualitative dimension of disturbances as it considers unexpected changes in quality of materials. We extend the disturbance classification of Svensson by adding the time dimension of disturbances that is related to unexpected changes in the beginning or ending of process realization, or process duration (i.e. delays or idle times).

In the end, the impact of disturbances on robustness of supply chain performances is crucial. In principle, the impact of a disturbance depends on the flexibility and responsiveness of the supply chain to adapt to the new situation caused by an unexpected event. Therefore, the impact of a disturbance can be local (e.g. delivery failure can have local impact on transport performance, but it will not jeopardize the production process if there is enough inventory or if a backup delivery option exists) or system wide (e.g. harvest failure or animal diseases outbreak can cause lack of raw material, which effects will be transmitted through the whole chain). In both cases, the causality of events has to be considered because a disturbance in one process can cause a domino effect and affect other processes and cause amplification of the impact [10]. The Bullwhip effect can be also seen as a system wide impact of disturbances in demand along the chain.

IV. RESEARCH METHODOLOGY

The main objective of the research methodology is that it helps in determining the best supply chain scenario that will enable robust supply chain performances for given circumstances. When we overview and integrate the literature on supply chain robustness and combine it with the findings of workshops and interviews [1], we find the following common steps that are relevant in this design process:

1) The description and analysis of the supply chain scenario for a particular case and the identification of KPIs;
2) The identification of unexpected events and disturbances that affect performances;

3) The assessment of performances, i.e. how much and how long can the supply chain withstand disturbances?
4) The identification of sources of vulnerability that explain process disturbances, and as such, wvhich may (strongly) affect the robustness of performance and eventually increase the vulnerability of the supply chain.
5) The identification of appropriate redesign strategies that eliminate disturbance by acting on sources of vulnerability or that reduce the impact of the disturbance by disabling the domino effect to other processes and supply chain performances.

Supply chain system is a typical complex system, which is characterized by its components. In our context we consider suppliers as components of supply chain. To analyze robustness and reliability we propose to consider supply chain model as multiple state system (MSS). MSS is mathematical model in reliability analysis that is used for description system with some (more than two) levels of performance (availability, reliability). MSS allows presenting the analyzable system in more detail than traditional Binary-State System. We use reliability analysis of MSS developed by Zaitseva [12].

In MSS is proposed, that system model for reliability analysis consist of n components. The system components are denoted as x_i (i = 1,…, n). A system and its every component have two states of efficiency: “zero” designates system or component failure (is not working) and state “one” declares of working of system or its component. The system reliability (system state) is depends on its components efficiency and is defined by the structure function:

$$\varphi(x_1, \ldots, x_n) = \varphi(x): \{0, 1\}n \rightarrow \{0, 1\} \qquad (1)$$

Every system component x_i is characterized by probability of the performance rate:

$$p_i = Pr\{x_i = 1\} \text{ и } r_i = (1 - p_i) = Pr\{x_i = 0\} \qquad (2)$$

The definition of structure function (1) is well known as the definition of Boolean Function [12]. This condition permits to use tools of Boolean Function analysis for the structure function measure. The dynamic properties of Boolean Function are revealed through Logic Deferential Calculation [13]. Therefore this tool can be used for the analysis of dynamic properties of structure function too.

Prof. Ryabinin have used Logical Derivatives [13]:

$$\partial\varphi(x)/\partial x_i = \varphi(1_i, x) \oplus \varphi(0_i, x), \qquad (3)$$

There are two kinds of dynamic reliability indices: Component Dynamic Reliability Indices (CDRIs) and Dynamic Integrated Reliability Indices (DIRIs) [14]. CDRIs are declared as the probability of the system failure and repair if the state of the i-th system component changes. DIRIs are another kind of DRIs and represent the probability of the system reliability changes with a modification of one or fixed system component states.

CDRIs of a system failure is the probability of the system failure that is caused by breakdown of the i-th component:

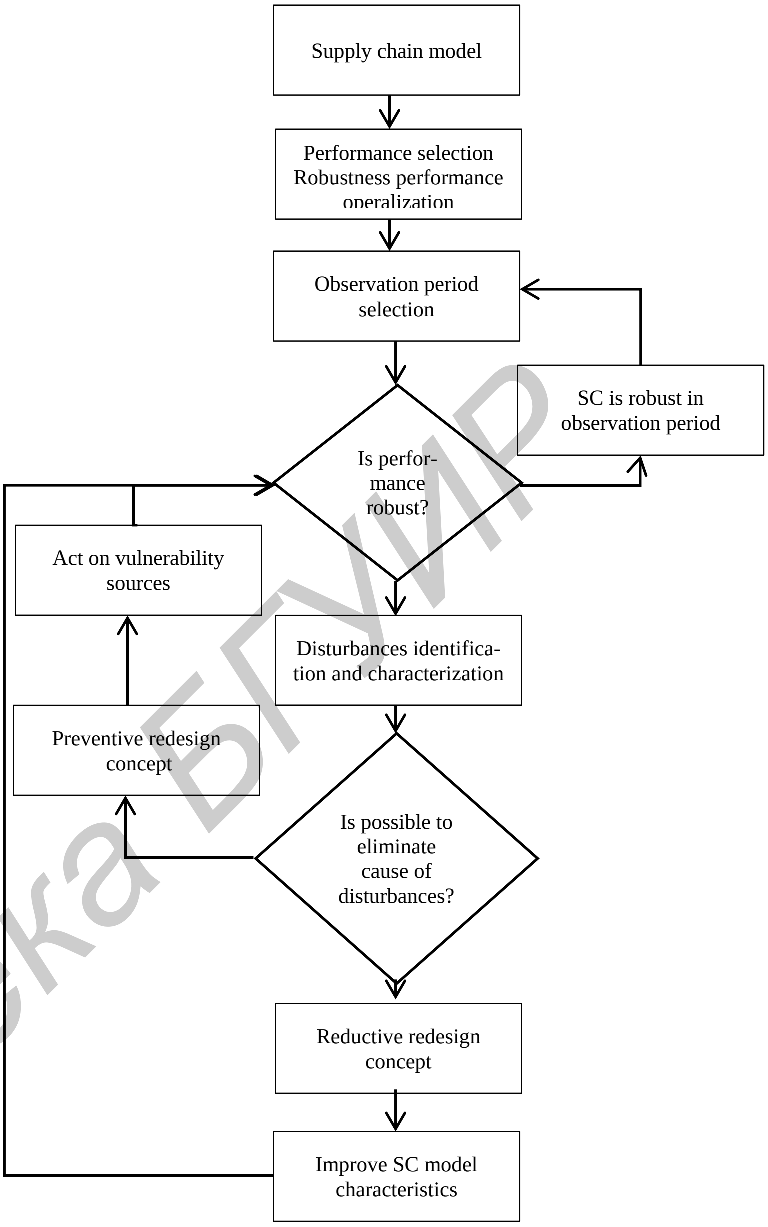

Fig. 2. The SC reliability analysis process

$$P_f(x_i) = (\rho / \rho_1) * r_i \qquad (4)$$

where ρ is the number of boundary system states for the i-th component; ρ_1 is the number of system states when $\varphi(1_i, x) = 1$ and is computed by structure function; r_i is the probability that is determined by (2). The number ρ is the number of non-zero values of Direct Partial Logic Derivative with respect to a corresponding variable.

CDRIs of a system repair is the probability of the system repair that is caused by replacement of the i-th component:

$$P_r(x_i) = (\rho / \rho_0) * p_i \qquad (5)$$

where ρ computed by Direct Partial Logic Derivative with respect to the i-th variable; ρ_0 is the number of system states when $\varphi(0i, x) = 0$ and is determined by structure function; ρ_i is the probability that is determined by (2) [14].

DIRIs of a system failure is the probability of its failure that is caused by breakdown of any component:

$$P_f = \sum_{i=1}^{n} P_f(x_i) \prod_{\substack{q-1 \\ q\neq i}}^{n} (1 - P_f(x_q)) \qquad (6)$$

where $P_f(x_i)$ is CDRIs of the system failure at the i-th component breakdown.

DIRIs of a system repair is the probability of system repair that is caused by replacement of any component:

$$P_r = \sum_{i=1}^{n} P_r(x_i) \prod_{\substack{q-1 \\ q\neq i}}^{n} (1 - P_r(x_q)) \qquad (7)$$

where $P_r(x_i)$ is CDRIs of the system repair for the i-th component replacement.

The algorithm for the supply chain system reliability estimation by importance analysis based on typical process of the estimation is in Fig.2. According to the algorithm number m of performance (reliability or availability) levels for the system and its components for estimation of this system is defined firstly. Then the structure function as mathematical model of this system is determined taking into account the number of performance levels. The CDRIs and DIRIs will present the robustness and reliability of supply chain system [14].

IV. A CASE-ORIENTED STUDY

One of the objectives of every company is to minimize disruption to its operation. It is an axiom of business that no business stands alone. The reliability of any business depends in part on the reliability of its upstream business partners. As a consequence, the level of disruption to a company's operations depends in part on the reliability of its upstream business partners. Every supply chain is composed of a network of businesses where each depends on upstream business for supplies and services. A reliability chain exists along supply chains. The reliability of one company in a supply chain depends on the reliability of its predecessor. The reliability of that predecessor depends on the reliability of its own predecessor along the supply chain and so on.

II. COMPONENT STATE PROBABILITY

Component	States		Component	States	
	0	**1**		**0**	**1**
x_1	0.03	0.97	x_6	0.07	0.93
x_2	0.12	0.88	x_7	0.01	0.99
x_3	0.03	0.97	x_8	0.23	0.77
x_4	0.08	0.92	x_9	0.02	0.98
x_5	0.02	0.98	x_{10}	0.06	0.94

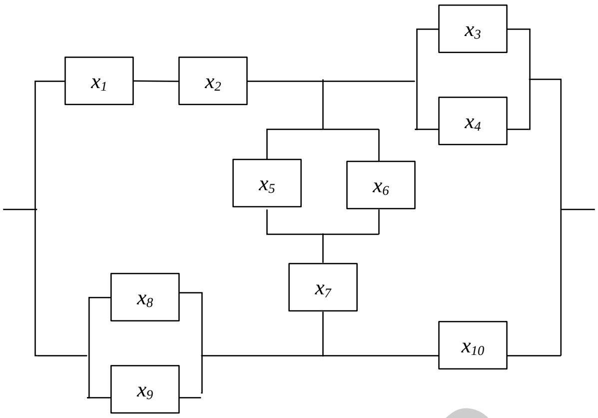

Fig. 3. The system of SC components

Ideally, a manufacturer would like to select its suppliers based in part not only on the reliability of its potential supplier but also on that of the upstream businesses to the potential supplier. The selection process of a chain of business partners is a multistage hierarchical process starting with the selection of the most upstream business and gradually proceeding with the selection process to businesses downstream in the supply chain until a direct supplier to the manufacturer is selected.

Consider an example of a system reliability analysis by CDRI's and DIRIs. For example, investigate possibility of the supply chain system (Fig.3) failure and repair, if one-component breakdowns or a failed component is replaced.

III. NUMBERS *P* AND CDRI

Component	ρ	ρ_1	ρ_0	CDRIs	
				$P_f(x_i)$	$P_r(x_i)$
x_1	96	342	266	0.0084	0.3501
x_2	96	342	266	0.0337	0.3176
x_3	64	326	250	0.0059	0.2483
x_4	64	326	250	0.0157	0.2355
x_5	28	308	232	0.0018	0.1183
x_6	28	308	232	0.0064	0.1122
x_7	84	336	260	0.0025	0.3198
x_8	128	358	282	0.0822	0.3495
x_9	128	358	282	0.0072	0.4448
x_{10}	234	411	335	0.0342	0.6566

According to the algorithm in "Fig.2" number *m* of the performance (reliability or availability) levels for the system and its components for estimation of the system is defined firstly. Then the structure function as mathematical model of this system is determined taking into account the number of performance levels. The structure function of the supply chain system is defined as:

$\varphi(x)$ = OR(AND(x_1, x_2, x_3), AND(x_1, x_2, x_4), AND$(x_1, x_2, x_5, x_7, x_{10})$, AND$(x_1, x_2, x_6, x_7, x_{10})$, AND$(x_8, x_{10})$, AND$(x_9, x_{10}))$

where x_i is performance level of the special supply chain component; OR (y, z) = max (y, z); AND (y, z) = min (y, z).

The supply chain network in "Fig. 3" includes ten components (n = 10) and let the probabilities of their states defined in Table 2. CDRIs for this system failure are calculated by (4) and DIRI's are determined according to (6). CDRIs for this system are in Table 3. CDRIs for the system in Fig.3 repair are computed by (5) and DIRIs are determined according to (7). CDRIs for this system are in Table 3 too. The numbers p are computed as the numbers of values 1 of derivatives $\partial_b\varphi(x)/\partial x_i$ and the numbers ρ_1 and ρ_0 are computed from the structure function.The system failure will be most possible if the eighth component breaks down, because CDRIs $P_f(x_8)$ have the maximum value $P_f(x_8) = 0.0822$. Therefore, replacing this component by another one with the larger probability of perfect working evokes decrease of possibility of the network failure if the eighth component fails.

The analysis of data in Table 3 shows that replacement of the tenth component has the best probability for system repair, because CDRIs of this component $P_f(x_{10}) = 0.6566$ is maximum. DIRIs for failure of this system is $P_f = 0.1699$. It is probability of network in Fig.3 failure if one of its components fails. The probability of the system repair by replacement of one of the component is determined as DIRIs for network repair and is $P_f = 0.0946$.

CONCLUSIONS

The paper contributes to a better understanding of the supply chain reliability, of the concepts of vulnerability and robustness and of related issues in supply chains. From a practical point of view, the involved managers of the company concluded that the research framework supports the analysis of supply chain's robustness and vulnerability, and helps in finding and categorizing disturbances, vulnerability sources and appropriate design principles and strategies. In this paper an integrated methodology is developed that guides companies in determining and managing disturbances and in improving the supply chain efficiency.

We proposed importance analysis to use for MSS reliability estimation depending on the system structure and its components states. Importance measures are widely used as tools for identifying system weaknesses, and to prioritize reliability improvement activities. Therefore MSS importance analysis is actual approach in reliability engineering because allows: 1) to investigate the system behavior in detail that include the quantification of different level of reliability; 2) to examine causes of the system failure; 3) to estimate the system reliability analysis in design.

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