PRELIMINARY RESEARCH ON ASSESSING SUPPLY CHAIN RELIABILITY UNDER UNCERTAINTY

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1. Introduction

With the war in Ukraine, military defence organisations have become the focus of attention. The Russian supply chain failures in Ukraine showed that military supply chains must be reliable to guarantee successful operations. Essential equipment, supplies and dedicated military units must be timely available anywhere in the world. However, the military supply chain members face a complex, continuously changing, deeply uncertain environment.

Supply chains are *complex* socio-technical systems (Behdani, 2012). A socio-technical system is a complex system comprising physical-technical elements and supply chains of independent human actors. The behaviour of a socio-technical system results from the behaviour of both social and technical elements of the system. The technical elements of a supply chain include (among others) suppliers' facilities, centralised and decentral warehouses, and transportation facilities. Such technical elements form a network by being physically connected. The social elements of a supply chain are the social actors that interact with each other formally or informally. These actors include suppliers, employees of the logistics departments, and end users. An example of social interaction within a supply chain is in an internal organisation like the military, agreements and negotiations between the demanding and supplying units.

Factors that further contribute to the complexity are:

a) The high number of actors, supplies and supply chains, and nodes in the supply network: Military organisations are massive and use various equipment and supplies.
b) Information is of strategic value to the enemy. Therefore, military organisations tend to be risk-averse in sharing information.
c) The absence of economic competition: a military organisation cannot go bankrupt nor aims for profit. Though, a military organisation has to be the better-performing one in a war theatre setting.
d) Some specific characteristics of the military supply chains contribute to complexity. For example, military organisations cannot always rely on the delivery of all supplies from supplying companies, especially not in threatening environments. In the case of military deployment, out-of-stock or untimely delivery can lead to life-threatening situations.

The environment is not only complex and continuously changing, but military organisations face a profoundly *uncertain* external environment. Examples of these uncertainties are uncertainties regarding operating context, e.g. the change in war theatre from desert to tundra, the required capacities (civil protection vs warfare), available funding due to political decisions, and new technological developments. Moreover, due to their complex bureaucratic internal environment, supply chain members face uncertainties that might lead to critical delays and thus threaten reliability.

Even in the face of changing requirements and demands, processes and procedures must be in place that ensures the required timely availability. The decision-makers in supply chain management do not always know what to decide, due to the unknown impact of potentially unpredictable events and the lack of transparency in the supply chain. A structured assessment method of supply chain reliability can improve decision-making under uncertainty. Therefore, this preliminary research aims to review several definitions and assessment methods of supply chain reliability under uncertainty as a first step towards creating an assessment framework. The research contributes to interpreting and using these definitions and assessment methods in the supply chain management context.

The remaining sections of this document are organised as follows: section 2 describes the research approach, section 3 discusses the results, and section 4 presents the conclusions.

2. Research Approach

A preliminary literature review was performed using seven databases covered by the TU Delft Worldcat Discovery tool, with the settings: peer-reviewed, libraries worldwide, and excluding duplicates. These databases index the most well-known supply chain management journals: ABI/INFORM Complete (ProQuest), Science Direct, Worldcat.org, Wiley Online, IEEE Publications database, SpringerLink, and Emerald collection. First, the concept of uncertainty was explored, and then supply chain reliability. Using reliability as the only keyword leads to a broad range of results from various subjects . Instead, the starting point for selecting relevant papers was combining the following search words ('supply chain reliability' OR 'supply chain's reliability' OR 'reliability of the supply chain') AND 'uncertainty'. Furthermore, combinations of searches with the search words 'reliability assessment', 'reliability evaluation', 'reliability measurement', AND 'supply chain' were performed. After that, papers were scanned for relevancy based on their abstracts. This selection resulted in twelve papers. The papers were analysed content-wise to develop themes representing the literature.

3. Results

The first section explores the literature on uncertainty, then supply chain reliability concepts are reviewed, and subsequently, the assessment of supply chain reliability under uncertainty is elaborated. Precisely because this research focuses on the military context with its uncertainties, it is relevant to examine the concept of uncertainty first.

3.1 Uncertainty

To better understand the tradeoffs decision-makers face, an understanding of uncertainty and risk is given, and how they lead to disruption. Uncertainty is a general property of any complex system and is defined as: 'any departure from the (unachievable) ideal of complete determinism (Walker et al., 2003)'. Ivanov (2021) complements this definition with 'uncertainty is a system property characterising the incompleteness of our knowledge about the system, its environment, and the conditions of its development'. Figure 1 shows how different levels of uncertainty lead to risk, which can form a disturbance and eventually disruption(Ivanov, 2018a). Norrman & Jansson (2004) define risk as the probability of the event x business impact (of the event).

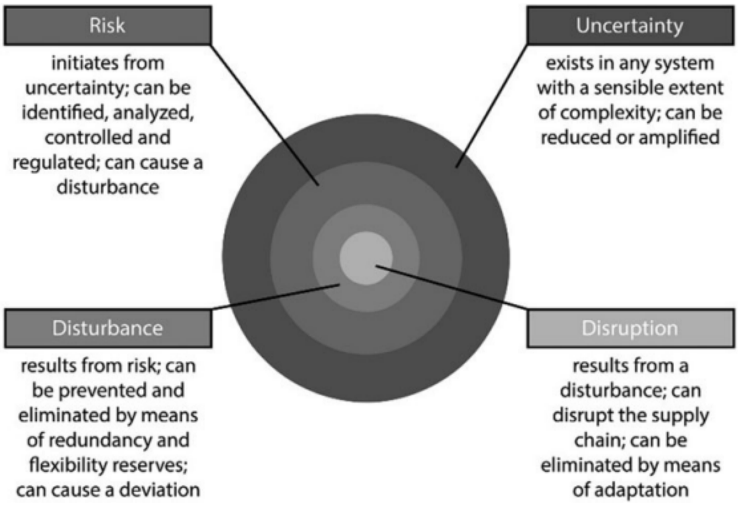


Figure 1 Interrelations of uncertainty, risk, disturbance and disruption (based on Ivanov, 2018)

Uncertainties can vary from demand uncertainty (e.g. for deployment in response to a natural disaster) and internal uncertainty (e.g. a breakdown from critical equipment, lacking data availability) to supply uncertainty like late delivery. Ivanov (2018) proposes that uncertainties are divided into stochastic factors (based on coincidence) and non-stochastic factors. The stochastic factors can be quantified via known probabilistic distributions. Though, the non-stochastic factors have unknown probability distributions. Ivanov's explanation is partially aligned with the often-cited so-called W&H framework of uncertainties, as developed by Walker et al. (2003) and updated by Kwakkel et al. (2010).

Marchau et al. (2019) define four uncertainty levels shown in Figure 2. Uncertainty is classified in levels such that a measure for uncertainties can be determined. There are two extremes: (i) complete determinism, where everything is known about the situation, and (ii) total ignorance, where nothing is known about the situation. These two extremes rarely occur in real-life situations. Hillier & Lieberman

(2015) explained Level 1 Uncertainty is a situation in which there is a clear enough future, so there is no need to create more certainty. Level 2 Uncertainty represents a situation where there are various probability-based futures. In this situation, the system or input of the system is stochastic (probabilistic), and probability distributions characterise the futures. Statistical data helps to get insight into probability distributions. Level 3 Uncertainty refers to a system where there are a few plausible futures which cannot be assigned by probabilities. Scenario analysis is applied to obtain a limited set of plausible futures and test policies. Level 4 Uncertainty is the situation with deep uncertainty. In level 4a, boundaries can still be defined based on many plausible futures, many relations, many outcomes and many weights (4a), or it is known what is unknown (4b).

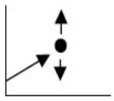
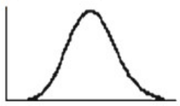
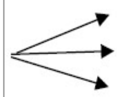
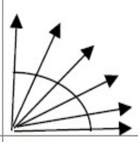
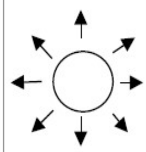
	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future 	Alternate futures (with probabilities) 	A few plausible futures 	Many plausible futures 	Unknown future 	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 2 Levels of Uncertainty (Marchau et al., 2019)

Lempert et al. (2003) elaborated deep uncertainty as 'the condition in which analysts do not know or the decision making parties cannot agree upon (1) the appropriate models to describe interactions among a system's variables (in System model), (2) the probability distributions to represent uncertainty about key parameters in the models (in Context, System model and System Outcomes), and/or (3) how to value the desirability of alternative outcomes' (Weights in Figure 2). Thus, the level of uncertainty stems from the system in which one operates.

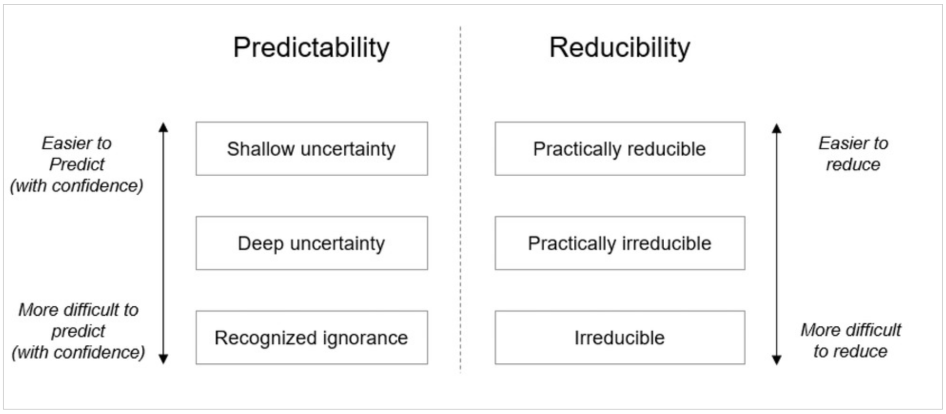


Figure 3 Amended framework to represent levels of uncertainty (Janszwood, 2022)

Recently, Janzwood (2022) amended the W&H framework into the framework shown in Figure 3 to solve two critiques. First, in contrast to the earlier mentioned scientists, he argues that uncertainty arises from a confidence deficit instead of a knowledge deficit. He distinguishes the uncertainty level based on the criterion of easier and more difficult to predict with confidence. Second, he proposes the extent to which uncertainty is reducible as a criterion. His reason is that the existing uncertainty frameworks address reducibility in their discussions of the nature of uncertainty.

Evaluating uncertainties with the above-described classification systems helps decision-makers be aware of potential disruptions or uncertainties. The classification could serve as a guide for discussion and assists in determining how vulnerable a supply chain is. The result of discussions can lead to more substantiated decisions concerning particular product flows, processes, or network design.

3.2 Supply chain reliability

Decision-making under uncertainty is the deciding aspect in the success of supply chain management (Sodhi et al., 2012, Ivanov, 2021). There are several approaches to defining and assessing supply chain reliability under uncertainty. The definition of supply chain reliability determines the perspective on reliability and, therefore, (often) the method for assessment.

An often-used definition for supply chain reliability in manufacturing companies is 'The ability to deliver the right product, to the right place, at the right time, in the right condition and packaging, in the right quantity, with the right documentation, to the right user' (*APICS Dictionary, 16th Edition*, n.d.). The definition is part of the Supply Chain Operational Reference framework (SCOR), an industry-wide, globally acknowledged supply chain management framework. An updated version, revision 12 of the SCOR framework, defines reliability as broader and process-oriented: 'The ability to perform tasks as expected. Reliability focuses on the predictability of the outcome of a process' (APICS Supply Chain

Council, 2017). This broader definition is also suitable for other industries and sectors than the manufacturing industry. Typical metrics for reliability still include on-time, the right quantity, the right quality, and the right documentation (APICS Supply Chain Council, 2017). In these metrics, supply chain reliability is outcome-focused. It does not consider the changing and future environment.

One approach to consider future situations is the application of probability distributions in reliability measurement. Thomas (2002) was the first who put forward a probability-focused definition of supply chain reliability: 'Supply chain reliability is the probability of the chain meeting mission requirements to provide the required supplies to the critical transfer points within the system'. He adopts the engineering reliability theory, which defines reliability as one minus the probability of failure. Most probabilistic approaches use additive or multiplicative methods. Examples of other papers using probabilistic approaches are papers written by Adenso-Diaz et al. (2012), Lukinskiy et al. (2014) and Ha et al. (2018). A drawback of these quantification methods is their reliance on well-characterised probability distributions for supply and demand.

Another approach in supply chain reliability evaluation is network analysis. Adenso-Diaz et al. (2012) studied the effect of supply network characteristics on reliability. They represent the supply network as a set of nodes linked together by arrows representing the flow between them. They conclude that network density, node criticality and complexity are significant elements impacting the reliability of networks. The total number of nodes in the network has the highest impact. Jia et al. (2018) emphasise that one of the main differences with conventional reliability theory is that every supply chain structure consists of interdependent serial or parallel nodes and links, instead of independent ones. They propose a probabilistic reliability measurement that captures these dependencies. Other researchers, like Tolooie et al. (2020) and Nazari-Ghanbarloo & Ghodratnama (2021), focus on network reliability as the central decision to choose a set of locations from a set of potential nodes that are robust under disruptions.
Chen et al. (2017) incorporated time boundaries and internal and external shocks (disruptions) into their definition. 'Supply chain reliability is the ability of a supply chain to fulfil end customer demand to the desired level continually over the planning horizon, despite the risks of external and internal shocks to the system and before any risk mitigation effort'. With this definition, they address the dynamic character of supply chains. Furthermore, Chen et al. (2017) added data availability as one of the sources of uncertainty. Their evaluation consists of calculations based on probability distributions per node-arc representation.

A third approach is the application of simulation-based models. Klimov & Merkuryev (2008) developed a simulation model for supply chain reliability evaluation using a reliability structure function. Their representation of the supply chain is in serial and parallel structures. G. Chen et al. (2015) constructed an algorithm based on the analysis of so-called common failures and used Monte Carlo simulation to measure its supply chain's reliability. A well-developed simulation imitates the system's behaviour and characteristics of the supply chain. Therefore, a simulation is applicable to studying a supply chain with disruptions.

The final described approach for assessing reliability is to use fuzziness. Miao et al. (2009) posed the definition, 'in general a supply chain is reliable in case it performs well when the parts of the chain fail'. They realised a performance model that transforms uncertainty from linguistic evaluation to its numerical representation. This method has its weaknesses in its subjectivity.

Supply Chain Reliability assessment in the organisation under study

To compare the literature with the situation in the organisation with which to collaborate, the organisation's reported metrics indicators are described below.

Table 1 Supply chain reliability metrics of the internal supplier department within the Dutch military organisation, Manual R425

KPI	**Description**	**Remarks**
1 Chain performance I	Percentage of order lines on time and in the correct quantity, in which the chain ends if the goods leave the central warehouse.	Rescheduling áfter the measurement has no influence anymore on the measurement.
2. Chain performance II	Percentage of order lines on time and in the correct quantity, in which the chain ends if the goods enter the receiving decentral warehouse.	Rescheduling áfter the measurement has no influence anymore on the measurement.
3. Backlog duration I	Average exceedance in calendar days of late delivered order lines, where the chain ends when goods leave the delivering warehouse. (often: the central warehouse)	Applies to ordered lines whose Chain Performance I is false.
4. Backlog duration II	Average exceedance in calendar days of late-delivered order lines, where the chain ends when goods arrive at the receiving warehouse.	Applies to ordered lines whose Chain Performance II is false.
5. Granted logistical response time (GLR)	Average overrun in calendar days of late-delivered order lines, where the chain ends when goods arrive at the receiving warehouse.	If rescheduled in time, this metric will give a more favourable result
6. Inventory availability	Percentage of order lines that are timely and fully stocked measured against the final desired need date (delivery date).	It does not mean that the needed supply is in stock at the moment of order, but it is in stock at or before the desired delivery date.

The organisation currently monitors the supply chain reliability metrics described in Table 1. The metrics focus on ' in time' and 'the right quantity' and thus partially align with the metrics described in the

Supply Chain Operations Reference model. The internal supplier organisation measures metrics related to the central warehouse (metrics 1 and 3) and decentral warehouses (metrics 2 and 4).

3.3 Supply chain reliability under uncertainty

Improving supply chain reliability under uncertainty starts with identifying and monitoring the uncertainties, for example, the ones that arise from volatility in demand and supply. Insight and control over these uncertainties increase the ability to take quicker and more effective decisive action. Not all uncertainties will be identified (known unknowns) or predictable.

Pre-disruption (proactive) and post-disruption (reactive) policies are two ways of hedging against disruptions arising from uncertainties. A proactive strategy, creating preparedness, is to design supply chains in such a way that they optimally adapt to unforeseen situations. Examples are redundancies like buffer capacity, prepositioned inventory, or a backup supplier. The objective of reactive strategies is to effectively adjust supply chain structures and processes after a disruption (Aldrighetti et al., 2023). Identification of the areas that need implementing pro- or reactive policies requires adequate reliability assessments. There is a challenge in creating a proper assessment framework: the assessment approach should be linked to the suitable uncertainty level to achieve a scientifically beneficial framework as well as match with the supply chain processes in practice. The deterministic situation, level 1 Uncertainty, is a simple situation in which an outcome assessment measure might logically be applicable. However, a future research avenue is to create an appropriate method to handle supply chains under deep uncertainty.

4. Conclusions

This paper deliberates on various theoretical perspectives of supply chain reliability under uncertainty. The findings point out several approaches to defining and assessing supply chain reliability. One approach for assessment is to use probabilistic models that quantify the likelihood of different events occurring and their impact on the supply chain. Another approach is to use network analysis that considers the interdependencies and interactions among the various components of the supply chain. A third approach is to use simulation-based models that copy the behaviour of the supply chain over time and evaluate different strategies under different uncertainty conditions. Finally, a fourth identified approach is to use fuzzy logic. The assessment methods developed over time by combining the approaches of network analysis, simulation and probabilistic computational methods.

A comprehensive framework to measuring and defining supply chain reliability for different levels of uncertainty is lacking. An appropriate method for supply chain reliability in the absence of probability distributions needs to be developed.

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