A Supply Chain Disruption Framework for Discrete Event Simulation

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***Abstract*—This article presents a supply chain disruption framework for discrete event simulation based on the analysis of the prior literature. The aim is to develop a better understanding of the elements that are required to meet the challenge of using discrete event simulation in this application. The framework identifies the main elements in terms of the disruption event, supply chain configuration, supply chain resilience and supply chain performance metrics. The review also identifies challenges for the use of discrete-event simulation in this way including the representation of rare disruption events and time-series interpretation of disruption events.**

Keywords-supply chain disruption, discrete event simulation.

I. INTRODUCTION

Discrete Event Simulation (DES) is usually considered a stand-alone software tool that is used to assess the steady-state performance of manufacturing and service processes. However recently it has been used to undertake the analysis of the effect of transient disruptive events in a variety of supply chain settings such as food retail [1], LED panel light manufacturing [2], medicine supply [3] and forestry log export [4]. In this context the lack of empirical data that could be used to understand these events is to some extent overcome by the use of structured experimentation using computer simulation experiments [5].

The purpose of this article is to review existing work on the use of DES to analyse disruptive events in a supply chain context. From this review a framework has been developed that identifies the key attributes of the combination of disruptive events, the supply chain configuration and supply chain resilience factors that lead to supply chain performance. By identifying key attributes associated with supply chain disruptions, this framework will provide a basis on which to develop a DES model of disruption events and measure their effect on supply chain performance.

II. REVIEW OF THE USE OF DES TO ANALYSE DISRUPTIVE EVENTS IN THE SUPPLY CHAIN

The review examines supply chain disruption in terms of the nature of the disruption event itself, the supply chain configuration, the supply chain features and relationships that lead to a level of supply chain resilience and supply chain performance metrics used to assess the response to disruption events.

A. Disruption Event

A disruption can be defined as an unplanned and unanticipated event that disrupts the normal flow of goods and materials in the supply chain [6]. An event that has the potential to occur, but has not yet done so, can be referred to in terms of 'risk' [7]. As well as the direct impact of a disruption on the supply chain we may need to consider the ripple effect defined as a disruption in a supply chain node that can spread to neighbouring nodes or links [8]. The ripple effect is associated with low-frequency, high-impact disturbance risks [8].

In the context of a supply chain for the source of risk (that leads to a disruption event) [9] define two main categories of internal risk and supply chain risk.

- Internal risks can be categorised as the internal risk of the process (value-adding processes) and the internal risk of control (systems which govern how a firm controls the processes).
- Supply Chain risks can be categorised as external to the firm but internal to the supply chain network (either downstream demand or upstream supply risks) or external to the supply chain network (events in the environment such as natural disasters or socio-political events).

Manners-Bell [10] states that although supply chain risks are the most relevance in the supply chain context, internal risks of process and control can also impact the wider supply chain.

In terms of DES models of the source of risks leading to disruption events, [11] models a combination of the following:

- internal firm risks such as machine breakdowns and internal quality problems
- internal supply chain risks such as delays in contracting with suppliers and raw material shortage
- external supply chain risks such as earthquakes and computer Denial of Service events

Borgos and Ivanov [1] model disruption events related to the external supply chain risk of the COVID-19 pandemic in terms of internal supply chain risks leading to shutdowns at supplier's factories, bottlenecks in transportation and panic buying by customers.

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In terms characterising a disruption event, [5] provide the following generic attributes:

- length (number of time periods over which the shock manifests itself),
- magnitude (the size of the initial negative impact, and the extent to which the shock subsequently reduces supply chain performance over time,
- shape (the way in which the disruption manifests itself – a step function, a ramp etc.)
- number (number and frequency of disruption that occur during a given event).

B. Supply Chain Configuration

In terms of the supply chain configuration, this can be described by the use of a supply chain map such as in [2]. Christopher [12] emphasises the importance of managing the critical nodes and links in the supply chain. MacCarthy et al. [13] define the minimum information for a supply chain map as nodes, the participants of the supply chain and links, how the participants are connected. Primary participants contribute direct to value-adding activities in the supply chain process, but we may also need to incorporate secondary participants such as third-party logistics providers in our analysis. The primary flows modelled by DES in the review are material flows, such as in [14] but information and financial flows could also be modelled.

C. Supply Chain Resilience Factors

In terms of factors that impact the resilience of the supply chain to disruption events, [15] distinguishes between the physical features of a supply chain such as its design matched to demand, shape, stocks, capacity, agility/flexibility and supply chain relationships such as collaboration and visibility. In addition [5] model the connectivity relationship between supply chain actors.

In terms of supply chain physical features examples cover the use of higher stocks and spare capacity, such as Garrido Rios [11] who provides an analysis of on-hand inventory and short-term manufacturing capacity. Ivanov [14] studies the use of a policy of backup capacity - using capacity in owned plants in the region and using the capacity of owned plants in neighbouring countries. In terms of supply chain relationships, [16] study the use of the policy of alternative suppliers and [2] study the use of backup suppliers.

D. Supply Chain Performance

In terms of measuring supply chain performance when submitted to disruption events, [17] define performance measures of speed of recovery, financial cost and customer impact. Borgos and Ivanov [1] define performance measures of profit, revenue, costs, delivery time, inventory levels, order backlog (orders lacking products) and late orders.

As well as direct supply chain design and operations measures most studies aim to provide a measure of supply chain resilience which is defined by [18] as requiring two capacities of resistance (ability to delay a disruption and reduce the impact once the disruption occurs) and recovery (ability to recover from a disruption). Garrido Rios [11] defines (static) resilience as a function of fill rate which is defined as the number of backorders and lost orders as a proportion of total orders. Borgos and Ivanov [1] use the service level ratio of on-time orders to overall number of outgoing orders as an indicator of disruption and recovery. Moosavi et al. [2] use the resilience metric from [19] and [5] provides an overall measure of resilience (defined as the relative percentage of functionality over time) derived from the three measures of the number of time periods in which a negative change in inventory is observed, the total negative change in inventory over the course of these time periods and the average negative change in inventory over this same interval.

III. DEPLOYING THE FRAMEWORK FOR DES

Based on the review a framework is presented which can be used when using DES to analyse disruptive events that impact on the supply chain (Fig. 1). Disruption events act on the configuration of supply chain design and combine with supply chain resilience factors to produce a level of supply chain performance. The supply chain resilience factors will be aspects of the current supply chain design that have an effect on supply chain performance. They can also be part of the simulation experimental design to analyse the effect of disruption events on future supply chain configurations.

We can now proceed to investigate how to operationalise the elements in the framework to enable its representation as a DES model.

Macdonald et al., [5] model the characteristic of a generic disruption event directly. If we wish to model a disruption event that has been derived from a source of risk, we will need to operationalise this event by characteristics of its length, magnitude, shape and number. For example, Garrido Rios [11] operationalises disruption events deriving from risks such as machine breakdown, using probability distributions for the number of occurrences and length of disruption. Uniform distributions are used to represent the time between disruption events based on the assumption that the likelihood of the event remains constant over the simulated time period.

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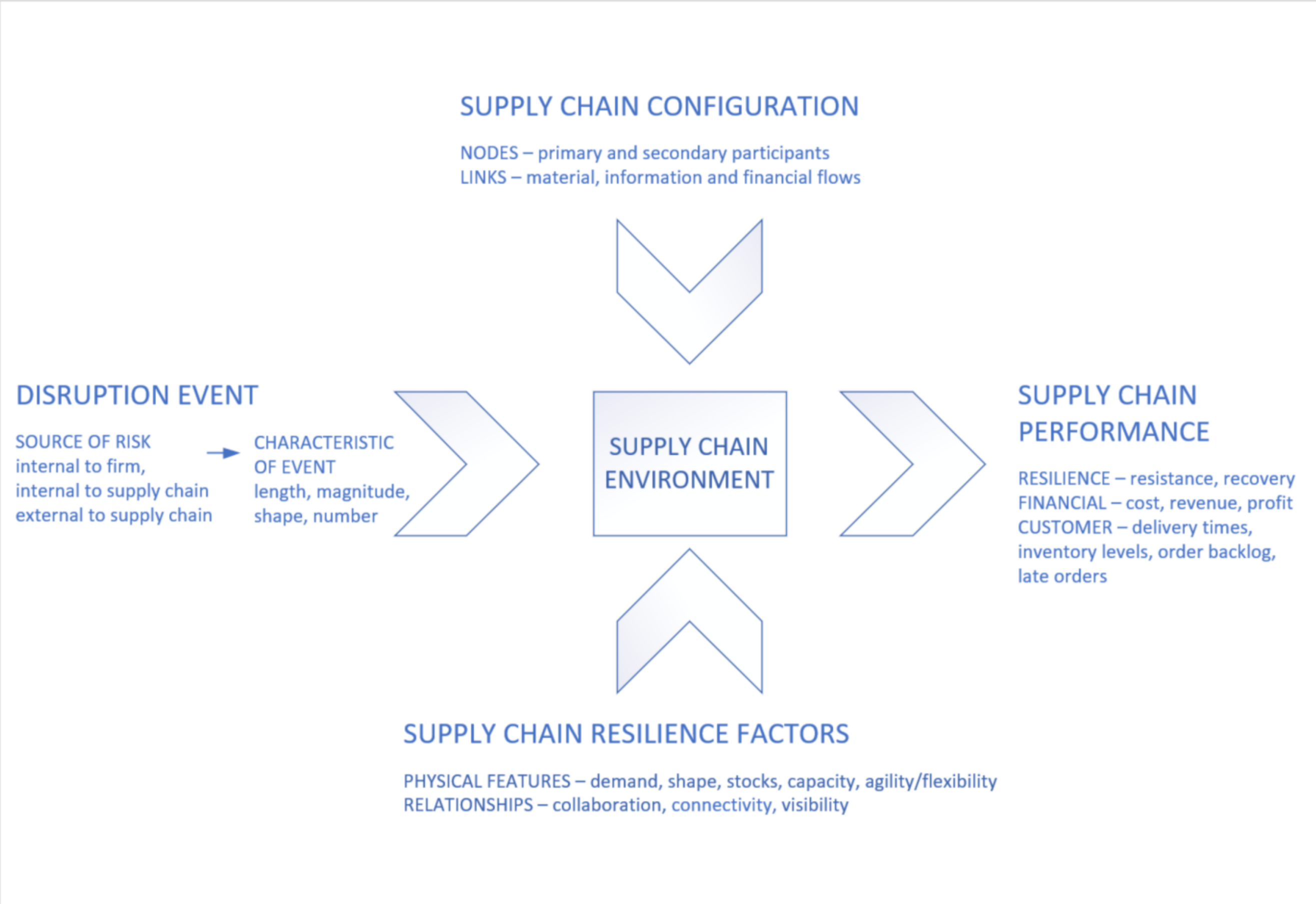

Figure 1. Supply Chain Disruption Framework for Discrete Event Simulation

In terms of supply chain configuration, the conceptual modelling stage of the DES study will require us to develop a diagrammatic representation, usually in the form of a process map, of the explanatory model [20]. MacCarthy et al. [13] argue that the degree of mapping the supply chain depends on the purpose and so introduce a classification of supply chain maps based on a hierarchy of supply systems. This may require high level supply chain and supply network maps to be decomposed to the process map level (as presented in a hierarchy for supply systems mapping, [13]) to enable modelling of material flows by the DES. To define the supply chain configuration in a DES, [21] organise the process map around the Supply Chain Operations Reference (SCOR) model categories of Source, Make and Deliver.

In terms of supply chain resilience factors, the current resilience of the supply chain can be assessed for a range of disruption events. In addition, the use of simulation scenarios incorporating either physical or relationship design changes can be employed. For example, connectivity is operationalised for a DES study by [5] by expressing connectivity between supply chain partners as a value between 0 (no connectivity) to 1 (full connectivity). Full connectivity means that the full effect of the disruption event would be passed between supply chain partners.

Finally supply chain performance can be expressed using traditional DES measures such as financial and customer-oriented metrics. These can be reported by simulating over multiple replications to provide confidence intervals around average performance across these metrics [20]. In terms of the concept of resilience this metric will require operationalising, for example as inventory fill rate [11]. Resilience may also require a time-based analysis to identify the nature of the recovery from the disruption event in terms of its magnitude and length. Melnyk et al. [16] outline a procedure for dealing with time series data that uses a differencing technique combined with an outlier detection approach [22]. The outcome is the quantification of system performance in terms of measures that define resistance and recovery.

IV. SUMMARY

The framework identifies the elements that need to be incorporated into the DES model and provides a roadmap for determining suitable methods for operationalising these elements in the DES. However, further work is needed to meet the challenge of modelling supply chain disruption using DES. For example, the representation of rare disruption events, the impact of the ripple effect, supply chain mapping decomposition at the conceptual modelling stage and time-series interpretation of disruption events at the experimentation stage.

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