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ESTABLISHING A FRAMEWORK FOR THE EFFECTIVE DESIGN OF RESILIENT SUPPLY CHAINS WITH INHERENT NON-LINEARITIES

Virginia L M Spiegler[1], Mohamed M Naim[2], Andrew T Potter[2], Denis R Towill[2]
[1] Corresponding author Brunel Business School, Brunel University London
Eastern Gateway Building, Brunel University London,
Uxbridge, London UB8 3PH, UK
E-mail:Virginia.Spiegler@brunel.ac.uk

[2] Logistics Systems Dynamics Group,
Cardiff Business School, Cardiff University, UK

Abstract
Purpose of this paper: Previous control theory research on supply chain dynamics has predominantly taken a linear perspective of the real world, whereas nonlinearities have usually been studied via a simulation approach. Nonlinearities can naturally occur in supply chains through the existence of physical and economic constraints, for example, capacity limitations. Since the ability to flex capacity is an important aspect of supply chain resilience, there is a need to rigorously study such nonlinearities. Hence, the purpose of this paper is to propose a framework for the dynamic design of supply chains so that they are resilient to nonlinear system structures.

Design/methodology/approach: Building on an existing framework to design supply chains (Naim and Towill, 1993) from a real world situation through data capture, modelling, analysis and onto redesign recommendations, we synthesize current research on supply chain resilience and recent developments in nonlinear control theory techniques. We then apply the knowledge gained to develop a new framework and demonstrate its application via a real world case study.

Findings: An updated framework is provided for the synthesis and design of nonlinear supply chain dynamics models and a future research agenda is developed. The framework improves the understanding of the system's behaviour and the impact of nonlinearities on system response. Consequently, supply chain resilience can be enhanced.

Value: The real world is nonlinear and the existence of such nonlinearities makes the understanding of system dynamics difficult. This paper has an academic value since the proposed framework aids system dynamics researchers to gain better insights into complex nonlinear model structures and acts as a precursor to simulation based approaches.

Practical implications (if applicable): The proposed framework may be applied in an industrial context for analysing nonlinearities in a real-world system. The framework provides a process by which supply chain designers gain more insights into nonlinear system dynamics behaviour without going totally relying on time-consuming simulation activity on its own.

INTRODUCTION

Modern supply chains are becoming more and more complex. With the supply chain leaning and lengthening as a result of globalisation, supply chains are becoming more vulnerable to disruptions (Christopher and Peck, 2004). Managers have optimised supply chains by reducing holding inventory, outsourcing noncore activities, cutting the number of suppliers and sourcing globally, on the assumption that the world market is a relatively stable and predictable place (Kearney, 2003). This uncertain and complex business environment has increased the importance of handling risks that can emerge from the customers' or demand side, the suppliers' side, manufacturing processes and control systems (Mason-Jones, 1998). Hence, the ability of a supply chain to be resilient became vital to sustain competitiveness (Pettit et al., 2010).

When investigating the dynamics of supply chain systems, previous analytically based research has predominantly taken a linear perspective of the real world, whereas nonlinearities have usually been studied via a simulation approach. Nonlinearities can naturally occur in supply chains through the existence of physical and economic constraints, for example, capacity limitations. Since the ability to flex capacity is an important aspect of supply chain resilience, there is a need to rigorously study such nonlinearities. Hence, the purpose of this paper is to propose a framework for the dynamic design of supply chains so that they are resilient to nonlinear system structures.

In 1994, Naim and Towill, based on a paper presented at the inaugural International Symposium of Logistics in 1993, developed a framework that used system dynamics modelling, analysis and simulation aids in the decision making process to design supply chain systems according to their management objectives. "This methodology is a direct offshoot of the pioneering works of Jay Forrester" (Bechtel and Jayaram, 1997) and it has been advocated, utilised and adapted by other authors (e.g. Kumar and Nigmatullin, 2011; Bhatti et al., 2012) to design efficient supply chains, re-engineer processes and analyse supply chains' dynamic behaviour.

Building on Naim and Towill (1994)'s work, we synthesize recent developments in nonlinear control theory techniques and current research on supply chain resilience. Our aim to apply the knowledge gained to develop a new framework and demonstrate its application via a 'real world' empirical case study.

NONLINEAR CONTROL THEORY

Nonlinear control theory is the area of control theory that deals with systems that are nonlinear and/or time-variant. Control theory is an interdisciplinary branch of engineering and mathematics that is concerned with the behaviour of dynamical systems and it has seen limited use in the study of supply chain dynamics.

While system dynamics simulation is often used in the analysis and redesign of supply chain models that exhibit nonlinearities, quantitative analytical approaches are more often restricted to linear representations of supply chains. Hence, much of the research on supply chain dynamics either takes a 'trial and error', experimental, simulation approach to redesign (Forrester (1958), Sterman (1989), Larsen et al. (1999); Laugesen and Mosekilde (2006); Hamdouch (2011)) or develops exact solutions of models that are already linearised approximations to the real-world situation (Disney and Towill, 2005; Gaalman and Disney, 2009; Zhou et al., 2010). In reviewing the control theory we found a number of methods for analysing nonlinear system dynamics including those used in supply chain dynamics research (Table 1).

Insights gained from nonlinear control theory literature

This research conducted an extensive literature search and review on the specific topic of nonlinear control theory. To date, simulation techniques have mainly been used to deal with complex, nonlinear supply chain systems. However, our research presents a more rigorous approach that permits mathematical analysis of nonlinearities (Figure 2) as a precursor to simulation experiments.

Firstly, simplification methods should be used to eliminate unnecessary complexities in the model and reveal the underlying relationship between the variables. Then, some of the linearisation methods presented in Table 1 were used to analytically investigate common nonlinearities present in a 'real world' supply chain system.

General approach	**Method of analysis**	**Supply chain application**
Linearisation methods	Small Perturbation Theory with Taylor series expansion	Jeong et al. (2000): Limited application for analysis in SC context Saleh et al. (2010): recommends for SC design but does not apply it.
	Describing Function	None identified
	Small Perturbation Theory with Volterra/Wiener series expansion	None identified
	Averaging and best-fit line approximations	Wikner et al. (1992): testing SC re-engineering strategies Naim et al. (2012): identifying analogies between seemingly different decision rules
Graphical and simple methods	Phase Plane and Graphical Solutions	None identified
	Point transformation method	Wang et al. (2014): Exploring nonlinear behaviour of inventory systems
Exact Answer	Direct solution	None identified
Complex method	Lyapunov-based stability analysis for piecewise-linear systems	Wang and Disney (2012): Stability of inventory systems
Simulation	Numerical and Simulation solution	Sterman (1989): Mis-perceptions of time delays and feedback loops Larsen et al. (1999); Laugesen and Mosekilde (2006): Shaping stability regions of discontinuous systems Shukla et al. (2009): Bullwhip and backlash analysis Hamdouch (2011): Effect of capacity and batching

Table 1. Summary of methods used to analyse nonlinear systems

While the use of this approach potentially yields insights to bear on the understanding of supply chain dynamics behaviour our empirical study is limited to consideration of discontinuities.

ASSESSING SUPPLY CHAIN RESILIENCE

The concept of resilience is multidisciplinary, arousing interest from scientists in various disciplines. In physics and engineering, resilience is the ability of a material to return to its original form after being bent, compressed, or stretched. In other words, it is the ability to behave elastically (Pytel and Kiusalaas 2003). In the supply chain literature, the idea of resilience has only recently emerged, and is essentially defined as ''the ability of a system to return to its original state or move to a new, more desirable state after being disturbed'' (Christopher and Peck 2004).

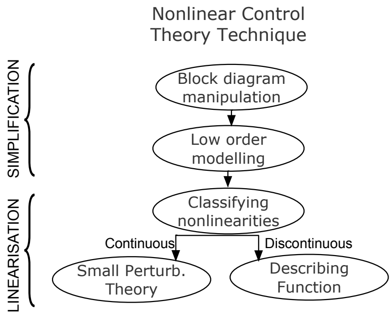


Figure 2: Application of nonlinear control theory

When reviewing the supply chain literature on resilience, we found a number of contradictions and a domination of qualitative aspects that are difficult to measure. In addition to this, several metrics have been used by quantitative researchers to assess resilience. It is important to develop a single measure of resilience to ensure consistency and repeatability of results. In order to achieve this, a clearer and exact concept is needed.

Using theory building, Ponomarov and Holcomb (2009) developed a holistic conceptual framework for supply chain resilience which was defined as: ‘‘the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at desired levels of connectedness and control over structure and function’’. This definition implies achieving the following.

(1) Readiness: being prepared or available for service. The implication of this definition is whether the supply chain can continue providing goods/services at reasonable costs according to the end customer requirements.
(2) Sensing: minimising the lag between the event occurring and the supply chain’s recognition of the event. It ensures the number of options available to the supply chain manager is maximized.
(3) Response: reaction to a specific stimulus. A quick response implies minimising the time to react to disruptions and beginning the recovery stage.
(4) Recovery: a return to, or finding an alternative ‘normal’ stable or steady-state condition.

Sheffi and Rice (2005) established how disruptions would affect companies’ performance, which can be measured by sales, production levels, profits and customer service. Their findings demonstrate different phases of the system’s performance response: after a disruption the performance decreases but as actions are taken the system’s performance will gradually be restored. Similarly, Tierney and Bruneau (2007) also highlight the relation between a disruptive event and business indicators. They call this loss of functionality from disruption followed by a gradual recovery the ‘resilient triangle’. According to them, this triangle should be minimised.

FRAMEWORK TO DESIGN RESILIENT SCs AND A REAL WORD APPLICATION

Based on Naim and Towill (1994), a framework to design resilient supply chains is presented in Figure 3. The main difference between Naim and Towill’s (1994) framework and the one presented in Figure 3 is the replacement of linear control theory with a nonlinear approach. Hence, this research has addressed the gap in Naim and Towill’s (1994) framework which considered only linear control theory techniques to investigate ‘presumably linear’ models. Moreover, we have addressed a gap in the supply chain literature by examining a particular business objective: to be resilient to nonlinear system dynamics. This qualitative performance objective was converted into quantitative measures in order to use the proposed framework in Figure 3. In this method, there are two distinct, but overlapping, phases of analyses. In the qualitative phase, both the objective of the study and the key drivers are identified through an intuitive and conceptual modelling process. Then, the relationships among key drivers are represented in a block diagram. The second phase is the quantitative analysis, which is associated with the development of mathematical and simulation models. Figure 3 also highlights the steps taken in the empirical research and the main contributions to the framework.

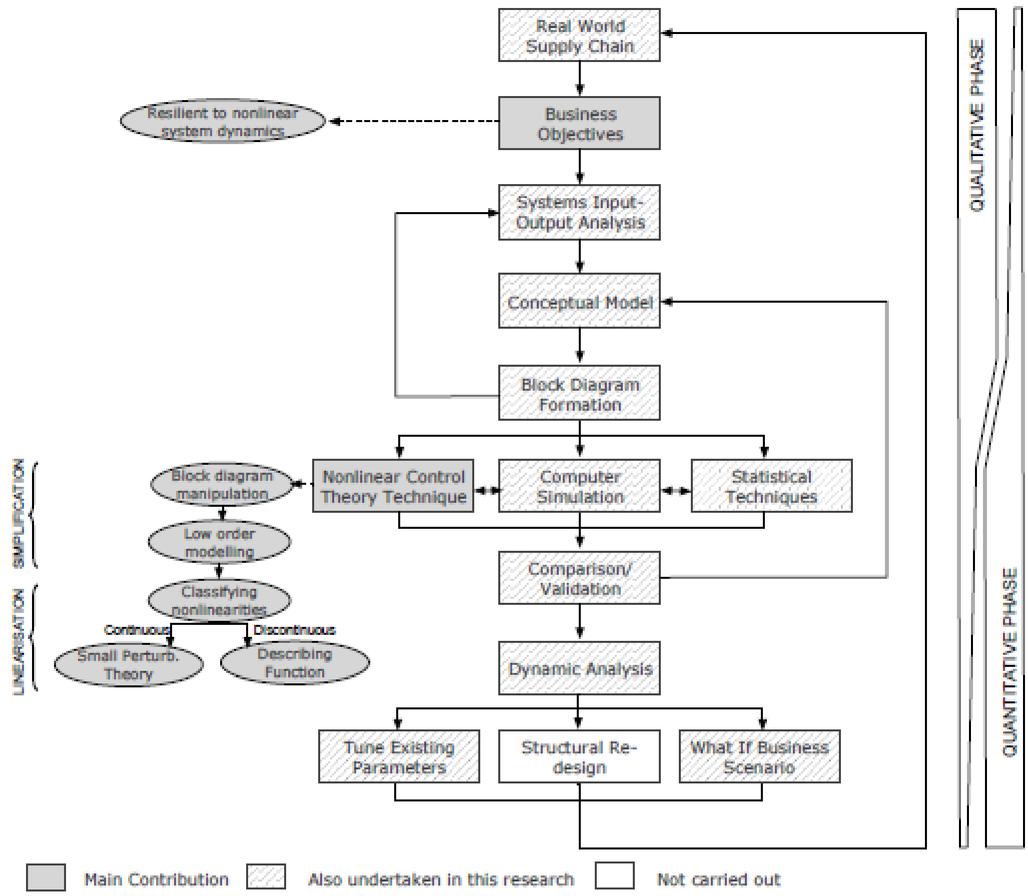


Figure 3: Proposed framework to design resilient supply chains
Extended from: Naim and Towill (1994)

Qualitative phase

This phase started by exploring a particular supply chain system: a major UK grocery retailer with the purpose to suggest improvements to the system, although the underlying structure could not be adjusted. For that, knowing the business and/or research objectives was very important. Forrester (1958) also indicated that in designing a model of an organisation the elements that must be included arise directly from the questions that are to be answered or objectives that are to be achieved. Moreover, since there is no all-inclusive model, different models should be created to address different questions about the same system and models can be extended or altered so that new objectives are achieved. Our research aimed at examining the resilience of their distribution centre (DC) stock ordering systems of the grocery retailer.

Naim and Towill (1994) suggested that four main business objectives could be evaluated using their framework. These are: inventory reduction target, controlled service levels, minimum variance in material flow and minimum total cost of operations and procurement. In this research, a fifth objective has been included: increased supply chain resilience. Moreover, organisations should be aware that there are trade-offs between these objectives and different weighting may be given to each of them.

The resilience term, which has mainly been described in qualitative aspects, was converted into a measurable form by exploring the literature of natural and social sciences. Then, supply chain metrics were chosen to represent this qualitative performance and an index, based on the Integral of Time Absolute Error criterion, was found to epitomise the resilience attributes (refer to Spiegler et al, (2012) for more detail). It was important that, before implementing this newly proposed resilience performance index, tests were made to verify whether this index could provide results consistent with the descriptions in the literature.

The next step was to describe how the material and information flows occur and how production control is managed. This input-output analysis (Figure 4) informs material and information delays, production and logistics constraints, how information is processed and how planning and scheduling operations are carried out. The information obtained from this step then supported the development of a suitable conceptual model.

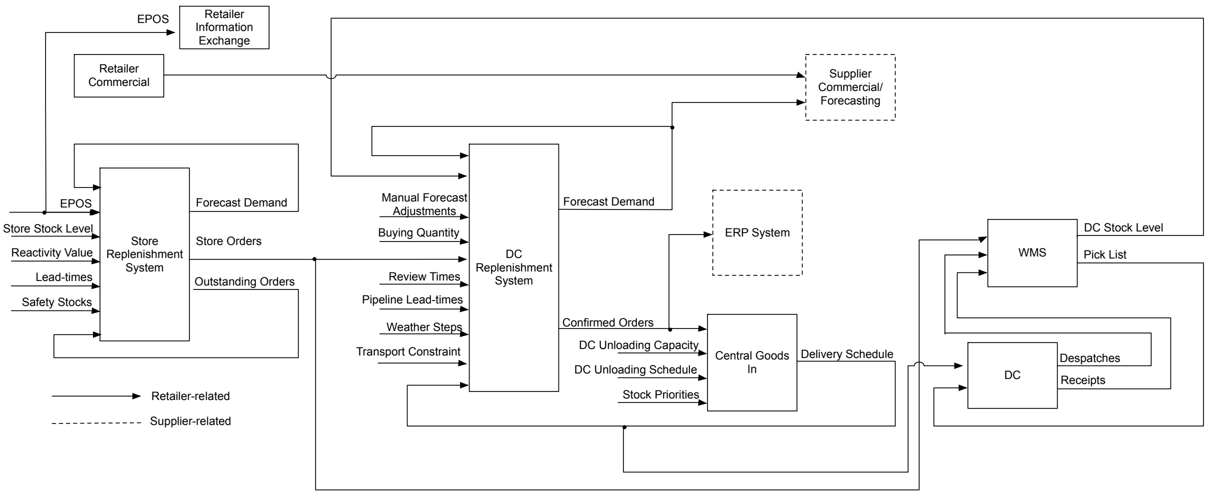


Figure 4. Input-Output diagram of replenishment information flows within the retailer

Finally, as the operations and control procedures become known, the soft system diagram was converted into control engineering block diagram form (Figure 5). This contains mathematical descriptions of the relationships between the various interacting variables in the conceptual model. Each block in the block diagram establishes a relationship by including a mathematical expression that, for example, may represent delays. At this stage, considerable insights into how supply chains work were attained.

Quantitative phase

According to Naim and Towill (1994), the first step of the quantitative phase is choosing one or more of three possible techniques for analysing the supply chain: control theory, computer simulation and statistical analysis. The choice of each method depends on the degree of complexity involved in the setting up of a mathematical model, the volume of data available for analysis and the analytical skills of the supply chain designer.

Nonlinear control theory: We firstly recommend the use of nonlinear control theory techniques before undertaking simulation analysis. This is due to the fundamental insights and understanding that this technique provides, as discussed previously.

The first step for the analysis of complex, high-order models was to undertake simplification. If the system can be simplified that is when underlying control mechanisms are revealed (Wikner et al., 1992). Moreover, because the simplification process provides a clearer view of the model it also aids in the analysis and synthesis of any nonlinear elements. The block diagram in Figure 5 is already in its simplified form and two nonlinearities are clearly identified: ROUNDING and CLIP functions.

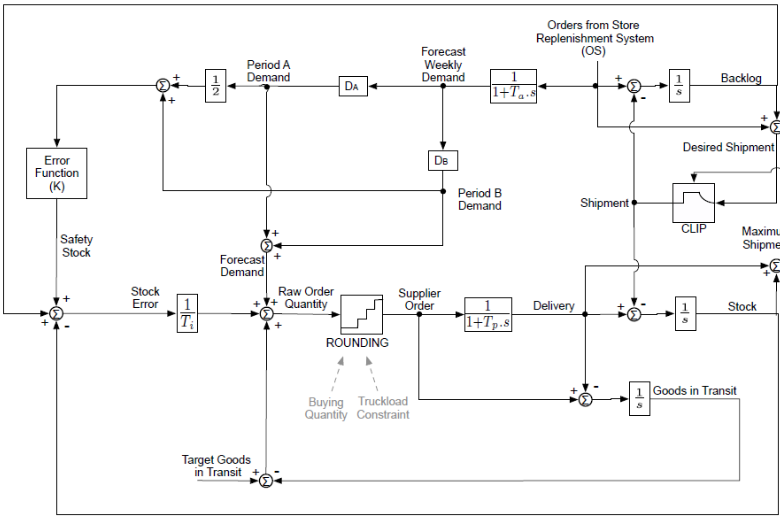
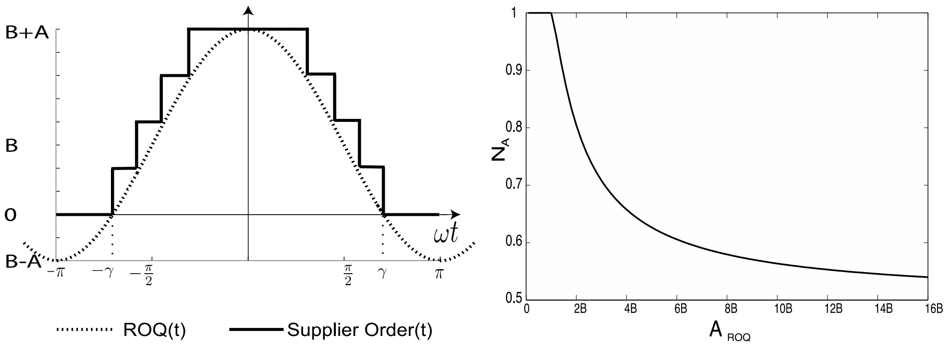


Figure 5. Block diagram of the DC replenishment system

The second step was to analyse the effects of the nonlinearities present in the system. In Table 1, several methods for the analysis of nonlinear models have been presented. In particular, the linearisation methods are recommended whenever a solution can be obtained in this way because there are a variety of techniques available in linear systems theory. We applied describing function techniques for the analysis of both discontinuous nonlinearities. For instance, in Figure 5 if a sinusoidal signal of $ROQ(t) = A.\cos(\omega t) + B$, where ω is the angular frequency, A is the amplitude and B the mean, inputs to the ROUNDING nonlinearity, an output (Supplier Order) of same frequency and phase but different amplitude and mean will be produced as shown in Figure 6a. Although the Supplier Order is nonlinear, it can be represented by piecewise linear equations:

$$Supplier\ Order(t) = \begin{cases} ROQ(t), & if\ ROQ > 0\ (-\gamma < \omega t < \gamma) \\ 0, & if\ ROQ < 0\ (-\pi < \omega t < -\gamma\ and\ \gamma < \omega t < \pi) \end{cases} \quad (1)$$



a) Time series for Supplier Orders *b) Amplitude gain of Supplier Order*

Figure 6. Application of describing function on the ROUNDING nonlinearity

The basic idea of the describing function is to represent a nonlinear element by a type of transfer function, or gain, derived from its effects on a sinusoidal input signal. Given ROQ as a sinusoidal input, the output Supplier Order can be approximated to:

$$Supplier\ Order(t) \approx N_A.A\cos(\omega t + \emptyset) + N_B.B \quad (2)$$

where ∅ is the phase angle and N_A and N_B are the amplitude and mean gains of the describing function, respectively. For describing function analysis on N_A is needed and this gain can be determined as a function of the input amplitude (A_{ROQ}) by expanding the series and estimating the first harmonic coefficients (Figure 6b)

Computer simulation: After having a better understanding of the system's behaviour and its underlying structures, single or repeated simulations were carried out to confirm the insights acquired in the previous step and to obtain a more exact result of the system responses. The advantage of simulations is that the original conceptual model can be studied without simplification or linearisation, but from experience gained in this research process it is very hard to gain insights from only simulating complex models. Moreover, previous researchers stated that simulation approach might overlook underlying mechanisms and dynamic behaviour (Karafyllis and Jiang, 2011).

Table 2 summarises the insights gained from conducting nonlinear control theory analysis prior to simulation experiments.

Analytical Insights	**Resulting simulation experiments**	**If not carried out**
• Possibility to find system's transfer functions	• Simulation process focused on important parameters for achieving supply chain resilience	• A lack of understanding of the effect of each control parameter on resilience.
• Possibility to find an inventory drift problem in the DC replenishment system	• Simulations were undertaken to visualise the problem and to test solutions	• Possibly gone unnoticed. Although step input simulation revealed the same result, this drift effect is only perceived if plotting both safety and current stocks together.
• Understanding the impact of the different nonlinearities and input amplitudes on system's damping ratio and natural frequency.	• Simulations were undertaken to check whether the analysis gave correct insights and more effort has been given to check unexpected results.	• The understanding of nonlinearities would be very difficult and some results would have been missed when using only simulation techniques.
• Understanding the impact of different input frequencies on system's behaviour	• Simulations were undertaken only to confirm analytical insights.	• Several simulation experiments would have been necessary to gain the same insights

Table 2. Summary of insights gained from the quantitative phase

Statistical techniques: Finally, statistical techniques can be used to analyse real data if sufficient volume of data is available for the purpose of analysis. Such techniques may involve de-trending, smoothing, range analysis, auto- and cross-correlations to identify features in the data, such as degree of scatter, short/long term trends, cyclical variation and exogenous events. In this research, this technique is used only for the initial validation process.

Comparison and validation of the model involved consultation with the interested parties in the supply chain by talking to the system manager through the equations entered into a spreadsheet. Spreadsheet system dynamics simulation was chosen so that the model could be easily understood by the staff at the retailer. This feedback of information ensured that there was no misinterpretation of the results. Then, tests using extreme input and parameter values and eliminating assumptions were undertaken. Finally, actual data from the real system has been used. The information on three different products, obtained on electronic point of sale (EPOS) and DC replenishment orders, has been used.

Following the validation process, the model was subjected to extensive dynamic analysis. The objective of this stage is to determine the dynamic performance of the supply chain by subjecting the model to severe test inputs. In this research the supply chain resilience performance was investigated by making a sharp, step change in the customer demand. Moreover, changes in damping ratios and natural frequencies have also been used as an estimation of the resilience performance.

Finally, the supply chain models were inspected by changing the control parameters, creating various scenarios and undertaking sensitivity analysis to reveal how vulnerable the supply chain is. Naim and Towill (1994) suggest a structured approach to exploit supply chain models:

- Tuning existing parameters: supply chains can be redesigned by varying the control parameters to improve performance, without changing the original structure. This research made use of this technique to find the resilience regions of the different parameter settings.
- Structural redesign: this involves altering the model's structure, such as re-moving an echelon or including a feedback information into the control system. The purpose of this research was to suggest improvements to the system without changing the underlying structure of the system.
- 'What if?' business scenarios: this involved testing how the supply chain performs for alternative business propositions or unexpected changes in the business scenario. This research tested the impact of expected changes in physical parameters, such as lead-times.

CONCLUSION

An updated framework has been provided for the synthesis and design of nonlinear supply chain dynamics models. The framework improves the understanding of the system's behaviour and the impact of nonlinearities on system response. Consequently, supply chain resilience can be enhanced.

More importantly, this research has contributed in providing a systematic procedure for the analysis of the impact of nonlinear control structures on systems behaviour. The previous framework developed by Naim and Towill (1994) suggested that nonlinearities could be only analysed by undertaking simulation experiments. By adopting nonlinear control theory, this research has found more accurate linear approximations for reproducing nonlinear models, enhancing the understanding of the system dynamics and actual transient responses. Moreover, the analytical phase was found to be an important precursor for undertaking simulations.

Furthermore, we have shown how the proposed framework can be applied in an industrial context for analysing nonlinearities in a real-world system. The framework provided a process by which supply chain designers gain more insights into nonlinear system dynamics behaviour without only relying on time-consuming simulation.

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