Proceedings Paper:

Montoya-Torres, JR, Huaccho Huatuco, L and Burgess, TF (2013) Simulation analysis of the sustainability performance of a supply chain subject to disruption. In: Proceedings of the 11th International Conference on Manufacturing Research. ICMR 2013, 19-20 Sep 2013, Cranfield, UK. Cranfield University Press , pp. 513-518. ISBN 9781907413230

SIMULATION ANALYSIS OF THE SUSTAINABILITY PERFORMANCE OF A SUPPLY CHAIN SUBJECT TO DISRUPTION

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ABSTRACT

In recent years, two main concerns have surfaced in relation to improving manufacturing supply chains; one is their sustainability and the other is their resilience to major disruptions. This first concern relates to the optimal use of ever-scarcer natural resources. Hence, supply chains need to be assessed and re-designed to accommodate this trend and take in to account the triple bottom line of environmental, economic and social measures. The second concern stems from the globalisation of supply chains which increases complexity and vulnerability to major disruptions. To survive, organisations within supply chains must be resilient in the face of such disruptions. This paper's study addresses these two concerns, i.e. sustainability and resilience, by using computer simulations to explore the effects of disruptions on the sustainability performance of a supply chain.

Keywords: supply chain, sustainability, resilience, major disruptions, computer simulations.

1 INTRODUCTION

A number of recent, prominent natural disasters have caused massive damage to businesses, and have caused management to change businesses and industrial operations, supply chains, strategies and structures. For example, the tsunami that struck Thailand in 2011 led to many businesses collapsing because they were unable to adapt and they lacked the knowledge and ability to manage the unexpected situation. Even many of those businesses that did not collapse were forced to close while the impact of the natural disaster was at its peak. Operating supply chains in these circumstances were extremely problematic. As a consequence of such prominent disasters, businesses are now seeking to learn how to cope with future disruptions and academics are looking to point the way for them.

Our paper aims to help by presenting our preliminary work that analyses supply chain sustainable performance when major disruptions impose new ways of working on parts of the supply chain. We carry out a computer simulation study on a supply chain structure taken from the literature.

This paper is divided into four further sections. Section 2 outlines the related literature. The next section (3) describes the supply chain under study, together with the different disruption scenarios. Numerical results are then presented in Section 4, and finally Section 5 provides some concluding remarks and suggestions for further research.

2 OVERVIEW OF RELATED LITERATURE

Managers' increased awareness of the occurrence and impact of natural disasters forces them to adapt and change their organisation's strategy and prepare plans to reduce the impact and protect themselves from disruption (Spillan and Hough, 2003). Some convincing arguments supporting preparation and adaptation exist, e.g. Autry and Bobbitt (2008) state that the company should be prepared by introducing supply chain security orientations which integrate both steps to address security vulnerabilities and risk management approaches to achieving competitive advantage. Securing the supply chain and managing supply chain risks can increase the organisation's ability to reduce a disruption's impact and to recover quickly. Busch (2011) stated that organisations need to develop capabilities to adapt to climate-related disruptions through resource supply, production process and production distribution. To remain competitive, organisations were advised to invest in securing the resilience of consumer markets, production and supply chains.

To begin with, organisations would need to develop a climate change strategy and planning capability in response to experiencing an unexpected climate surprise. They need to include climate trend in their strategy development because of its unpredictability and its impact on their operations. Nevertheless, many adaptations are reactive rather than proactive ways to mitigate risks and impacts (Haigh and Griffiths, 2011). A study of small businesses shows that entrepreneurs are concerned with crisis planning because of their past experience in crisis events, rather than the existence of a crisis management plan (Spillan and Hough, 2003).

Many researchers have analysed the impact of disasters on organizations and have introduced plans and the concepts of adaption, preparedness and response. Duncan et al. (2011) suggested that to survive businesses should plan and prepare the organisation using the Continuity of Operations Planning (COOP) framework . The framework requires two factors: leaders and resources. Winn et al. (2011) analysed the length and type of impact that natural disasters had in each sector of an industry. They presented the concept of Massive Discontinuous Change (MDC) for organisations to respond to climate impact by improvements in sustainability, crisis management, risk management, resilience and adaptive organisational change. Linnenluecke et al. (2012) dealt with how extreme weather events impacted on adaptation and organisational resilience. They proposed theoretical and practical frameworks related to the organisation's adaptation and resilience to strengthen its capacity to respond to and reduce the impact of extreme weather events. Beermann (2011) categorised the impact of climate change into direct and indirect impact. Pro-active adaptation that focuses on building resilience while combining adaptation and mitigation strategies, is advocated. Therefore, the concept of resilience management (Ponomarov and Holcomb, 2009) can assist in identifying risks and opportunities, coping with climate change both in the short and the long term.

According to Kolk and Levy (2001), the organisation shifts its corporate climate strategy position because of organisation-specific factors, corporate history of profitability and location, market assessments, degree of centralisation and the presence of climate scientists. In this connection, its trends and market activities are examined at company level (internal) and at the company's supply chain level which can assist managers to develop strategies for climate change (Kolk and Pinkse, 2004). Previous studies have focused on the relationship of climate change and sustainable development, and the role of multi-stakeholder partnerships in developing countries on mitigation and adaptation strategies (Pinkse and Kolk, 2012).

From the literature examined, not many studies have shown business strategies are related to extreme weather events. The literature focuses mostly on the government level, disaster impact, organisation preparedness and climate change strategies. Chakravorti (2010) indicates that difficult situations offer rich opportunities for innovative entrepreneurs. Organisations could exploit these opportunities through implementing strategies and operation's activities for making consumer markets, production and supply chains more secure.

3 A CASE STUDY BASED ON COMPUTER SIMULATION

3.1 Description of the Supply Chain

This research explores the effects of disturbances on sustainability performance (Carter and Rogers, 2008) of a supply chain by using a computer simulation. An exploratory study is conducted on a three-echelon supply chain that is based on the automotive industry supply chain presented by Carvalho et al. (2012). Some simplifications were incorporated to run the simulation faster. We evaluate alternative supply chain scenarios that consider both supply chain sustainability and resilience in the face of two major disruptions.

Since the automotive supply chain is very complex, with hundreds of parts, components and materials flowing from hundreds of suppliers, located in different countries, to the automaker, it is critical to establish meaningful features of the supply chain analysed (Srai and Gregory 2008; Brintrup et al., 2012). For practical purposes, only a subset of the supply chain is selected and analysed here (See Figure 1). Critical tier-1 suppliers are considered, since a delay in the components delivered by these suppliers causes a disruption in the automaker's production line. In turn, tier-2 suppliers are also taken into account since they become critical for tier-1 suppliers. Included in the model are stochastic transportation times (Table 1) and processing times (Table 2) for each node of the supply chain. A triangular distribution is assumed for the times. The final demand was considered to be stable.

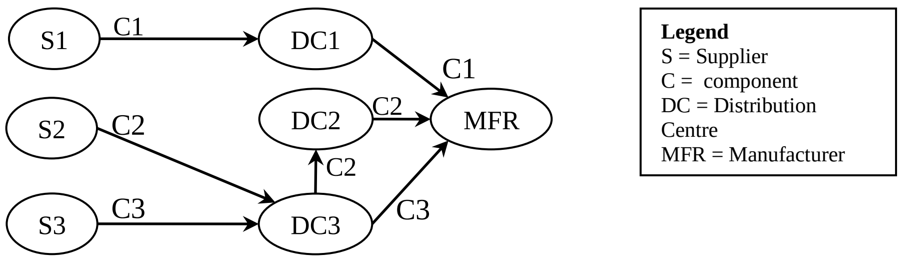

Figure 1: Schematic representation of the supply chain under study.

Table 1: Transport times (triangular distribution) and type of transport.

From	To				Transport type
	MFR	DC1	DC2	DC3	
S1		(5.2, 5.5, 6)			Aeroplane
S2				(5.7, 6, 7)	Lorry
S3				(5.7, 6, 7)	Lorry
DC1	(0.5, 0.55, 0.6)				Small lorry
DC2	(0.5, 0.55, 0.6)				Small lorry
DC3	(0.5, 0.55, 0.6)		(0.5, 0.55, 0.6)		Small lorry

Table 2: Processing times (triangular distribution).

	Product	Administrative processing	Manufacturing or packaging
S1	C1	(0.95, 1, 1.1)	(4.18, 4.4, 4.93)
S2	C2	(2.85, 3, 3.3)	(2.85, 3, 3.3)
S3	C3	(6.65, 7, 7.7)	(3.23, 3.4, 3.91)
DC1	C1	(5.7, 6, 6.6)	(1.11, 1.17, 1.35)
DC2	C2	(1.9, 2, 2.2)	-
DC3	C2 C3	(4.75, 5, 5.5) (4.75, 5, 5.5)	- (0.79, 0.83, 0.95)

3.2 Performance Metrics

To evaluate sustainability, economic, social and environmental performance metrics are considered as outputs of the simulation model. The total production time represents the economic dimension. The social dimension is measured by the number of additional jobs the automaker creates due to growth in the market. Finally, the environmental dimension is represented by carbon emissions of the transportation modes. These metrics are calculated before (initial system) and after each disruption, then compared statistically.

3.3 Simulation Scenarios

In this preliminary study, two major disruptions are compared to the initial, base scenario:

- **Initial Scenario:** this scenario corresponds to the initial configuration (current state) of the supply chain prior to facing disruption.
- **Disruption 1:** In this scenario, the transportation time between DC2 and DC3 increases. We suppose that components have to be re-routed between these two distribution centres because of a natural disaster (e.g., an earthquake or a flood). This is modelled with a triangular distribution with parameters 20, 24 and 26 per entity.

- **Disruption 2:** In this scenario, distribution centre DC2 is closed and hence component C2 must be delivered to MFR from distribution centre DC3 in addition to C3, but using the same small lorry.

4 ANALYSIS OF RESULTS

The system was simulated using ARENA® software, and run for 720 hours in stationary state. A total of 57 replications were carried out. The initial supply chain configuration (initial scenario) was studied and statistics collected on the relevant performance metrics (see Figure 2). We observe in Figure 2 that the highest average time an entity spends in a process corresponds to the Administrative Process at distribution centre DC3 (named Adm. Process 5.Queue in the Figure). This process also has the highest number of entities in queue and its resource (Resource 9 in the simulation model) has the highest utilisation rate. This resource has the highest workload since it has to process both components C2 and C3. As a consequence, it seems adequate to increase the number of resources (i.e. people working on these operations). Later on in this analysis, we will observe that some disruptions on other nodes of the supply network will have a negative impact if the number of resources is increased.

For the economic performance, Table 3 presents statistics about the total production time of components C1, C2 and C3 in the system. Component C1 has the lowest time in the system: it flows through supplier S1 and distribution centre DC1, while product C3 has the highest value (flowing through supplier S3 and distribution centre DC3), mainly due to delays in the administrative process of distribution centre DC3. Table 3 also presents statistics about the system's behaviour when the supply chain is subject to the first disruption. A hypothesis test on the means, with a confidence of 95%, shows that there is no statistical evidence to reject the null hypothesis of no difference between the average production times of all products, when comparing the initial supply chain with the one subject to the first disruption (Disruption 1). In other words, although there is an increase of 4% on the average time an entity spends in the system, there is no statistical evidence to say that increasing the transportation time between distribution centres DC2 and DC3 will increase the total processing time of components C1, C2 or C3.

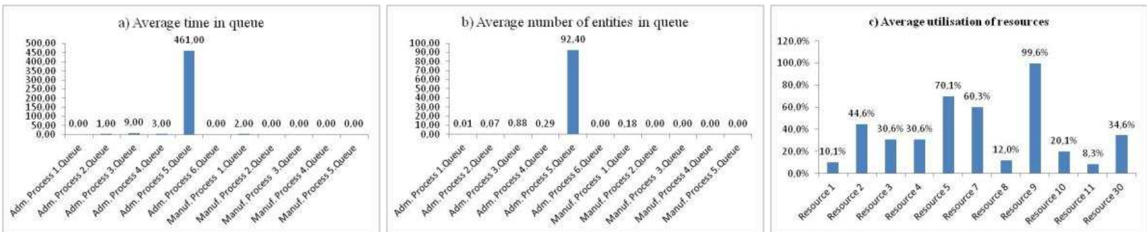

Figure 2: Average time in queue and average number of entities in queues.

Table 3: Economic dimension: Total processing time in the system.

	Initial system		Disruption 1		Disruption 2	
	Average	Half width	Average	Half width	Average	Half width
C1	23.7175	< 0.03	23.7388	< 0.03	23.7623	0.08
C2	482.94	< 15.99	516.90	< 17.05	570.70	50.66
C3	494.03	<16.04	505.18	< 17.09	584.64	50.89

When comparing the initial system with the situation for Disruption 2, the hypothesis test between means (see Table 4) shows that, with a 95% confidence level, there is no statistical difference between the average production times of both configurations. In other words, with a 95% level of confidence, the increase in transport time for component C2 does not impact the total time required to complete its manufacturing.

Table 4: Total processing time in the system .

	Levene test		t-test						
	F	Conf.	T	dof	Conf. (2-side)	μ1–μ2	St.dev. (μ1–μ2)	95% confidence interval Lower	Upper
Assuming equal variances	1.781	0.185	1.680	112	0.096	6.512.554	387.654	-116.832	1.419.343
Not assuming equal variances			1.680	109.39	0.096	6.512.554	387.654	-116.832	1.419.343

Regarding the environmental performance, i.e. the level of carbon emissions, Figure 3a compares between the different simulation models (initial system and Disruption 1 and Disruption 2). The average quantity of CO2 due to transport activities in the initial system is higher than in both situations under disruptions, although the transportation times in Disruption 1 and Disruption 2 have increased. A statistical test between means revealed no reason to reject the null hypothesis that both means are the same. The impact of using lower carbon emission modes of transport, e.g. electric vehicles, was analysed. Assuming that the time required by the electric vehicles will be the same, in the case of Disruption 1a reduction of 32,640 kg-CO2 was observed. Also, when closing facility DC2 (Disruption 2), the reduction in comparison with the initial scenario was about 82,210 kg-CO2.

Finally, regarding the social performance, Figure 3b compares Disruption 1 and Disruption 2 to the initial scenario, The objective here is to evaluate the performance of human resources in the administrative stages of the supply chain. We observe the actual reduction of 21% (6 posts) on the number of jobs in the supply chain due to the disruption of closing distribution centre DC2. This is clearly a negative impact.

a) Environmental dimension: Average level of carbon emissions (kg-CO_2)

b) Social dimension: Average number of new jobs

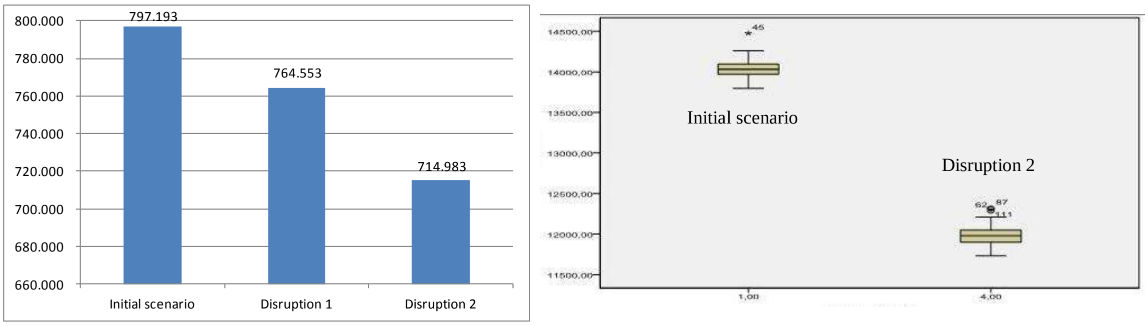

Figure 3: Results for environmental and social dimensions

5 CONCLUSIONS AND FURTHER RESEARCH

From the results in Section 4, it can be concluded that the disruptions have a neutral effect considering the economic dimension of processing time in the system. In a way the system is resilient as the neither disruption impacts on the processing time. The results for the environmental dimension show improvements after both disruptions with a decrease in carbon emissions - this is mainly due to the use of alternative modes of transport with a lower carbon emission rate than those used in the initial scenario. The results for the social dimension show a deterioration in performance with a decrease in newly created jobs, although these could be official paid jobs and some voluntary jobs are generated but not captured by the model.

One of the main limitations of this study is that a hypothesised supply chain with estimated data is analysed. To improve the results it would be necessary to collect real-world data through case studies to fine tune the computer simulations. The implications for theory is a proposed model for testing resilience in supply chains under disruptions taking into account all three sustainability dimensions. The implications for practice are that automotive manufacturers could use similar models to better understand their resilience in the face of disruptions. Future work would need to further test and validate the proposed model with case study and/ or survey methodologies.

ACKNOWLEDGEMENTS

This research is supported by a Marie Curie International Incoming Fellowship within the 7th European Community Framework Programme (project “DISRUPT”, grant No. ESR- 299255).

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