A Model for Designing Sustainable Supply Chain Network under Disruption Risks and Carbon Tax Charges

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Abstract

Although most of the firms' top management now recognises the negative effects of supply chain disruptions on the firm's performance, yet there is little guidance how to Designing Sustainable Supply Chain Network under Disruption Risks. Furthermore, carbon regulatory policies, such as the carbon tax, force companies to adopt supply chain designs that can cope with uncertain natural and human-made disruption risks. This paper proposes a model to tackle the trade-off between the total cost and the carbon tax charges in the design of supply chain network subject to potential disruption risks. The proposed model is a linear programming type that aims to identify the effects of the potential disruptions of external suppliers as well as the variability of order quantity, lead time, and transportation mode on the total cost and associated carbon tax charges of supply chain and in several scenarios of its design related to the changes in these variables. Based on sensitivity analyses, the disruption risks significantly affect the whole structure of the designed supply chains and must be taken into consideration for effective and efficient performance of sustainable supply chain networks. Supply chain managers can use the proposed model to design sustainable and resilient supply networks by considering sustainability via embodied carbon tax charges while coping with uncertain natural and human –made disruption risks.

Keywords: Sustainable Supply Chain Networks, Disruption risks, Carbon tax

1. Introduction

Typically, supply chain design comprises the decisions regarding the number and location of production facilities, the amount of capacity at each facility, warehouse location, transportation modes to serve market, as well as supplier selection for raw materials, components and parts (Chopra and Meindl, 2013). In a global context, supply chain design includes selection of facilities at international locations, ports, incoterms, tax advantages, and market factors (Meixell and Gargeya, 2005). During the last decades, companies have turned their focus on supply chains as a source of competitive advantage (Tang, 2006). Motivated by a number of factors such as globalisation, demand uncertainty, sustainability, and increasing competition, companies have become increasingly interested in the design of their supply chains in ways to achieve multiple objectives, such as cost efficiency, reduced lead times, and sustainability (Sodhi, Son, and Tang, 2012). Despite a growing literature on modelling supply chains (Seuringa and Müller, 2008), there is scarce evidence how to optimise multi-objective supply chains under disruption risks (Olhager, Pashaei and Sternberg, 2015). Supply uncertainty has become a major concern for global supply chain management (Fang and Shou, 2015). Therefore, supply chains that are designed to be sustainable and resilient are more likely to resist in an uncertain environment and at the same time be cost effective and efficient (Tang, 2006). In addition to the financial performance, it is

expected that the design of supply chain to consider the carbon emission regulatory policies represented by tax carbon (Peng et al., 2016). Yet, this has not been investigated widely in the literature and most supply chain models either assume that all parameters are known with certainty (Cordeau et al., 2006 and Ozceylan and Paksoy, 2013) or model new chains stochastically (Listes, 2007).
The contribution of this study is to develop an optimisation cost model for simultaneously reducing the cost and risks effects in organisations that use a JIT approach. Also, from the main focus of the proposed model is considering scenarios in which orders for a set amount of raw materials, to satisfy customer requirements, are shipped by both external and local suppliers using different transportation modes. The optimisation model proposed in this paper is illustrated with real data relates to assembling process for a type of vertical hollow shaft pump motors. The paper is structured as follows: next section the problem definition and the model mathematical formulation are discussed in subsequent sections. A case example is then demonstrated with a simple assembly process for an electric motor with a hollow shaft. Results and discussion follow and conclude the paper with recommendations for further research.

2. The proposed optimisation model

2.1 Problem statement

In order to take into account that variations of pricing for the same product in global marketing, we will assume here that a distribution network consists of supplying raw materials from external suppliers. Further, and to meet JIT strategy, the raw material is instantaneously replenished in the assembly system. In doing so, costs related to stocking up raw materials or to store the final products will be no taken into account. Occurrence of unexpected disruption risks related to economic crises, poor weather, natural or man-made disasters, or a combination of any other risks, affecting external suppliers. No doubt, all of these unforeseen disruption risks are high impact risks on the process, control and the whole supply chain network. However, having local suppliers undermine efforts to improve supply chain system cost efficiency. This is because such plan to reduce effects of disruption risk may be costly due to higher prices links with a lowest occurrence risk and with a shorter lead time. Also, in order to reduce operation cost and promote service quality, the proposed optimisation model takes into account scenarios included orders for a set amount of the input materials from different types of suppliers (external & local) by means of well-handled transport modes. The main modes of transport of logistic are waterways, railways, road ways and airways.

2.2 The model mathematical formulation

The indexes, parameters, and decision variables are described using the notations of El Dabee et al. (2013). For more details about those notations, the reader can be referred to the El Dabee's research.
The objective of the proposed model is minimising the total product cost and risk effect in JIT systems C_T, and carbon tax in the supply chain network C_{tax}. This objective can be formulated as following:

$$Minimise\ C_{Total} = \sum (C_T + C_{tax}) \qquad (1)$$

Various costs associated with total supply chain cost are calculated in formulas (2) – (8). The purchase costs of materials "C_{RM}" from various suppliers are computed in formula (2). The worker cost "C_W" which represents the wages paid to the employee for performing certain duties in any organisation in a time unit, is calculated in formula (3). Formula (4) computes the utilities cost "C_U" of the whole supply chain. The total product cost via supply chain system can be computed as in formula (5). Details about calculations, syntax and semantics of six main types of costs involved in total cost of production can be found in research work done by El Dabee et al. (2013). The costs are: Ordering Cost "C_O", Holding Cost "C_H", Purchasing Cost "C_P", Transportation Cost "C_{tr}", Duties Cost "C_D", Transfer Price Cost "TP".

$$C_{RM} = \sum_{s=1}^{N_{SLB}} C_{UOs} \times OF + \sum_{i=1}^{N_P}\sum_{s=1}^{N_{SLB}} (C_{UHi})_s \times \%d_{RM} \times \left(LT_j + SF\right) + \sum_{i=1}^{N_P}\sum_{s=1}^{N_{SLB}} (C_{UMSLBi})_s + \sum_{s=1}^{N_{SLB}}\sum_{l=1}^{N_T}\sum_{i=1}^{N_P} T_{SLB_s,V,m} \times t_{m_l} \times \%V_i \quad (2)$$

$$C_W = \sum_{i=1}^{N_P} C_W = \sum_{i=1}^{N_P} C_{L_i} + h_i \quad (3)$$

$$C_U = \sum_{i=1}^{N_P} \%Util \times C_{RM_i} \quad (4)$$

$$C_{Tp} = C_{RM} + C_W + C_U \quad (5)$$

C_{Tp} is a cost associated with procuring raw materials from an external supplier. Calculation of this cost is given below:

$$C_{Tp} = \sum_{j=1}^{N_{SE}} C_{UOj} \times OF + \sum_{i=1}^{N_P}\sum_{j=1}^{N_{SE}} (C_{UHi})_j \times \%d_{RM} \times \left(LT_j + SF\right) + \sum_{i=1}^{N_P}\sum_{j=1}^{N_{SE}} (C_{UMSEi})_j + \sum_{j=1}^{N_{SE}}\sum_{l=1}^{N_T}\sum_{i=1}^{N_P} T_{SLB_j,V,m} \times t_{m_l} \times \%V_i + \sum_{i=1}^{N_P}\sum_{j=1}^{N_{SE}} C_{UP_i}(1 - IF_j) \times D_j + \sum_{j=1}^{N_{SE}}\sum_{i=1}^{N_P} tp_j \times C_{UP_i} + \sum_{i=1}^{N_P} C_{L_i} + h_i + \sum_{i=1}^{N_P} \%util \times C_{RM_i} + \sum_{i=1}^{N_P}\sum_{k=1}^{LH_k} \frac{LH_k \times I_k}{Max(LH_k \times I_k)} \times C_{pt_i} \quad (6)$$

Besides, in order to cope with disruption risks depending on supplying the raw materials from local backup suppliers, here CTP calculation will be different. The calculation is:

$$C_{Tp=} \sum_{s=1}^{N_{SLB}} C_{UOs} \times OF + \sum_{i=1}^{N_P}\sum_{s=1}^{N_{SLB}} (C_{UHi})_s \times \%d_{RM} \times \left(LT_j + SF\right) + \sum_{i=1}^{N_P}\sum_{s=1}^{N_{SLB}} \left(C_{UMSLB_i}\right)_s + \sum_{s=1}^{N_{SLB}}\sum_{l=1}^{N_T}\sum_{i=1}^{N_P} T_{SLB,V,m} \times t_{m_1} \times \%V_i \quad (7)$$

$$C_{Tp} = \sum(C_{RM} + C_W + C_U) \quad (8)$$

In order to narrow the disruption risks topic in this paper, the current research considers each supplier impacts supply chain of the production system in a different way including the availability of raw material needed for production system, and ways in which company interacts with their suppliers. Hence, the proposed model sets a score for each supplier based upon its impact on supply chain system. Formula (9) computes this cost:

$$C_R = \sum_{i=1}^{N_P}\sum_{k=1}^{LH_k} \frac{LH_k \times I_k}{Max(LH_k \times I_k)} \times C_{pt_i} \quad (9)$$

$$C_T = \sum(C_{Tp} + C_R) \quad (10)$$

In regard to the carbon emissions in the supply chain, formula (11) computes the total carbon emissions occurring during the transportation of the materials from suppliers to customer zones.

C_E=Σ (mass of raw materials (tonnes or volume) × Destination of required raw materials (km) × emission factor of transport mode or vehicle type (kg CO_{2e}/tonne or volume/km)):

$$C_{Ei} = Q_{Mi} \times v_i \times E_{fmi} \qquad (11)$$

This is the carbon dioxide (CO_2) emission for the raw material's *i* quantity that is needed in each patch to meet the routine weekly production (unit). E_{fmi} is the emission factors for the type of transportation mode used for raw material shipping. v_i represents the destination travelled of required raw materials. Hence, the whole CO2 emission for producing one product:

$$C_E = \sum_{i=1}^{N_P} Q_{Mi} \times v_i \times E_{fmi} \qquad (12)$$

Based on environmental reporting – guidelines for companies on GHG emissions (DEFRA, 2013), the CO_2 default emission factors, depending on the type of transportation mode used for raw material shipping as following: for road transport (petrol & diesel) is 2.31, while for the LPG fuel it is 1.51. And for rail, air, and shipping transportation modes, it will be 0.03, 0.57, and 0.06 respectively. To quantify the cost of carbon emission amount, which associated with logistic operations, a moderate fee level of carbon tax in this research is assumed 25 m.u per ton of CO_2 emitted. Therefore, the total carbon tax associated with transport operations at the SCN is:

$$C_{tax} = C_E \times 25 \qquad (13)$$

3. Case example

The optimisation model proposed in this paper has been tested with a simple assembly process for an electric motor with a hollow shaft. It uses multiple and identical operations to assemble twenty-five individual parts into the finished product ($N_P = 25$). In the case example, the assumption was the production system having trading with 11 individual foreign (external) suppliers (N_{SE} =11) to provide the necessary raw materials in fixed lot size. Since, trading with external suppliers raise an issue of disruption, another assumption was made here to cope with such case represent by using seven domestics (local backup) suppliers ($N_{SLB} = 7$) can provide raw materials with a lower risk factor, shorter lead time but with a higher cost. With adopting Just-in-Time strategy, receiving raw materials from those local and external suppliers subjects to the need in the production system and according to the scheduled specified time as listed in Table 1. Table 1 also summarises of the weight of items (in kg) required for producing one electric motor. The production system consists of a collection of five operations. In order to run these, the company utilises five workers (W_1, W_2, W_3, W_4, and W_5 respectively) and each worker runs an operation alone. The daily shift hours N_h are based on a schedule of eight hours per day for a five-day working week. The hourly wage per worker C_{Wi} is fixed at a rate of 14 monetary units (m.u)/ hour). Utilities cost C_U is assumed to be equal to 10% of raw material cost. The production system can benefit from discounts offered when purchasing extra amounts of raw materials from both external and local suppliers. The discounts offered by external and local backup suppliers for purchasing extra raw materials are approximated around 5 to 14%. Seventy units per day, is the constrained production schedule. In the first instance, raw materials are procured from regular, external, suppliers S_E, when this is disrupted, by one or more of these suppliers, local backup suppliers are used S_{LB}. The suppliers lead time directly affects the order so it is imperative to take this into consideration when meeting customers' needs during fixed intervals and at normal times. Any time delay delivery of raw materials can greatly affect other items and production schedules. The end user or the customer, who ultimately uses or consumes the product, purchase it at 485 m.u. Further details about required data of this case example for applying the proposed model, are presented in El Dabee et al. (2013).

Part No.	Weight (kg)	Supplier type					
		Local Backup Supplier			External Supplier		
		Supplier No. S_{LB}	Lead-Time (*LT*) (Days)	Destination of Required Raw Materials (*v*) (Km)	Supplier No. S_E	Lead-Time (*LT*) (Days)	Destination of Required Raw Materials (*v*) (Km)
1	3	1	4	350	1	24	5000
2	2.5	1	4	350	1	24	5000
3	0.15	2	6	500	2	32	5000
4	3	1	4	350	1	24	5000
5	0.75	3	3	300	3	18	7500
6	0.1	4	5	400	4	38	6000
7	2.2	4	5	400	4	38	6000
8	6	4	5	400	5	42	6500
9	0.25	4	5	400	5	42	6500
10	0.75	3	3	300	3	18	7500
11	0.2	2	6	500	2	32	5000
12	2.5	5	2	250	6	28	5000
13	1.2	5	2	250	7	35	8000
14	0.15	5	2	250	7	35	8000
15	0.3	5	2	250	6	28	5000
16	0.15	3	3	300	9	20	3500
17	0.25	6	8	500	8	45	4000
18	0.1	2	6	500	2	32	5000
19	0.15	6	8	500	8	45	4000
20	0.25	3	3	300	9	20	3500
21	0.15	6	8	500	8	45	4000
22	0.25	7	7	600	10	28	5000
23	0.15	7	7	600	10	28	5000
24	0.25	7	7	600	10	28	5000
25	0.25	7	7	600	11	21	4000

Table 1: Details of electrical motor parts, external and local backup suppliers of these parts, the required lead-time and destination associated with supplying these parts from those suppliers

4. Results and analysis

In this section, computational experiments are performed to measure of how robust the optimised solution to the changes in different levels of decision variables. To solve the resulting model, that is find the values to be given to the decision variables to achieve lowest C_{Total}. One of the decision variables will be the S_{Ej}; the number of external suppliers providing raw material to the production system is 11 suppliers. The allowable level for each supplier is two levels (0 &1). When S_{Ej} = 1, the assumption is S_E can supply raw materials, and C_T can be calculated by using formula 3. While when $S_{E\,j}$= 0, S_E has disruption and formula 4 is to be used to in the calculation of C_T. In both cases of calculation to C_T, the daily customer demand (limit by one here) from the final product represent, *dp* is used in these calculations. *dp* has four levels (*dp* = 1, 2,3, 4). Also, from the model components is t_m. It represents the critical transportation measurement of raw materials shipped using transportation mode *m* with 11 suppliers, which has 4 levels (*m* = 1, 2, 3, 4) represent freight transport mode: road transport, rail, air, and shipping respectively. Finally, the weekly production rate of the final product involves ordering a batch from 11 suppliers. Based on the level of production rate that is needed to meet anticipated sales for the next week, the order quantity "*QM*" has seven levels: 350, 700, 1050, 1400, 1750, 2100, and 2450).

4.1 Scenario one: different cases of occurrence for external supplier's disruptions and decision variables change are made to different levels

When the company used previously mentioned external and local suppliers (N_{SE}=11 & N_{SLB}=7) to supply the raw materials for their final production process, the main concern is occurring many disruptions to the supply chain system. To better understand this concern, likelihood of both suppliers' disruptions (non- performance) is assumed as follows: when the external supplier (denoted by *j*) has disruption: i.e $S_{E\,j}$= 0 else S_{Ej} =1. For simplicity, this model assumes the same for local supplier. Table 2 illustrates a random selection of ten such disruptions. The table showed that the optimum combination obtained through C_{Total} was superior to the ones obtained by optimising the decision variables separately. Obviously, from the results, the total cost of producing the product is a function of examined decision variables here; quantity of raw material procured from both types of suppliers (external & local), customer demand, lead time to deliver raw material to the production facility, and transportation mode. During any disruption occurs to the system, any change in one of the decision variables will cause or affect change in the final cost result. Within this context, based on local supplier reliability while all external suppliers are disrupted, and using a higher level of decision variables, it is found that several costs can be altered in response to these changes. In compare to other disruptions, C_P has the highest rate of change. However, under these changes, the change in C_{tr} value is relatively lower as it results when transporting raw material from origin to the production system.

No.	External supplier situation in the supply chain											Q_{RM} / week (unit)	d_p / day (unit)	t_m (unit)	C_T (m.u)	C_{tax} (m.u)	C_{Total} (m.u.)
	1	2	3	4	5	6	7	8	9	10	11						
1	1	1	1	1	1	1	1	1	1	1	1	350	70	1	393.40	230.1	623.5
2	1	1	0	0	1	1	0	0	1	0	1	350	70	2	428.00	183.7	611.74
3	1	0	1	1	0	0	1	1	0	0	0	350	70	1	447.95	148.3	596.27
4	0	0	0	1	1	0	0	0	0	0	0	1050	140	4	444.54	1799	2243.14
5	1	0	1	0	0	1	0	1	0	1	1	350	70	1	458.79	141.5	600.26
6	1	1	0	1	1	0	0	0	1	0	0	1050	140	1	412.15	553.8	965.90
7	0	1	1	0	0	1	1	0	1	0	1	350	70	1	464.23	87.96	552.19
8	1	1	0	1	1	0	1	0	0	1	1	350	70	1	430.95	206.7	637.67
9	0	1	1	1	0	0	0	1	1	0	0	350	70	1	449.90	70.50	520.40
10	1	1	1	0	0	1	0	1	1	1	0	350	70	1	456.35	145.4	601.73

Table 2: Computational results for some external suppliers' disruption using different levels of the decision variables

4.2 Scenario two: different cases of occurrence for external supplier's disruptions and decision variables are remained unchangeable variables are remained unchangeable

Here, a comparative case is undertaken to investigate how the supply chain system performs economically under two statuses. The first, when all external suppliers were able to supply their raw materials to the production system and the second where those suppliers had disruptions to their production system. Examined status results are presented in Figure 1. Here, a comparison illustrates the effects of disruptions on the cost types. The outcomes from supply chain disruptions include purchasing the raw materials from local back-up suppliers. The expectation payment for this type of suppliers is higher when compared to the external suppliers. C_P and C_R are higher than other cases when all suppliers are disrupted and C_H, C_{tr}, *TP* and C_D are the lowest.

4.3 Scenario three: different levels of decision variables in presence of disruptions to some external suppliers

A sensitivity analysis in this scenario assumes the external suppliers "S_{Ej}" hold the Odd numbers: *j* =1, 3, 5, 7, 9, and 11 are in-active where $S_{E\,j}$=1, and the rest of external suppliers hold Even numbers: *j* =2,4,6, 8, and 10 are disrupted where S_{Ej} = 0. The results in Table 3 show the minimum total cost objective (C_T = 418.2) is small, while the other objective is relatively high. This shows that sustainable supply chain system cannot be economical in this group of proposed design. C_{tr}, C_U and C_R are the cost components which are mainly affected by disruptions. C_{tr} is directly impacted as long as it is dependent on the transportation mode used to supply raw materials to the production system from multiple suppliers at different locations; external as well as local. Affecting C_U by disruption results as it is a percentage rate of some cost types mentioned previously. Thus, C_R arises and is caused by using additional suppliers to cope with supply chain disruptions.

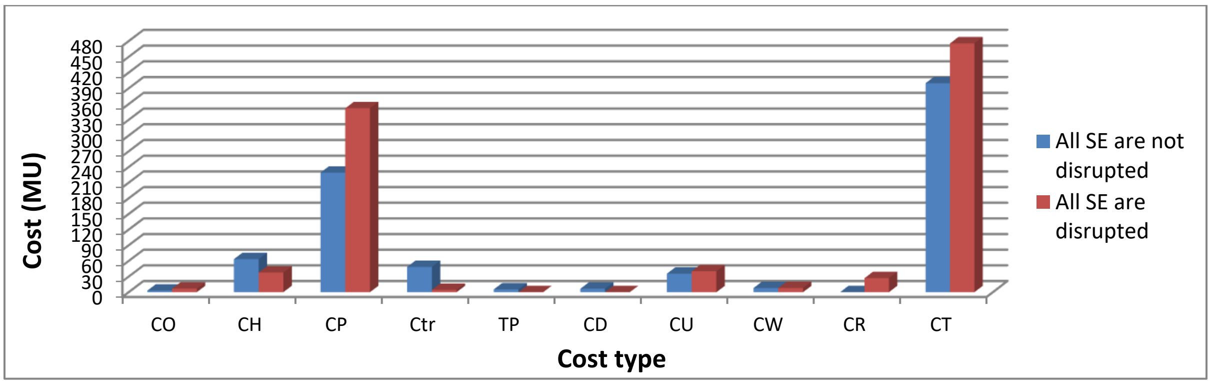

Figure 1: Cost type comparisons between all external suppliers (1) uninterrupted (2) disrupted

No.	External supplier situation in the supply chain											Q_{RM} / week (unit)	d_p / day (unit)	t_m (unit)	C_T (m.u)	C_{tax} (m.u)	C_{Total} (m.u.)
	1	2	3	4	5	6	7	8	9	10	11						
1	1	0	1	0	1	0	1	0	1	0	1	350	70	1	435.8	197	632.76
2	1	0	1	0	1	0	1	0	1	0	1	350	70	3	447.8	31.75	479.55
3	1	0	1	0	1	0	1	0	1	0	1	700	95	1	428.3	394	822.28
4	1	0	1	0	1	0	1	0	1	0	1	1050	140	2	425.4	50.5	475.89
5	1	0	1	0	1	0	1	0	1	0	1	1750	115	3	484.1	158.5	642.59
6	1	0	1	0	1	0	1	0	1	0	1	2100	140	4	523	6165.	6688.2
7	1	0	1	0	1	0	1	0	1	0	1	1050	170	1	418.2	591	1009.2
8	1	0	1	0	1	0	1	0	1	0	1	1400	210	2	425.7	67.5	493.2
9	1	0	1	0	1	0	1	0	1	0	1	2100	155	3	489.9	190	679.9
10	1	0	1	0	1	0	1	0	1	0	1	1050	210	4	462.5	3083	3545.3

Table 3: Decision variable change results (computed) for the case when: S_{E1}, S_{E3}, S_{E5}, S_{E7}, S_{E9} and S_{E11} are active (S_{EJ} =1 not distributed), other external suppliers: S_{E2}, S_{E2}, S_{E4}, S_{E6}, S_{E8} and S_{E10}, are distributed (S_{EJ}=0)

5. Conclusion and further research

Consider catastrophic tsunami in Japan, which had significant impact on the supply chain of many companies, as well as ongoing turmoil in the middle east which is also adversely affect global supply chains in particular of possible disruptions of oil supplies, this paper addressed raised questions regarding supply chain disruption risks and how to manage it. To that end, this paper has presented an optimisation model for designing an integrated supply chain system, which not only for a simultaneous cost-risk reduction in JIT systems, but it also considers into account the tax carbon charges of the system in the proposed design. The model incorporated dealing with two types of key suppliers; local and external who provide the company with required materials into production process and options that can have with different cost and lead times to respond unpredictable risks. Both types of multi-suppliers, external and local, were used to manage disruptions due to occurring natural and/or human caused disasters and economic crises. To validate and improve the proposed model, an industrial case example was used to test the model. The numerical experiment results obtained from conducted case example showed the validity of the model. It also proved that the proposed model is effective in measuring supply chain design scenarios performance and identifying whether a proposed design could be the one that meets design expectations. the work in this paper can be extended to propose a model to solve design of supply chain system problem that contains supplying multi product and multi process supply system can be divided into sub-problems where each one has its own processes.

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