Linking Carbon Performance and Effectiveness of Supply Chains

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Abstract. Rendering the supply chain more eco-friendly is an innovative idea progressively adopted by industry. Consequently, our research focuses on the CO2 emissions along the supply chain due to freight energy use and storage. A supply chain approach by using a discrete event model was developed. Our proposed tool is able to model Re Order Point production management policy (ROP) and the main demand response strategy Make To Stock (MTS). In addition, the Overall Equipment Effectiveness indicator (OEE), the location of the firms and their types of products are modeled. This method is applied to mechanical and textile industries. The principle objectives of the study are twofold: develop a supply chain simulation benchmark and conduct pertinent experiments to improve green supply chain.

Keywords: simulation, carbon emissions, supply chain.

1. Introduction

Companies have been interested in supply chain management since the 1980s because of the benefit when collaborating downstream with suppliers and upstream with customers all along a chain. In 1987, the Bruntland report incorporated the definition of "development that meets the needs of present without compromising the ability of future generations to meet their own needs"[1]. This concept has begun to be adopted among many companies during the last few decades. Moreover, sustainability has become a way in which organizations distance themselves from the pack, with the resulting improvement in environmental and social factors and the advantage of reducing cost or even increasing competitiveness. The comprehensive and efficient design of supply chain still lacks some conceptual tools to understand the complex ties between industrial indicators (mostly inventory and delay) on one side, and the environmental impact of meeting their day to day needs on the other. For instance, Carrier (UTC group), a large cooler manufacturer, currently has dealt with a challenging design problem with some success. In another sector, textile, Zannier Group also looks for methodologies to design green supply chains. Roughly, their main problem is how to select suppliers so as to lessen environmental impact without adversely affecting industrial efficiency.

To address part of these concrete issues, our paper studies how localization of suppliers influences both industrial and environmental performance within a supply chain. While inspired by these two real life industrial cases, our model encompasses other settings as well. It consists of three manufacturers operating along the same value stream, and addressing a final market. With this, three tier supply chains can be evaluated in term of CO_2 emissions. Different scenarios can be generated to compare these emissions. One of the objectives is to determine best practices to balance green performance and supply chain efficiency. To do so, discrete event simulation is used to benchmark supply chains composed of firms with various levels of efficiency, two types of products (depending on weight and bulk) and four different locales. We evaluate their resulting performances in terms of inventory levels, customer service, and CO_2 emissions due to storage and transportation.

The remainder of this paper is organized as follows: section 2 presents a brief state of the art on green supply chain modeling and simulation. Section 3 suggests a supply chain model. Section 4 explains the way an enterprise library of standard cases has been built to support the model. Section 5 discusses the configuration and the calibration of the simulator and explains the experimental approach. Section 6 shows the main results. Section 7 goes into further detail on these results and provides some managerial insights. Finally, the conclusion provides some perspectives on possible future research.

2. Green supply chain modeling and simulation: state of the art

Increasingly, firms are pushed by their customers, shareholders and governments to adopt environmental measures. In addition, several authors show empirically that environmental and financial performances have a positive relationship [2]. Many papers have also indicated that it is financially beneficial for companies to adopt a green supply chain [3]. In addition, other articles also establish a link between green initiatives and increased competitiveness, but do not always have enough evidence to measure the importance [4].To assess performance, green indicators have been studied [5-7]. Several authors have selected relevant indicators [8]. Examples of indicators and their use in research are given in [9]. They agglomerate them in six groups according to activity in the supply chain. On top of that, an eco-efficiency analysis has been conducted [10]. In their study, the societal weighting factors used indicate that emissions, energy and raw materials consumption are the three principal factors (approximately 20% each). Additionally, air pollution emission accounts for 50% of all emissions. As most are aware, the greenhouse gas CO_2 is the measurement of reference. Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC) the most important problem facing our planet is global warming with the resulting increase of CO_2 [11]. Based on the aforementioned literature, our research focuses on the CO_2 emissions along the supply chain.

One of the results of a survey was that supply chain availability, quality, and lower level of greenhouse gas emission (mostly CO2 emissions) are positively linked [12]. An article based on an analytical hierarchy process (AHP) proposed to evaluate a supply chain of an environmental point of view through a Delphi group of environmental experts [13]. But the AHP seems to have some drawbacks: there is no single hierarchy for most criteria, and human trials may bias the results. Another approach used a model called Interactive Selection Model which systemizes the processing steps before the implementation of AHP [14]. But all these studies rely on statistical analysis based on collected data. This restricts the cases and requires data of high quality. These limitations motivated us to propose another methodological approach based on a discrete event simulation model.

Simulation methods are gaining more and more importance both in research and industrial practices. Indeed, making it possible to explore policies and operating procedures is one of the greatest advantages of simulation [15]. This ability to evaluate "what if" scenarios with a variety of inputs makes simulation a useful technique for analyzing supply chains [16]. Some authors argue that the increasing popularity of simulation as a tool in supply chain management is due to its excellent capacity to evaluate system variation and interdependencies [17]. This enables a decision-maker to assess changes in part of the supply chain and visualize the impact of those changes on the other parts of the system, and ultimately on the efficiency of the entire supply chain. A recent study used the simulation to create a green supply chain [18]. The study is based on ideal conditions and the authors underlined that it could be interesting to make it more realistic.

Therefore studying a CO_2 indicator throughout a supply chain and demonstrating the changes with different management choices seems relevant. With these aims in mind, a data driven supply chain model is proposed here to analyze supply chains which differs by the choice of location of product of the players involved.

3. Supply chain conceptual model

The proposed model consists in a raw material supplier, a supply chain composed of three enterprises, and a final customer. The raw material supplier is considered to have an infinite supply of stock. The final customer orders according to a stochastic external demand.

Between each enterprise, a delivery module will simulate transport and buffer storage due to delivery time amongst firms. It is composed of a transportation resource to be chosen and downstream and upstream inventory buffers that will be sized according to the frequency of delivery. A CO_2 Data collector is attached to the delivery modules.

Each enterprise is comprised of a Planning and Control System to manage procurements with a reorder point (ROP) rule, and synchronize the flows according to a Make to Stock (MTS) policy. The physical system is made of a reception module and two serial processes, transforming raw material (RM) into semi-finished goods (SFG) and SFG into finished goods (FG). These production processes are transfer lines where two product flows are simultaneously treated.

4. Enterprise instance collection

A library of enterprises has been built to provide the three tiers within the supply chain model. A consistent way to construct a realistic library was to utilize real manufacturing data to categorize production systems. In this article, the data came from the two industrial cases: Carrier and Zannier groups. More generally, in the model manufacturers have been classified according to three main attributes: Overall Equipment Effectiveness (OEE), localization and type of product.

4.1. Overall equipment effectiveness

An effectiveness level is used in the model as a metric to categorize the manufacturing systems. OEE is defined as follows: OEE = Availability × Performance × Quality. Availability is measured in amount of downtime. Performance is assessed in losses of speed. Finally, Quality is gauged by percentage of defects. The OEE indicator is widespread, easy to calculate for firms and offers a comprehensive evaluation of a production process. Furthermore, OEE can be embodied quite easily within simulation parameters like cadences, breakdowns, scrap rates and set up times. Many studies have provided OEE levels in various industrial sectors [19-20]. The typical world class manufacturing target tends to be approximately 90 % (data of Carrier).

4.2. Plant locations and types of products

Shipment of raw materials, parts, and finished goods from one location to the next in a supply chain happens by truck, boat or plane. To calculate the CO_2 emissions, we need to model the shipping distance between two companies as well as estimate the weight and bulk of the manufactured product. Transport pollution types and levels are dependent on cargo weight, mode of transportation and distance travelled. Indeed, the unit of the CO_2 emissions is calculated in g per m² or ton-km.

First, the plant locations are defined by four areas representing the distance between two successive echelons of the supply chain: local (50km), regional (500km), continental (1600km) and global (8000km). In the transportation module, in case of delays, a speedy transportation mode is modeled. A standard or express transportation is automatically chosen whether the expected delivery date is attainable (including the transport time). Here, discrete event simulation provides a powerful tool to dynamically calculate the delays and trigger express transports with respect to the manufacturing parameters (set up, breakdowns, scraps items and inventory buffers).

Second, we have categorized products into four types according to the following attributes: heavy/light and bulky/small. Only the two extremes are studied: bulky/heavy and small/light. The others are linear combinations of the other two. Configuration 1 is typical of the mechanical industry, and will be illustrated by data from Carrier. The data of the product 1 are: 8,44 tones and 53,93 m². Configuration 2 is widespread in the textile industry and will be instanced with data from Zannier group. The data of product 2 are: 0,0002 tones and 0,0005 m².

For freight energy use, only the weight of the product and the number of kilometers between two firms are used. The French Agency of the Environment and the Energy Mastery (ADEME) provides the figures of CO_2 emissions per ton-km. Table 1 indicates the number of CO_2 emissions in gCO_2 equivalent per ton-km according to the transportation. For the local, regional and continental loci trucks are often used. Worldwide delivery employs container shipping. To explain more fully the figures from table 1 it is important to know that for local transportation, the trucks used are smaller than for the regional or continental shipping so the CO_2 emissions are higher per kg.km. When time is of the essence, planes are used and they emit more CO_2 during take-offs and landings than during the flight itself. Therefore, emissions per km are significantly higher for medium haul than long haul. The warehouse is considered as an industrial shed.

Table 1. CO_2 emissions due to the transportation according to the location and storage (uncertainty)

Location	gCO_2 equivalent per ton-km/ per m²
Local (l)	145,10 (10%)
Regional (r) or Continental (c)	74,90 (10%)
Global (g)	37.68 (10%)
Express continental air freight	570 (20%)
Express global air freight	320 (20%)
Industrial shed	75 000 (50%)

5. Simulation model and calibration

5.1 Configuring simulation

Before the start of the simulation, the supply chain needs to be configured. Adding a manufacturer type to the library entails (i) opting a locale (l, r, c and g), (ii) choosing a type of product (product classes 1 or 2). Therefore, the three tiers may have different profiles. These are picked up from the library. Then, the model is automatically formed. ARENA simulation software is used.

5.2 Simulation characteristics

Final customers are modeled with a normal stochastic distribution with an average of 50 units, a standard deviation of 5 at an arrival frequency of once a day. Customer requests are directly transformed into delivery orders at the finished goods, following a Make To Stock policy. If enough finish goods are available, then delivery proceeds from stock. Otherwise, a delay is recorded in the case for local or regional destinations. If the order date is overdue, an express transportation is effectuated in the case for continental or global shipping. A buffer stock due to the delay of transportation is forecasted and another buffer is required for the lead-time between two transportations departures.

Production processes, set up and changeover times have been modeled using stochastic triangular distributions with variability. Availability is adjusted via breakdowns modeled by exponential functions representing mean times among failures and repairs and set up times. Performance is set via machines cadences. All these parameters are fixed to meet effectiveness target values, and correspond to average measures from our case studies. After having set these variables in an enterprise profile, command variables such as replenishment reorder points and batch sizes are calibrated. In our approach, the command variables have been calibrated so that the supply chains always meet the final demand without any delay. This means that extra inventory buffers have been sized to compensate for the distance between firms in the case of regional, continental and global locations. This calibration makes it possible to compare supply chains offering identical customers' performance, and to focus on CO_2 emissions.

Twenty simulation runs of 10 000 hours were performed for each configuration. Simulation campaigns are sufficiently numerous and long-term to overcome the system's transitional phase and seem to take account the possibility of most random phenomena.

6. Results of simulation

128 configurations can be simulated because two types of product can be chosen and four locations can be designated. Discrete Mobile Centers method is used to categorize the locations with both transport and storage CO_2 emissions. Six classes were obtained (table 2).

Table 2. Location according to classes

class 1	**rgr, grl, glr, cgr, gll, ggr, lgl, grr, ggl, rcl**
class 2	rrg, gcg, cgg, grg, ggg, glg, lgg, llg, ccg, rgg
class 3	rcc, crc, clg, ccc, glc, lgc, grc, lcg, crg, rgc, llc, clc, rlc, lcc, lrc, rlg, rrc, rcg, lrg, gcc, cgc, ggc
class 4	rcr, gcl, cgl, grc, crr, ccl, rgl, lgr, cll, lcl, clr, lcr, crl, ccr
class 5	rrl, rlr, rrr, llr, rll, lrl, lrr
class 6	Lll

Figure 1 shows the distribution of 6 classes. Class 2 has the highest level for emissions due to storage and transportation. We find Xgg, gXg and XXg configuration for product 1. Class 3 presents fewer emissions than Class 2 and is composed of Xcc, cXc. Class 6 has the lowest level for both emissions with the 3 local configurations. Class 5 emits more according to storage than class 6 and is composed of configurations which are combinations of regional and local. The other classes 1, 4 are concentrated and are composed of regional or local in the last tier. If an analysis of product 2 were to be presented the same classification would be found with a decrease of an average of 10^5. The results of the products 3 and 4 are obtained with linear combinations.

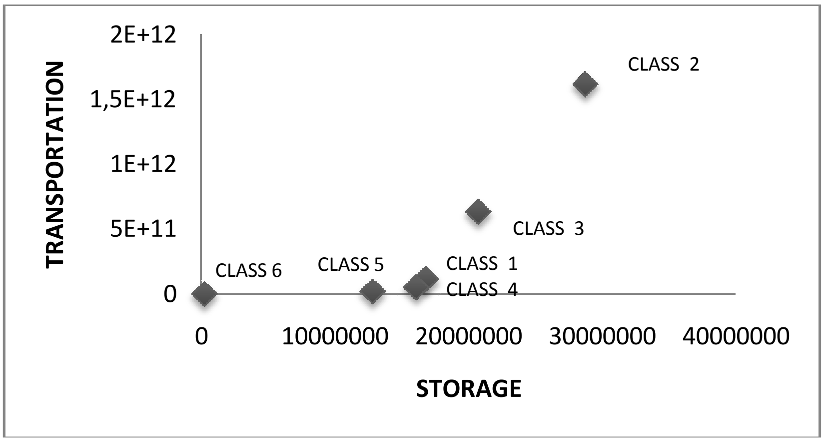

Fig. 1. Distribution of classes according to CO_2 emissions due to storage and transportation in kg CO_2 equivalent

7. Discussion and managerial implications

Simulation results highlight the following findings: according to the type of product, the CO_2 emissions could increase of a factor of 10^5 for storage and 10^4 for transportation. When the supply chain is homogeneous, the CO_2 emissions logically increase is in the order of 3 local, 3 regional, 3 continental, 3 global. If the supply chain is very heterogeneous (containing local and global locations), then the green performance degrades as the global locations are located further downstream the supply chain. Indeed, the second and also the last tier have to absorb the delays and so on of the upstream tier. Therefore there is more transportation required at the end of the supply chain as well as more express transportation. Generally, when the arrangement is heterogeneous, the more distant the location is downstream the more their CO_2 emissions increase: llr, llc, llg are emitting more CO_2 than lrl, lcl, lgl and than rll, cll, gll.

The results provide a basic guide for logistics partner selection helping to choose their supplier to optimize their green supply chain. While not obvious at first glance, it is crucial to pay attention to the position of the farthest link in the chain. Even if the first two locations are quite close, farther the end producer is from the final customer more the emissions increase.

8. Conclusion and perspectives

In this paper a supply chain model is developed, implemented and assessed. Simulation is used to evaluate a wide variety of supply chain scenarios. This simulation tool has been tested in the case of a supply chain in a make to stock environment to produce two flows of products with two types of products and with four locations choices (local, regional, continental and global). Types of products affected the CO_2 emissions considerably. The effect was linear. Unexpectedly, last tier's locations have significantly influenced simulation results with global locales being the worst choice.

This brings an irksome question: in a green supply chain, would it be better in term of CO_2 emissions to have in place a local supplier with poor production management and high stocks, or a global supplier with world class results and lean inventories? Future work may focus on this question by decreasing the OEE performance of some tiers and fine tuning consequently the simulation parameters. A more complete view of the ecological performance of enterprises could be simulated.

11. References

1 Bruntland G., http://www.ecoresponsabilite.environnement.gouv.fr. , 05/26/2009
2 King A. & Lenox M., Does it really pay to be green? An empirical study of firm environnmental and financial performance. The Journal of Industrial Ecology, vol., pp. (2001).

3 Porter M. E. & Van der Linde C., Green and competitive : ending the stalemate. Harvard Business Review, vol. 73, pp. 120 (1995).
4 Rao P. & Holt D., Do green supply chains lead to competitiveness and economic performance? International Journal of Operations & Production Management, vol. 25 (9), pp. 898-916 (2005).
5 Brent A.C. & Visser J.K., An environmental performance resource impact indicator for life cycle management in the manufacturing industry. Journal of Cleaner Production, vol. 13 (6), pp. 557-565 (2005).
6 Siracusa G., Sterlini S.E., A new methodology to calculate the environnemental protection index. A case study applied to a company producing composite materials. Journal of Environmental Management, vol. 73, pp. 275--284 (2004).
7 Srivastava S.K., Green supply-chain management: A state-of-the-art literature review. International Journal of Management Reviews, vol. 9 (1), pp. 53 (2007).
8 Scherpereel C. et al, Selecting Environmental Performance Indicators. Greener Management International, vol. (33), pp. 97 (2001).
9 Tsoulfas G.T. & Pappis C.P., A model for supply chains environmental performance analysis and decision making. Journal of Cleaner Production, vol. 16 (15), pp. 1647-1657 (2008).
10 Saling P.*, et al.* Eco-efficience analysis by BASF : the method. The International Journal of Life Cycle Assessment, vol. 7 (4), pp. 203-218 (2002).
11 Soytas U. & Sari R., Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. Ecological Economics, vol. 68 (6), pp. 1667-1675 (2009).
12 Vachon S. & Mao Z., Linking supply chain strength to sustainable development: a country-level analysis. Journal of Cleaner Production, vol. 16 (15), pp. 1552-1560 (2008).
13 Handfield R. et al, Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. European Journal of Operational Research, vol. 141 (1), pp. 70-87 (2002).
14 Kannan G. et al, Analysis and selection of green suppliers using interpretative structural modelling and analytic hierarchy process. International Journal of Management & Decision Making, vol. 9 (2), pp. 1-1 (2008).
15Banks J., Handbook of Simulation : Principles, Methodology, Advances, Applications, and Pratice (John Wiley, New York) 1998.
16 Hellström J. & Johnsson M., Using discrete-event simulation in supply chain planning. *The 14th Annual Conference for NRL* (2002).
17 Wyland B., Buxton K. & Fuqua B., Simulating the supply chain. IIE Solutions, vol. 32 (1), pp. 37 (2000).
18 Hui K., Spedding T.A., Bainbridge I., & Taplin D.M., Creating a green supply chain : a simulation and a modeling approach. *Greening the supply chain by J. Sarkis*, ed SpringerLondon), pp 341-363, (2006).
19 Ahmad M.M. & Dhafr N., Establishing and improving manufacturing performance measures. Robotics & Computer-Integrated Manufacturing, vol. 18, pp. 171 (2002).
20 Muchiri P. & Pintelon L., Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. International Journal of Production Research, vol. 46 (13), pp. 3517-3535 (2008).