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Demand Driven Material Requirements Planning buffer positioning considering carbon emissions

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Abstract. Firms are more and more interested in reducing the carbon footprint related to their activity. Their supply chain remains one of the main sources of carbon emissions. Better operational routines and planning adjustments have proven to be an effective way to reduce the carbon emissions but not enough. In this paper, the carbon footprint is taken into consideration in the Demand Driven Material Requirements Planning (DDMRP) strategic buffer positioning problem. The focus is put on the storing activities and transportation, for which a function was proposed to quantify the associated emissions. Two environmental regulations are simulated: carbon emissions tax and carbon emissions cap. These approaches have been implemented in a buffer positioning model with a cost minimization objective function. The resulting models were solved using CPLEX solver for multiple instances. The numerical results provide a better measurement of the buffer positioning impact on the carbon emissions. The observed sensibility of the problem to the environment parameters would give insights for further research work.

Keywords: Buffer positioning problem · DDMRP · Carbon footprint.

1 Introduction

The optimization of logistics and production activities has been based only on economic criteria (cost minimization or profit maximization) over a long period of time, regardless of the negative impacts these activities may have on the environment, mainly in terms of carbon emissions [1]. Over the past decade, environmental concerns have become increasingly relevant to businesses as government environmental policies have become stricter and customer awareness of the environment has increased. As a result, many traditional logistics and production management issues have been re-examined with the environmental considerations [2].

Besides, many research projects were engaged recently to try to measure, minimize or completely substitute the polluting supply chain activities. Some researches focused their work on specific supply chain configurations. Hong et al. [3] studied the carbon emissions problem for a green product type with a

stochastic demand in a guaranteed service time configuration with carbon cap strategy. They optimized the service time and option selection decisions while minimizing the costs. Tiwari et al. [4] studied the same problem for a deteriorating product integrated in a single-vendor single-buyer inventory model. Their model minimized the inventory level and the carbon emissions through a better product delivery planning. Hovelaque and Bironneau [5] linked the carbon emissions to the price and environmental dependant demands for an inventory with Economic Order Quantity (EOQ) policy, providing the order quantity that minimizes the holding costs and ordering costs, maximizing in consequence the profits. Ni and Shu [6] presented a formal presentation of a carbon emission function to optimize the safety stock placement in a multi-echelon supply chain with guaranteed service model. Their work finds a trade-off between service time and carbon emissions to position safety stocks. They show that a potential increase in the inventory levels may reduce the emissions with the proper carbon cap or carbon tax price. Hammami et al. [7] and Manupati et al. [8] generalized the problem to a multi-echelon setting. Our work fills the gap of the carbon emissions problem for a DDMRP [9] setting with guaranteed service configuration.

In this article, we present a model of buffer positioning with an ecological aspect. The installation of a buffer leads to the setting of a stock and thus adds a source of CO₂ emissions. However, the frequency of replenishment orders is considerably reduced, thus intriguing a production mode with much lower emissions. To study this problem, we introduce the parameters and the settings of the environment in Section 2. In Section 3, two strategies are implemented, that of the carbon tax and that of the authorized emissions limit. The first one translates the emissions in terms of budget which is added to the objective function formula representing the sum of the costs. The second one sets a cap on emissions not to be exceeded during production, thus adding a constraint to our model. The experimentation results are presented in Section 4 with a related analysis of the deduced observations. A conclusion is made in Section 5 with the perspectives of our future research work.

2 Model setting and assumptions

For a better accuracy, the simulated environment should be well set and defined. We present in the next paragraphs the different parameters on which the proposed research is based and where our model would be tested and simulated. In addition to the approach strategies to carbon emissions sources and regulations that would be discussed.

To set the **supply chain configuration** for this paper, we consider a single echelon Supply Chain with a guaranteed service approach [10]. A standard case of a firm with a set of manufacturing facilities and suppliers are represented by a Bill of Materials (BOM). The nodes represent the flowing products of the Supply Chain: the raw materials, the intermediate products, and the final product. A fictional root node representing the end customer is also added to the structure

of the BOM, as seen in our previous work [11]. It would be referred to as node $i = 0$. The following modeling assumptions are considered:

- Lead times are considered to be deterministic for the parts of the BOM.
- A separate BOM is considered for each final product for which the firm satisfies the internal and external demand.
- A component may serve only one downstream node.

Carbon Emissions Function is introduced to simulate the carbon emissions generated by the supply chain. The following approach is considered. We start by determining the different sources of CO2 along the processes of the production line. Mainly the emissions are due to transportation and inventory settings. We would focus on these two major sources, as they also are impacted by the decision of the buffer positioning process. The Carbon Emissions function is then the sum of the emissions for an average flowing quantity (avg_i) of every item i . With $X = \{x_i\}, \forall i \in N$ the decision variable of the problem indicating whether the item i is buffered or not, the Carbon Emissions function E would be formulated as:

$$E(X) = \sum_{\forall i \in N} E(x_i) \quad (1)$$

Transportation is a key element of the supply chain, as it is needed to complete the gap between the nodes of the BOM when it is the case as in between raw material suppliers and the first processing site. We consider that each item i has a quantity of emissions β_i due to its transportation along the factory premises. We suppose in this article, that the same type of vehicles is used, and that all items average the same quantity of transportation emissions TE for the whole activity cycle, equal to $\beta = 1500gCO2/unit$. By simulation of the buffer positioning model in our previous paper [11], it is observed that buffered items have a low frequency of replenishment orders compared to non-buffered items that needs daily deliveries in the absence of inventory. It considered for this work that the transportation emissions, related to the replenishment activity, is lowered by 3. While all items are supposed to average the same quantity of transportation emissions, the buffered items transportation emissions would be equal to $\beta^* = \beta/3$. These emissions of an item i would be expressed as follows :

$$TE(x_i) = \beta^* \cdot avg_i \cdot x_i + \beta \cdot avg_i \cdot (1 - x_i) \quad (2)$$

Inventory Settings are crucial in case of buffered items. Setting up an inventory, brings two types of emissions: the constant emissions and the variable emissions, that would represent its Inventory Emissions IE . The constant emissions α_0 are due to the facility or the warehouse fixed running resources, as in the consumed energy and the needed human resources. Its amount is supposed to be the same for all the items, as we consider the same storing conditions. It could be product specific in case of condition-sensitive products, as they require

special facilities. The variable emissions, $\alpha_i \quad \forall i \in N$, are due to the amount of products stored on site. Each product represents a percentage of potential waste that can, in addition to its handling operations, take part in its carbon footprint. These emissions would be formulated as follows:

$$IE(x_i) = (\alpha_0 + \alpha_i \cdot avg_i) \cdot x_i \quad (3)$$

For non buffered items, these emissions are not considered.

Carbon Tax Strategy consists in simulating government CO2 tax rates. Their cost comes as a compensation to allow firms to adapt their configuration for better performance. To integrate these potential taxes in the total cost of the supply chain, we consider an average tax compensation price e_i for every quantity gCO2 of carbon emissions resulting from the activities of the site. The objective function gets new terms, besides the holding costs, representing the carbon emissions tax cost of every item.

Carbon Cap Strategy consists in simulating the regulation of emissions target caps. The carbon emissions function is used to sum the emissions of all the items in the BOM, and then added in the model as a constraint limiting its value to the restricted emissions target cap noted as $ECap$.

3 Model formulation

Based on the model from our previous work [11], the two strategies are implemented to take into consideration the carbon emissions into the DDMRP buffer positioning model. The models are tested separately on different instances generated to simulate the market data. The notations used for the considered model are presented in Table 1:

Table 1. The modelization notations.

Variable	Signification
a_i	Lead time of the i^{th} part
SvT	Customer service time
adu	Final product average daily usage
rqt_f_i	Needed quantity of the i^{th} part to produce the final product
TC	Total of Storing costs
u_p_i	Unit price of the i^{th} part
aih_cost_i	Average inventory holding cost rate of the i^{th} part
lt_f_i	Lead time factor of i^{th} part
var_f_i	Variability factor of i^{th} part

The Carbon Emissions Function would be written as follows:

$$E(X) = \sum_{\forall i \in N} [IE(x_i) + TE(x_i)] \quad (4)$$

which would be expressed after factoring the decision variable:

$$E(X) = \sum_{\forall i \in N} (\alpha_0 + \alpha_i \cdot avg_i + \beta^* \cdot avg_i - \beta \cdot avg_i) \cdot x_i + \beta \cdot avg_i \quad (5)$$

For the **Carbon Tax Model** strategy, we include the emission compensation costs in the objective function. It would be minimised in parallel to inventory holding costs of positioned buffers. The model would be formulated as follows:
Minimize

$$TC = \sum_{\forall i \in N} u \cdot p_i \cdot aih_cost_i \cdot (1, 5 + var_f_i) \cdot lt_f_i \cdot adu \cdot rqt_f_i \cdot a_i \cdot x_i + e_i \cdot E_i(x_i) \quad (6)$$

s.t.

$$a_0 \leq SvT$$

For the **Carbon Cap Model** strategy, the total emissions are limited to $ECap$. It would be a second constraint beside the service time constraint to our problem. This limit is expected to be reasonable and allows the manufacturing process to progress. The model would be formulated as follows:

Minimize

$$TC = \sum_{\forall i \in N} u \cdot p_i \cdot aih_cost_i \cdot (1, 5 + var_f_i) \cdot lt_f_i \cdot adu \cdot rqt_f_i \cdot a_i \cdot x_i \quad (7)$$

s.t.

$$\begin{aligned} a_0 &\leq SvT \\ E &\leq ECap \end{aligned}$$

4 Experimental Analysis

According to our research settings, many sets of instances are generated to test the model with its both strategies. Each set is composed of a BOM with a different number of items tested to a selection of service times. The parameters of the items were generated following the logic of an assembly line where the final product is more expensive, more complicated to store and more polluting. The lead time and variability factors are parameters related to the DDMRP method, they were calculated following the rules in the book [9]. Some of these parameters are considered the same for all items for simplification purposes. The model has been run on the version 12.8.0 of CPLEX solver on a machine with Intel i7-4700MQ 2.40 GHz with 8GB of RAM, with a Windows 8.1 operating system. The instances were generated using a Typescript program, as it is on an online user-ready platform.

Results and Analysis

The results of the strategic DDMRP buffer positioning model and its green variant with both carbon cap and carbon tax strategies are listed in Table 2.

Table 2. Total cost and carbon emissions comparison.

Instance	SvT	No Buffer emissions (KgCO2)	Strategic Buffer Positioning			Carbon Cap Strategy				Carbon Tax Strategy			
			TC	Emis (KgCO2)	Comp time(s)	Cap (KgCO2)	TC	Emis (KgCO2)	Comp	Tax	TC	Emis (KgCO2)	Comp time(s)
5	6	3216	15600	1507	0,21	1200	33280	1097,6	0,26	0,03	58416	1251,2	0,1
						1300	20880	1251,2	0,16	0,01	30672	1507,2	0,16
13	6	23448	66912	18592	1,07	18500	67232	18337	0,15	0,03	404780	10190	0,21
						17000	70036	16282	0,18	0,01	197680	10604	0,16
	15		39040	19625	1,08	19000	39120	15104	0,21	0,03	387610	10725	0,13
						15000	40272	14511	0,24	0,01	162430	11615	0,22
26	10	26256	568240	27467	1,1	26000	572160	25915	0,41	0,03	1313500	23132	0,27
						20000	905760	19990	0,33	0,01	831310	25915	0,22
	20		369840	25779	1,04	24000	436880	23976	0,26	0,03	1123200	24142	0,22
						20000	778480	19928	0,36	0,01	627630	25779	0,25
50	10	172460	776560	178560	1,06	170000	837360	137430	0,79	0,03	4429700	99121	0,33
						120000	1046600	117120	0,51	0,01	2206300	131130	0,3
	20		627120	125370	1,06	100000	816960	96596	0,31	0,03	3699400	94354	0,27
						85000	1338100	84990	0,57	0,01	1782900	96596	0,34
80	6	1101400	888800	1120200	1,19	1000000	1328000	999900	0,41	0,03	22311000	557790	0,5
						800000	2057600	799210	0,41	0,01	9744700	740150	0,46
	30		443520	1100500	0,93	600000	3753600	584460	0,4	0,03	21092000	541990	0,42
						500000	6432200	499900	0,54	0,01	8973400	719930	0,42
	34		224640	1104200	1,16	400000	11234000	399990	0,73	0,03	21092000	541990	0,43
						380000	12941000	379850	0,53	0,01	8790600	723540	0,44
123	6	270380	1374480	321120	1,32	300000	1513200	299910	0,96	0,03	9468200	188710	1,79
						260000	2005800	259710	1,84	0,01	4474600	283420	1
	30		132160	263600	1,14	250000	248960	249610	0,78	0,03	7136800	188940	0,6
						200000	1188200	199970	0,67	0,01	2743800	247900	0,72
140	6	2077200	18556960	1014100	0,08	1000000	18576000	894170	0,75	0,03	43665000	781090	0,76
						800000	20168000	799910	0,8	0,01	27428000	879510	0,7
	15		12460200	980020	0,11	800000	14043000	799270	1,12	0,03	36636000	749970	0,69
						650000	30753000	646650	3,85	0,01	21021000	848390	0,71
160	6	11415000	184320248	2868700	0,17	2800000	184340000	2799000	0,76	0,03	2,64E+08	2648500	0,82
						2700000	184820000	2699900	0,83	0,01	2,11E+08	2649000	0,94
	15		88211448	2832900	0,23	2800000	88221000	2798200	1,74	0,03	1,67E+08	2616000	0,71
						2700000	88299000	2698600	1,15	0,01	1,15E+08	2616300	0,72
200	6	5472200	49082048	2825400	0,11	2800000	49086656	2756000	0,85	0,03	1,06E+08	1899400	1,64
						2600000	49082048	2559000	0,83	0,01	68303000	1913600	0,97
	15		19062360	2717200	0,34	2500000	19062000	2450800	1,12	0,03	73801000	1819500	1
						2000000	19067000	1853900	1,08	0,01	37369000	1827400	1,03

The instances are sorted by the number of items in the BOM. Every instance has its no buffer emissions, which is the working scenario where the BOM is not decoupled and we have no DDMRP applied to our supply chain. Then the emissions of the strategic buffer positioning model with no carbon emissions restrictions is given next. For each set of service times, two capacities and two carbon compensation tax prices were tested to measure the sensibility of the parameters. This also allows to measure the impact of the two strategies. The performance of the linearized model, for both variants, is remarkable as we obtain results in very short times.

With the carbon cap strategy, the model repositions buffers along the BOM to satisfy the emissions limit. In some cases, like the instance of 80 items for a service time of 30, the total cost dropped by 42% for an easier emission cap. Even though, the product takes the same time to be produced. This is because the model changed the buffers for more expensive ones but less polluting. In better cases, like the instance of 5 items, the more strict emission constraint, allowed the product to be produced in a better time all while reducing the carbon footprint of the process. However, a much lower emissions cap would push the model to a non feasible solution in case no possible buffer configuration could produce that little emissions.

The carbon tax strategy, appears to be a more expensive option by an average of 52%. With some exceptions where we have a better cost minimization but for a higher carbon emissions quantity, the case of the instances: the BOM of 26 items when the tax price is set to 0.01, the BOM of 80 items for a service time of 34 when the tax price is 0.01 and the BOM of 140 items for a service time of 15 when the tax price is 0.01. It is though more efficient in terms of the carbon footprint reduction by an average improvement of 45%. The model is also sensitive to the tax compensation price. The appropriate pricing would be crucial to find the optimal compromise between setting a buffer and relying more on transportation.

The performance of the two strategies is compared to the strategic buffer positioning model with no restriction in figure 4. An adapted carbon cap is considered for each instance and a carbon tax of 0.03 is considered for all of them. Each instance has its own behaviour as they were independently generated. The graphs show that the carbon tax strategy is better performing in term of minimizing the carbon emissions, followed by the carbon cap strategy.

5 Conclusion and perspectives

In this paper, the carbon footprint aspect was considered in a DDMRP buffer positioning problem with client service time constraint. Two strategies have been adopted to simulate the environmental regulations: carbon emissions cap and carbon emissions tax. A function has been proposed for modeling these emissions that are mainly related to storing activities and transportation. The numerical results showed the impact of buffers positioning on the amount of generated emissions. Hence, the usefulness of our model is to find out which of the

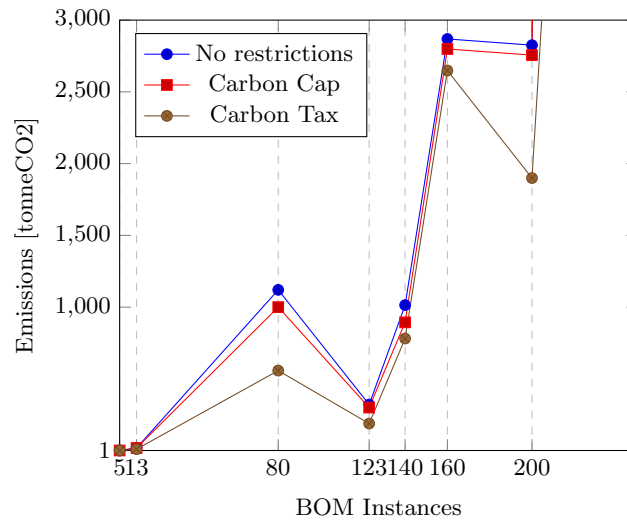


Fig. 1. Carbon emissions by strategy

buffer settings is the most suitable for both economical and ecological aspects. Transportation was considered brief and standard in this work, adding distance variability and transportation costs to the equation would make the problem more complicated. A hybrid version of the two carbon emission strategies may be considered in the future. The impact of buffered items on the replenishment frequency and its transportation emissions minimization could be considered at a future tactical study of the DDMRP method. The difference of carbon tax pricing from a region to another may rise the question of inventory location for multi-echelon supply chain.

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