Reducing carbon emission of ocean shipments by optimizing container size selection

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Reducing carbon emission of ocean shipments by optimizing container size selection

Edwin Chong Lik Ming, Nang Laik Ma, Kar Way Tan, Member IEEE

Abstract— Human’s impact on earth through global warming is more or less an accepted fact. Ocean freight is estimated to contribute 4-5% of global carbon emissions and manufacturing companies can aid in reducing this amount. Many companies that ship goods through full container loads do not have the capabilities to ensure the containers they are using minimizes their carbon footprint. One of the reasons is the choice of non-ideal container sizes for their shipments. This paper provides a mathematical model to minimize companies’ shipping carbon footprints by selecting the ideal container sizes appropriate for their shipment volumes. Using data from a selected real-world business case in the manufacturing industry, we show that our model can provide a 13.4% reduction in carbon footprint. We believe that our model is generic for ocean shipment and can be easily adoptable by other manufacturing companies, to be more environmentally sustainable by selecting the appropriate container sizes and reduce the carbon footprint of their ocean freight.

Keywords: carbon emission, carbon footprint, sustainability, data analytics, optimization, ocean freight

I. INTRODUCTION

Manufacturing companies may choose to ship their products using a third-party logistics service provider (LSP) by purchasing a full container; this is known as the Full Container Load (FCL). Using FCL means they will be responsible for the packing of the container. After packing the container, the logistics service provider will be responsible for transporting the container from the packing site to the final destination. Unfortunately, companies may not be able to maximize the utilization of the container’s capacity. A typical company with varying trade volumes may order a fixed set of containers per shipment period (e.g., weekly, monthly) by contract and fill them up with whatever demands, resulting in low container capacity fill during low demand periods, larger total number of shipments and thus a higher total carbon footprint due to the larger number of shipments. We observed from our data from a real-world LSP that the phenomenon of less-than-ideal container capacity fill is common. Another shipping option for companies is known as less-than-container load (LCL). In this situation, whatever volume of goods required to be shipped is passed to the LSP and the LSP will be responsible for moving the goods, the size and fill rate of the container is transparent to the customer. It is common for companies to use a combination of FCL and LCL to meet their shipping needs.

In this paper, we consider the scenario in which the company has planned shipment volumes with a known shipping date. Based on the volumes, we built an optimization model to calculate the optimal number of containers and determine the combination of containers sizes (e.g., 20-feet standard – 20S, 40-feet standard – 40S and 40S and 40S and 40H) that minimizes the carbon footprint, i.e., total amount of carbon emissions per shipment. Henceforth, we shall use the term carbon footprint to refer to total amount of carbon emissions per shipment. An end-to-end supply chain carbon footprint takes into account the entire transportation journey, from departure location to port of loading, port of loading to port of discharge, and port of discharge to final destination. The optimization model focuses on the carbon footprint of the journey from the port of loading to the port of discharge; only this leg of the journey is focused due to the limitation of the data available. The model takes the total volume to be shipped, selects the combination of container size and total number of containers that minimizes the carbon footprint. We observed that by reducing the carbon footprint, the resulting model also lead to the reduction of the total number of containers required over a measured period (e.g., a year) and therefore reduce the total monetary cost of transportation for the company as well.

Our contribution is in two folds. Firstly, we provide a model that optimizes the carbon footprint by considering both the selection of ideal sizes of containers for the shipment volume and the determination of the optimal number of containers that satisfies the shipment dates. Secondly, we demonstrate with a real-world business case (and data) that our model is applicable to a manufacturing company and reduces the carbon footprint of the shipments. Our model can be implemented by generally available software tool such as Microsoft Excel and AIMMS (Advanced Interactive Multidimensional Modeling System) that support linear programming. We believe that our approach and implementation technology can be easily adopted by manufacturing companies in the industry.

II. LITERATURE REVIEW

In 2012, Dekker, Bloemhof & Ioannis [1] covered an overview on operations research for green logistics that contributes in terms of the background of containerization, containers and the container related activities. It also covers how do some variables affect the carbon footprint of the shipment. No optimization model was presented to reduce the carbon footprint of the shipment.

Other studies done with the focus from a sustainability or green point of view are Lirn, Lin & Shang (2014) [2] whom focused on green shipping management capability and

There are many difficulties in calculating the actual carbon footprint of particular shipment as the efficiency of the ship differs between them as well as the different routes that may have been taken between two ports. Leonardi & Browne (2009) [4] developed a method for assessing the carbon footprint of ocean freight, but not an optimization problem. For the purpose of our optimization model, we found that detailed method for calculating carbon footprint is not necessary. To determine the optimal number of containers and their sizes, a ratio of carbon consumption of the various types of containers is sufficient, e.g., the carbon consumption ratio of container types 20S : 40S : 40HC is 1 : 2 : 2.2. Using ratio simplifies the computations of the optimization model.

Another area of research is the container-packing problem. Thapatsuwan, Pongcharoen, Hicks & Chainate (2012) [5] have developed algorithms to solve packing rectangular boxes into a set of containers. In their scenario, the size of the containers was fixed. Another work by Jin, Ohno & Du (2002) [6] looked into solving the container-packing problem with additional practical constraints such as loading stability, the rotation of items around the height axis, and the fixed loading (unloading) orders. None of these works relate to computation of container sizes.

There is another collection of work on freight consolidation and containerization. A recent paper by Qin, Zhang, Qi & Lim (2014) [7] constructed a model to solve issues with shipping from a port to multiple destinations after arriving at the port of discharge. This work did not consider environment sustainability. However, it is an interesting idea for future work with additional considerations of carbon emission.

To our best knowledge, none of the work in the literature considered selection of appropriate sizes of containers. This is a fundamental decision a manufacturing company needs to make if the company ships using FCL. In addition, our model is supported and validated with a real-world data set. We show in our next 2 sections, how we transform the data and how we select the useful data to be used in our model. Thereafter, we present our mathematical model, the results of the analysis and how the model was implemented.

III. REAL-WORLD BUSINESS CASE

The business case is based on a company that manufactures its goods all around the world but the majority production is in Asia. Goods are shipped to the US for sales. The company conducts sales through the physical stores and e-commerce. This study has been motivated by the fact that initial data exploration suggests optimization potential in selecting the ideal containers (in terms of size) for its shipment volume, hence resulting in incurring lower carbon footprint. This company uses a combination of FCL and LCL services to transport its goods globally.

Our data consists of 8,749 shipments between the period of April 2009 and December 2013 (4.5 years). We build a model that takes in the volume per shipment and its associated container sizes as inputs, and produces the optimized container sizes required for the volume as output. The model calculates current and optimized carbon footprint to show the possible savings. Our results show that the carbon footprint can be reduced when the appropriate container sizes and number were optimized for the required volume.

The data set consisted of 17 columns of information for each shipment, for example weight and volume of the shipment, container length and height, port of loading and discharge, and total carbon emission generated for the shipment. A cleanup of the data revealed that some of the numerical data and port names needed to be standardized to ensure that the analysis is accurate. At the end of the cleanup, a total of 20 rows of data were removed due to inconsistencies, 8,729 rows can be used for analysis.

Correlation studies highlighted 3 pairs of numerical variables that have high correlation. In each of this pair of variable, one of the variables is the base data while the other is a derivative of the base data. Therefore, the base data of all the 3 pairs are selected for the model.

Ocean freight contributes an average of 89.5% of the carbon footprint in entire transportation journey, with the remaining 10.5% contributed by warehousing and the other modes of transportation between the departure location and the port of loading and the port of discharge to the final destination. The data suggests that manufacturers closest to the ports have minimal intermodal transportation and warehousing emissions as for these shipments of ocean freight contributes 99.8% of the total carbon footprint in the supply chain.

The data also revealed that the majority of the shipments originated from China (57.6%). Other originating countries include Vietnam (13.8%), Taiwan (11.3%), Hong Kong (SAR of China) (8.4%), the remaining shipments (8.9%) originated from other countries in Asia, Europe and United Arab Emirates (UAE). The vast majority of the shipments were delivered to the United States of America (99.7%).

Although China makes up more than half of the originating shipments and the USA close to all of the delivery, it would be unwise to take it as simply as country to country shipping. Both China and USA are large countries with multiple ports scattered over different geographical locations. There are a total of 10 ports in China and 14 ports in USA used for shipments, meaning that production happens in various parts of China and the goods are delivered as final products in various parts of USA straight from the manufacturing plants. Vietnam and Taiwan also ships from multiple ports to various destinations in the USA.

Future study into the shipment dates reveals that shipments are not made on a daily basis, out of the 4.5 years period there were only shipments on 69.6% of the days. For daily shipments, the smallest and largest volume recorded was 0.16 and 2,122.32m³ respectively, the mean was 235.97, median was 148.52, lower and upper quartiles were 55.56 and 324.3m³. At the 90th percentile the volume is only at 541.72m³, revealing that large volumes were outliers rather than the norm.
The size of containers reveals that LCL makes up 46.7% while the FCL container shipments make up 53.3%. Of the FCL shipments, the distributions of the sizes of container used are shown in Figure 1. There was only 1 occurrence a 20-foot high cube container being used.

### Figure 1. Distribution of container sizes

#### IV. DATA SELECTION

Before a model can be built, the data needs to be transformed as the current format provides information on per shipment level, but in order to optimize the shipment volume, we need to understand that total volume per day per trade lane. A trade-lane is defined as a unique port of loading and port of discharge. With a per day per trade lane granularity, then will the model be able to compare the difference between the original shipment container sizes against the optimized container sizes.

The following steps have been taken to transform the data:

1. Combine the values in port of loading and port of discharge to create a new column of data called trade lanes
2. For each trade lane, identify the dates that the data shows shipments that were made
3. For each date that there were shipments, count the total number of each container size per trade lane
4. For each date that there were shipments, compute the total amount of shipment volume

After the transformation has been completed, the data set consists of 4,357 data points.

The transformed data set consists of a total of 171 unique trade lanes. For these 171 trade lanes, we will split them into 2 categories; trade lanes that have between 1 and 100 shipments in the data set, and trade lanes that has between 101 and 700 shipments in the set. Figure 2 shows that trade lanes that have between 1 and 100 shipments make up 88% of the data set, and trade lanes that had between 101 and 700 shipments made up 12% of the data set.

In fact, between 1 and 100 shipments represents 150 out of 171 trade lane, and within these 150 trade lanes, there are a total of 91 trade lanes that had 10 shipments or less.

Diving deeper into the data, the trade lanes that have between 101 and 700 shipments make up 73% of the total number of shipments within the data set, and trade lanes that have between 1 and 100 shipments only make up 27% of the total number of shipments as shown in Figure 3.

#### Table I

<table>
<thead>
<tr>
<th>#</th>
<th>Port of Loading</th>
<th>Port of Discharge</th>
<th>Number of days with shipments</th>
<th>Percentage of total shipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>X</td>
<td>680</td>
<td>7.8%</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>Y</td>
<td>671</td>
<td>7.7%</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>X</td>
<td>517</td>
<td>5.9%</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>Y</td>
<td>443</td>
<td>5.1%</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>X</td>
<td>362</td>
<td>4.1%</td>
</tr>
<tr>
<td>6</td>
<td>D</td>
<td>X</td>
<td>321</td>
<td>3.7%</td>
</tr>
<tr>
<td>7</td>
<td>E</td>
<td>X</td>
<td>319</td>
<td>3.7%</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>X</td>
<td>319</td>
<td>3.7%</td>
</tr>
</tbody>
</table>
The above analysis reveals that the company has regular shipping from a small number of cities and very small volume ad-hoc shipping for a large number of cities. This may be because there are many factories located in the same city and ad-hoc manufacturing is only required for special products and located in distributed cities.

With the data in a format that is ready for analysis, the next step is to filter out data that will not be used. For each volume in each trade lane, check if the volume was shipped via FCL, LCL or a mixture of both, only shipments made via FCL will be analyzed. This is done in order to fairly compare whether there is an improvement in terms of carbon emission between the original choice of container sizes and the selections given by our model.

The containers selected for this study are the most commonly available ones that are easily transported within the supply chain by ocean freight. The dimensions in meters by length, width, and height of 3 containers sizes are 5.9 by 2.35 by 2.4 for the 20-foot standard container, 12.0 by 2.35 by 2.4 for the 40-foot standard container, and 12.0 by 2.35 by 2.70 for the 40-foot high cube container. Based on the dimensions of each size of container, the volume that theoretically can be made full use of is shown in Table II. In reality, 100% usage of the container is rarely the case due to packing issues and size of goods, hence in this model we will use the highest capacity fill shipment found in the data set of ~95%. Table II shows the available container volumes at the two different capacity fill rates.

<table>
<thead>
<tr>
<th>Number of shipments</th>
<th>Percentage of total shipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>3.4%</td>
</tr>
<tr>
<td>10</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

**TABLE I. TOP 10 TRADE LANES**

Integer programming is used to solve the container size selection problem as we are looking for decision variable which is the container sizes has to come as positive integers and decimals are not accepted in this model.

There are a few assumptions made: (1) companies can pack up to 95% of the container volume (as observed from our data source that such a percentage is possible). (2) All shipments are made through FCL. (3) Containers required are always available. (4) The weight of the ship does not impact the carbon footprint of the containers.

The amount of carbon emission per container kilometer (KM) on container ships is mostly determined by the efficiency of the ship itself. The older ships are less fuel-efficient and hence emit more carbon dioxide as compared to the newer ships that are more fuel-efficient and emit between 20-40% less carbon dioxide, and therefore the carbon footprint of each container size on different ships will differ. Hence for the purpose of this optimization model, instead of attempting to arrive at what is the appropriate carbon emission number to apply for the 3 container sizes, a predetermined ratio is used.

The LSP had internally fixed carbon emissions for the 3 container sizes, they are a 40-foot standard container emits twice the amount of carbon dioxide of a 20-foot standard container and a 40-foot high-cube container emits almost 20% more the amount of carbon dioxide of a 40-foot standard container. Therefore in this model we shall use the we shall use the ratio of 1 : 2 : 2.2 for 20S : 40S : 40HC. This ratio shows that for ocean shipments, the 20-foot standard and 40-foot standard containers actually have the same carbon footprint per cubic meter, the main reason to choose one over the other will be the actual volume required to minimize the carbon footprint.

Table III lists the input parameters used in the model:

<table>
<thead>
<tr>
<th>Variables</th>
<th>20 foot standard container (i=1)</th>
<th>40 foot standard container (i=2)</th>
<th>40 foot high cube container (i=3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_i) Maximum volume (cubic meters)</td>
<td>31.28</td>
<td>63.78</td>
<td>71.78</td>
</tr>
<tr>
<td>(C_i) Carbon Emission per Container KM</td>
<td>1</td>
<td>2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
In addition, from a business point of view, not only would a company like to reduce the total of carbon footprint, they would also like to ensure that the amount of unused volume in the containers are minimized, hence there will be an additional constraint in the model to limit the total amount of unused volume. In the case of multiple combinations of containers, this unused volume will be distributed across all containers.

The following variables will be used in the mathematical model:

Input parameters:
- \( C_i \) = Carbon Emission per container KM for each container size
- \( i \) = Type of container size, 1 for 20S, 2 for 40S and 3 for 40HC, \( \forall i = 1, 2, 3 \)
- \( j \) = Port of loading, \( \forall j = 1, 2, 3 \ldots n \)
- \( k \) = Port of discharge, \( \forall k = 1, 2, 3 \ldots m \)
- \( V_i \) = Volume for each size of container
- \( D_{jk} \) = Volume to be shipped on each trade lane
- \( E \) = Maximum excess volume set to 10m³ for this model

Decision variable:
- \( X_{ijk} \) = Number of containers of size \( i \) for port of loading \( j \) and port of discharge \( k \).

The objective function is to minimize:

\[
\sum_{i=1}^{3} C_i \sum_{j=1}^{n} \sum_{k=1}^{m} X_{ijk}
\]

Subject to:

\[
\sum_{i=1}^{3} V_i X_{ijk} \geq D_{jk} \quad \forall j,k \quad (1)
\]

\[
\sum_{i=1}^{3} V_i X_{ijk} - D_{jk} \leq E \quad \forall j,k \quad (2)
\]

\( X_{ijk} \in Z^+ \)

The problem aims to find the best mix of containers with the objective of minimizing the total carbon footprint.

Constraint 1 ensures that the required volume is met by mandating that the optimized volume across the containers be equal or larger than the required volume for each trade lane represented by \( j \) and \( k \).

Constraint 2 takes into account the excess volume of the optimized solution. Set to an arbitrary upper limit of 10m³ for this model, the problem will be solved when the optimized containers selected have a total sum of less than or equal to 10m³ of excess volume. There will be cases where this constraint cannot be met and results in no solution.

VI. THE RESULTS

After breaking down the data by trade lanes, a total of 837 problems had to be solved. The problems were solved using AIMMS optimization software.

Out of the 837 problems, 228 of them could not be solved within the maximum excess volume of 10m³; this group of 228 problems was solved excluding the excess volume constraints.

The results were encouraging as it revealed that almost 80% of shipments had the potential of reducing its carbon footprint, while the remaining 20% shipments had the same carbon footprint between the original and optimized container selection.

![Figure 5. Distribution of carbon savings results](attachment:image)

Comparing the carbon footprint of the original against the optimized container selection, Table IV shows a 13.4\% reduction.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Optimized</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Footprint</td>
<td>5,780.0</td>
<td>5,006.0</td>
<td>-13.4%</td>
</tr>
</tbody>
</table>

TABLE IV. TOTAL CARBON FOOTPRINT REDUCTION

Focusing on the 665 shipments that had a carbon footprint reduction, Table V show an overall reduction of 9\% to 2,296 containers of the container requirements between the original and optimized data.

<table>
<thead>
<tr>
<th>Container size</th>
<th>Original</th>
<th>Optimized</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-foot standard</td>
<td>368</td>
<td>602</td>
<td>64%</td>
</tr>
<tr>
<td>40-foot standard</td>
<td>1,064</td>
<td>912</td>
<td>-14%</td>
</tr>
<tr>
<td>40-foot high cube</td>
<td>1,187</td>
<td>867</td>
<td>-27%</td>
</tr>
<tr>
<td>Total</td>
<td>2,619</td>
<td>2,381</td>
<td>-9%</td>
</tr>
</tbody>
</table>

TABLE V. DIFFERENCE IN CONTAINER SELECTION

Table VI shows the savings on the top 5 highest volumes and top 5 highest carbon footprint reductions respectively:

<table>
<thead>
<tr>
<th>#</th>
<th>Total Current Emissions</th>
<th>Total Optimized Emissions</th>
<th>Percentage Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.2</td>
<td>50.4</td>
<td>11.9%</td>
</tr>
<tr>
<td>2</td>
<td>57.1</td>
<td>43.8</td>
<td>14.5%</td>
</tr>
<tr>
<td>3</td>
<td>35.6</td>
<td>31.2</td>
<td>12.4%</td>
</tr>
<tr>
<td>4</td>
<td>33.4</td>
<td>28.2</td>
<td>15.6%</td>
</tr>
<tr>
<td>5</td>
<td>32.4</td>
<td>28.2</td>
<td>13.0%</td>
</tr>
</tbody>
</table>

TABLE VI. TOP 5 SHIPPING VOLUME RESULTS
Putting the savings into perspective, through the use of a carbon calculator provided by YouSustain.com, if it is assumed that a 20-foot standard container emits 0.2Kgs per container KM and the average shipment distance is 10,000 KM, in this data set the company would have reduced a total of 1.55 million KG of its carbon footprint, which is the equivalent of taking off 304 cars off the road for a year.

For the shipments that had no improvements in their carbon footprint, the shipment volumes are low, between 65 m³ and 141 m³. Other shipments without improvements can be up to 280 m³. This is consistent with intuition because at low volumes, it is easier to more accurately select the right containers of sizes that meet the shipment volume requirements.

VII. MODEL DELIVERY

In order to make this optimization model widely available to companies and end-users, consideration of the software available and the ease of use have to be taken into account.

In addition to the AIMMS model, we have also developed a model using Microsoft Excel for smaller scale short-term planning. Microsoft Excel is the most commonly available software in companies and it provides solver as an optional add-in, therefore without any additional outlay of software investment or significant amount of training, users within a company should be able to quickly make use of the model.

The model is built on a spreadsheet with 3 user inputs: namely volume, the maximum percent of capacity fill, and the excess volume (m³) limit. Two macros are written to enable users to clear the previous data and then run the solver once they have keyed in the data. The model is built to allow 7 rows of inputs, 7 has been chosen with the assumption companies use 1 row per day and therefore the model can support up to 1 week of planning. The time taken for solver to come up with a solution depends on the number of problems that need to be solved, the size of the shipment volume and the speed of the computer’s processor. In our experiment using the shipment volume, the capacity fill percentage, and the maximum excess volume, a solution is produced within 10 minutes for the planning of 7 shipments.

Excel’s default basic solver is capable of accepting up to 200 decision variables. 7 rows of input implies a total of 21 (7 X 3) decision variables, as the number of decision variables increase, the amount of time taken for solver to find a solution exponentially increases and therefore it is also a technical limitation that the model is confined to 7 rows. In addition, the time taken for solver to arrive at a solution is also highly dependent on the volumes, the larger the volume the longer the amount of time will be required.

Although in this paper the problems were solved using AIMMS optimization software, we understand that there is additional cost in acquiring the software and training required for personnel in order to operate it. Therefore, we provide Excel as an alternative software for wider adoption. On the other hand, companies looking to manage larger volumes than what the current Excel model can provide should look into investing in the software and training the people to be competent in modeling and running them to generate results for operations usage.

VIII. FUTURE WORK & CONCLUSION

This paper has shown that there are opportunities for companies to reduce their carbon footprint from the supply chain. With our container size optimization model, we showed, with a dataset from a real-world company, that almost 80% of shipments had the potential of reducing their carbon footprint. This led to a 9% decrease in the overall container requirement and a reduction of 13.4% of their carbon footprint on the average.

The current model optimizes one part of the company’s supply chain opportunity, which is minimizing the carbon emission by selecting the ideal container size. Future work will consider optimization capabilities by consolidating shipments from the various cities via trucking overland within a country such as China and then shipping them to one destination port. The future model will compare the carbon emission between directly shipping the goods and consolidating them at a port for each city and generate a decision list for users to make the final decision. The container size optimization will be useful for direct shipping without consolidation or for use at the port of consolidation.

The challenges in this expanded work includes the inclusion of another mode of transport that is the trucking of goods overland, making this an intermodal model. From city to port of consolidation, additional information such as distance between cities, driving time required, local driving hour limitations and carbon emission of the truck will have to be taken into consideration. Also, the model needs to be able to perform container size optimization as part of the calculations to determine whether a particular shipment should be directly shipped or to be consolidated.

REFERENCES