A MULTI-OBJECTIVE OPTIMIZATION MODEL FOR SUSTAINABLE DISTRIBUTION PLANNING UNDER ECONOMIC AND ECOLOGICAL CONSTRAINTS

Seyhan Teoman¹, Nagehan Uca²

Abstract- In recent years, developing concept of sustainability have had an important place in supply chain and logistics management context. All supply chain activities and mainly transportation are significant sources of greenhouse gas emissions and air pollution. Recent increase in legal pressures and customer consciousness on environmental concerns compels the business executives to pay more attention to environmental and social issues in their logistics practices than ever before. Those initiatives are called Green Logistics. However, it is a fact that improving the environmental quality comes at a cost. Thus, one of the most important questions in green logistics practices is how to identify preferred solutions that balance environmental and business concerns? In other words, which are the trade-offs between the environmental impacts of an economic activity and its costs. In this study, through an illustrative network, we propose an enhanced multi-objective mixed integer programming model as a decision support tool, which aims to optimize the overall system costs (i.e. transportation, handling, investment) and environmental aspects (i.e. carbon-footprint, air pollutants) occur in product distribution process. We mainly focus on transportation mode and truck type selection considering its economic and environmental impacts from a much wider perspective than previous studies.

Keywords– Green logistics, Multi-objective optimization, Sustainable distribution

I. INTRODUCTION

The operations in supply chain and logistics are part of today's most important economic activities as they remain to be vital tools for businesses to remain competitive [1]. Traditionally, supply chains and logistics structures have been designed based mainly on economic objectives. In other words, the minimization of cost and time performance has always been the main objective in most logistics systems [2]. However, with the increasing concerns of environmental aspects, the logistics structures that consider both economic and environmental performances have been more decisive factor within the supply chain management context.

Today’s top environmental concern is global warming. The effect of large scale of greenhouse emissions on climate change has strongly been perceived by governments, international organizations and companies. On the other hand due to more environmental conscience on a global level (Kyoto Protocol, government regulations etc.) an increasing attention has to be given to develop environmental strategies. These issues have raised concerns on reducing the amount of emissions worldwide [1]. Additionally, corporate social responsibility issues have also revealed the importance of a green image as a practice that could lead in higher sales and thus profitability. Companies have started to understand the importance of ensuring a long term competitive advantage based on “green” policies.

All supply chain activities are significant sources (totally %30.8) of greenhouse gas emissions and air pollution, also creating harmful effects on living health and leading to global warming [3]. Therefore today supply chain management practices that take into consideration both the cost and the environment are playing more important role at all strategic, tactical and operational decision levels. Those initiatives are called “Green Supply Chain Management. To this end, “Green Logistics Management” could be defined as the integration of ecological considerations in the design of logistics networks and operations.

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One of the most important questions in green logistics is how to identify preferred solutions that balance the environmental and business concerns [4]. Improving environmental quality comes at a cost, so the question is which trade-offs occur between the environmental impacts of an economic activity and its costs, and what are best solutions balancing ecological and economic concerns? The aim is to determine solutions in which environmental damage can only be decreased if costs are increased. These solutions are called eco-efficient [5].

Transportation activities are significant sources of air pollution and greenhouse gas emissions. Transport (freight and passenger transport) accounts for 20% of all EU greenhouse gas emissions. Emissions from freight transport account for approximately one third of total transport greenhouse emissions. Transportation is also a main source for air pollution (i.e. NOX, SO2, and PM-particulate matter emissions). 93-95% of greenhouse emissions from transport operations is accounted for by CO2 emissions and the rest by other air pollutants (i.e. SOx, NOx, PM2.5) [6]. Within supply chain systems, transportation CO2 emissions amount to some 19.7% of total emissions, both at global and EU level [7].

Level of emissions varies from one transportation mode to other, and it is vital to create a balance between the economy and ecology on choosing a mode. But it is highly related with the type of products since it mostly limits the choices. Under fixed utilization loads, a simple yet important observation is that the bigger the transport unit in the same mode, the fewer the CO2 emissions per g/ton/km. The most CO2 efficient mode is considered to be the water transportation due to the fact that water can easily carry heavy loads. However, while transport by rail is more ecofriendly than road transport, air is the most harmful mode when compared with the other modes of transportation.

It is a fact that efficiency-oriented logistics systems have created a high degree of dependence on the truck-only system (the road freight market share amounts to about 44% in the European Union). However, over the same time period, road freight transportation has been one of the most rapidly growing contributors to carbon dioxide (CO2) emissions. Totally 35% ratio of transportation greenhouse gas emission is actualized via heavy and light trucks which are commonly used in the supply chain transportation.

Despite the fact that road transport is the largest contributor of emissions, significant emission reductions have been achieved in recent years. The EU has set standards for NOx, SO2 and PM emissions for trucks. If rail transport and inland navigation continue to refrain from innovations, the gap will close even further. As a result, trucks meeting the highest standard to date (Euro VI) are much cleaner than most ships and trains [5]. This is another trade-off between air pollutant emission level and transportation cost as the higher Euro class, the higher freight cost. In this study, we mainly focused on choosing an alternative mode between rail and road transportation and we further provided an option for choosing Euro1, Euro3 and Euro5 vehicle when road transport is preferred. We disregarded the option of Euro 6 since no data is reached related with it regarding the fact that it is a very newly developed technology.

It is therefore one of the main choices in transport is the mode of transportation. In addition to cost and environmental impacts, transportation modes have different characteristics in terms of transit time and accessibility. After deciding upon the transport mode, a decision must be made on the type and size of the transportation unit. This decision has impacts on capacity, speed, economics and environmental performance. Carrying the goods with full truck load (FTL) or less than truck load (LTL) is also within the scope of this study. As aforementioned, the larger the transportation unit, the fewer CO2 emissions per kg transported which also means the fewer emissions of other air pollutants such as NOx, SO2 and PM.

In the next section, some useful data are presented related to greenhouse gas emission factors on rail and road transportation by vehicle type options (i.e. FTL trucks and LTL delivery vans) that we focus in this study. The following air emissions from transport sources are covered: CO2 emissions that cause climate change by global warming and PM2.5, NOx and SOx emissions that cause on air pollution [7].

Emission factors for trucks and delivery vans can be divided in two sets [7]:

1. Emissions that are related to fuel type and fuel consumption (CO2, SO2). CO2 emission factors are derived by diesel consumption while SO2 derived by carbon and sulfur content of diesel.
2. Emissions that are related to vehicle technology and driving pattern (PM\textsubscript{2.5} and NO\textsubscript{X}). These emission factors are based on emission factors per Euro class and road type.

The recommended average CO\textsubscript{2} emission factor for road transport operations is 62g/ton-km. This value is based on an average load factor of 80% of the maximum vehicle payload and 25% of empty running [6]. For rail transport, the emission factors per train-km for all pollutants are calculated from the energy consumption per train-km. The energy consumption figures for rail transport are based on different train types (i.e. diesel and electric) and weight classes [7]. The recommended average CO\textsubscript{2} emission factor for rail transport operations is 22g/ton-km. This value is based on: (a) the average split between diesel and electric haulage (b) the average carbon intensity of the electric power source (c) the average energy efficiency of the locomotive (d) assumptions about average train load factors. For the road/rail intermodal combination, the recommended average CO\textsubscript{2} emission factor is 26g/ton-km [6]. Emissions of loading and unloading play a role in multimodal transport. These emissions should be considered when transport options are considered that require additional transshipment as compared to other options.

Besides, diesel and electric energy used in distribution facilities are other significant emission sources. Therefore our next consideration is the building structure of distribution centers. Green or Eco building is a structure that: reduces the impact of global warming by using renewable energy, protects the clean and renewable water resources by minimizing the water consuming and protects natural habitats with waste management and recycling, does not harm human health with removing all the disorders within the building. Many criteria of land selection, recyclable material selection, shadowing design, natural lighting and natural air conditioning are taken into consideration. Such kind of buildings can be used for the designing of distribution centers. Furthermore environmental impact can be taken into consideration while determining the equipment to be used for handling operations at DC. In this study, we take into consideration the energy consumption, handling, CO\textsubscript{2} and air pollutant emission of DCs separately according to its building technology (i.e. normal or ecologic).

We consider another important criteria to decide on the appropriate mode of transport is lead-time. Slower modes of transport cause increase in the lead-time thus increase inventory holding costs due to delay on delivery. It should also be noted that direct (plant warehouse-regional dealers) and indirect (plant warehouse-distribution center-regional dealers) distribution also have impacts on lead time as well as the running and handling speed of transport modes and means.

In literature, the multi-objective optimization models are widely used as the core of the decision-support tool to find the optimal freight system and to estimate the trade-off between freight costs and CO\textsubscript{2} emissions [2]. Thus, in this paper, through an illustrative distribution network, we also propose a multi-objective mixed-integer model formulation for examining the effect of both total system operational cost and quantity of CO\textsubscript{2}+Air Pollutant emissions minimization objectives on (i) strategic decisions related to the number and location of operating distribution centers and their building standards (i.e. Normal or Ecologic) (ii) tactical decisions related to the type of transportation modes employed (i.e. Road or Rail) and (iii) operational decisions on the selection of type of trucks (i.e. FTL, LTL) and their ecological norms(i.e. Euro1...6), considering leased transportation through long term contracts and invested distribution centers.

**II. LITERATIVE REVIEW**

The environmental impact of transport is significant because it is the most visible aspect of supply chains. In literature, there are many studies using multi-objective optimization models to design supply chain networks from economic perspective. They mainly focus on minimizing transportation costs. However, when transportation process is analyzed from both economic and ecological point of view certain studies come to the forefront, which are summarized in Table 1.
Table 1. Summary on Literature Review

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Model used in study</td>
<td>Multi-objective Mixed-Integer</td>
<td>Multi-objective Linear</td>
<td>Multi-objective Linear</td>
<td>Multi-objective Mixed-Integer</td>
<td>Multi-objective Mixed-Integer</td>
</tr>
<tr>
<td>Number of objective functions</td>
<td>2</td>
<td>2</td>
<td>4*</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Resolution Method</td>
<td>Ideal based (Pareto Optimal)</td>
<td>Preference based</td>
<td>Ideal based (Pareto Optimal)</td>
<td>Ideal based (Pareto Optimal)</td>
<td>Ideal based (Pareto Optimal)</td>
</tr>
<tr>
<td>Numerical Example</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

**Economic determinants considered in Objective Function 1**

| Transportation costs (unit base) | √ | √ | √ | √ | √ |
| Rental Fee of trucks (fixed) | | | | | |
| Handling costs | √ | | | | |
| Facility Set-up cost (fixed) | | √ | | | |
| Waste treatment costs at facilities | | | | | |
| Energy consumption costs at facilities | | | | | |
| In-transit inventory holding costs | | | | | |
| Investment for environmental protection | | | | | |
| Purchasing cost of raw materials | | | | | |
| Penalty cost for extra CO2 emission | | | | | |

**Ecological determinants considered in Objective Function 2**

| Quantity of CO2 emissions produced in transportation | √ | √ | √ | √ | √ |
| Quantity of CO2 emissions produced in facilities | | | | | |
| Quantity of Air Pollutants emission produced in transportation | | | | | |
| Opportunity profit over recyclable raw materials purchased from suppliers | | | | | |

**Constraints**

| Quota on CO2 emission level total | √ | | | | |
| Quota on Energy Consumption costs | | | | | |
| Limited truck capacity | | | | | |
| Limited truck availability | | | | | |
| Limited environmental level of facilities | | √ | | | |
| Transportation Modes availability | | | | | |
| Limited Handling Capacity at facilities | | | | | |

**Decision Variables**

| Quantity of product flow between the nodes | √ | √ | √ | √ | √ |
| Transportation Mode | √ | | | | |
| Intermodality | | | | | |
| Type of Trucks (FTL or LTL) | | | | | |
| Capacity of Trucks | | | | | |
| Age of Trucks | | | | | |
| Ecologic (Euro) Norm of Trucks | | | | | |
| Number and location of facilities to be opened | | | | | |
| Building Technology (environmental protection level) at facilities to be opened | | | | | |
| Recyclable rate of raw materials purchased from suppliers | | | | | |
| Total amount of raw material purchased from suppliers | | | | | |

*First two objective functions for minimization transportation costs. One for forward, one for reverse logistics. Third objective function is for minimization the total CO2 emission and the penalty cost. The last objective function is for minimization the total purchasing costs via maximization the total opportunity profit derived from recyclable ratio of raw materials purchased.
III. PROBLEM DEFINATION AND MODELING

In this paper we consider an illustrative network for spare parts distribution in automotive sector (Figure 1). The parts are produced in a central manufacturing plant and dispatched from its warehouse to regional dealers throughout the country, using three alternative transport modes/means; delivery vans (LTL), heavy on-road trucks (FTL) and train.

As illustrated in Fig.1, from plant-warehouse to cross-docking distribution centers, products can be transported by train which is cleaner and cheaper than FTL truck, but with longer lead-time. Lead-time differs by the speed of transport means and routes. The longer lead-times cause increase on inventory holding costs as well as delays on delivery. In some cases of urgent delivery, the goods can be shipped from plant-warehouse directly to regional dealers by using LTL vans. However, because of limited availability of LTL vans, this flow could not exceed by 25% of total flow. Transportation fees per ton are quoted by a 3PL company by types and by standards of transport means and distances.

By cross-docking functionality, the distribution centers insure the transshipment and the distribution of products to regional dealers by LTL vans. The damage to environment and human health caused by electricity, diesel consumption and waste over the handling operations are considered. There are three optional locations determined for opening cross-docking distribution centers for regional distribution by LTL trucks. Numbers and locations of DCs are optional but maximum three.

Figure 1. The Illustrative Model for Optional Distribution Channels and Transport Modes

Energy : Electricity and Diesel

CO2+Air Pollutant Emissions and Waste

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Apart from overall distribution costs, the company needs to control environmental impacts of distribution system due to quality standards which should be matched. Therefore, some trade-offs between costs and environmental outputs mainly greenhouse gas emissions must be taken in consideration. Transport means are the main source of gas emissions i.e. CO$_2$ and other air pollutants (SO$_2$, NO$_X$, PM). From this point of view rail is friendlier to the environment. Heavy trucks are classified by Euro norms (between Euro1-6) what restricts their air pollutant emission level. The trucks with higher Euro standard produce less air pollutant but cost more because of investment on high-tech. On the other hand, operational facilities like cross-docking centers also generate gas emissions because of intensive use of energy like electricity and diesel. Eco-efficient buildings and equipment are much costly but helps to reduce the negative effects on environment.

**Problem**

In order to

1. Minimize system-wide cost
2. Minimize CO$_2$+Air Pollutant emission level produced within distribution system;

- Which transport modes/means should be used between nodes?
- What should be the standard of LTL trucks in terms of Euro emission standards?
- Which DCs should be operated and on which capacity?
- Which standard (i.e. Normal or Ecologic) should be applied at DC to be operated
- What quantity (tons) of goods should be transported between nodes?

**Assumptions and Limitations**

1. Differences on capacity and Loading Factor on Trucks and Rail Wagons are not considered.
2. Availability of Euro1 / Euro3 / Euro5 FTL Trucks and Rail Wagons is not limited
3. Because of limited availability of LTL Trucks, direct flow between PW and Regional Dealers is limited by 25% of total flow.
4. Demand from Regional Dealers are stable and all must be satisfied
5. Transport costs are for each route on lease-base €/ton quoted by 3PL. Transport fees include all running costs plus loading and unloading fees.
6. Each Distribution Centre handling capacity is different and limited
7. The CO$_2$ emission restriction constraint, defined as quota, developed on the basis of the Kyoto Protocol and other traffic characteristics [2].

**The Model**

There are two types of multi-objective optimization problems: (i) preference-based optimization problems are the internalization of CO$_2$ emissions in the objective function. Thus, the solution is similar to the one for single optimization problems (ii) the ideal multi-objective optimization problem considers two issues (i.e., in this case, distribution costs and CO$_2$ emissions) separately and estimates their relationship (i.e., the trade-off). The problem with the preference-based approach is that it is extremely difficult to estimate the price of CO$_2$ (e.g., by use of a conversion factor such as the number of euros per kilogram of CO$_2$). In addition, the conversion factor can conversely be approximated by this approach once the trade-off has been estimated. The ideal multi-objective is presented in its general form and is then applied to the relationship between cost and CO$_2$ emissions in the system. The relationship can be drawn as a trade-off graph and is called a Pareto optimal solution. The aim of our study is to determine an appropriate transportation mode, means and channel split that ensures minimum system costs and the minimum level of CO$_2$ emissions, subject to the demand and the capacity. The final solution might not be a single point but a curve or a line. Therefore, the multi-objective optimization problem was found to be highly suitable for the aim of this study.

In the model we have two objective functions. The first one measures the total cost of distribution system: fixed setup cost, total transportation cost, energy consumption cost and in-transit inventory cost by lead-times. The second objection function measures the total CO$_2$ and Air Pollutant emission produced in transportation and handling process in distribution centers.
Mathematical Formulation

Notations:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW</td>
<td>Plant Warehouse</td>
</tr>
<tr>
<td>DC</td>
<td>Set of possible cross-docking DC locations with the number of $Dc = 1, 2, 3$</td>
</tr>
<tr>
<td>RD</td>
<td>Set of Regional Dealers with the number of $Rd = 1, 2, 3, 4, 5, 6$</td>
</tr>
<tr>
<td>$D_{Rd}$</td>
<td>Demand of Regional Dealers ($Rd = 1, 2, 3, 4, 5, 6$)</td>
</tr>
<tr>
<td>LTL</td>
<td>Transportation using LTL truck</td>
</tr>
<tr>
<td>FTL1</td>
<td>Transportation using FTL truck with Euro1 standards</td>
</tr>
<tr>
<td>FTL3</td>
<td>Transportation using FTL truck with Euro3 standards</td>
</tr>
<tr>
<td>FTL5</td>
<td>Transportation using FTL truck with Euro5 standards</td>
</tr>
<tr>
<td>RAIL</td>
<td>Transportation using RAIL</td>
</tr>
<tr>
<td>$T^{LTL}$</td>
<td>Transportation Cost per ton by LTL truck</td>
</tr>
<tr>
<td>$T^{FTL1}$</td>
<td>Transportation Cost per ton by FTL truck with Euro1 standards</td>
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<tr>
<td>$T^{FTL3}$</td>
<td>Transportation Cost per ton by FTL truck with Euro3 standards</td>
</tr>
<tr>
<td>$T^{FTL5}$</td>
<td>Transportation Cost per ton by FTL truck with Euro5 standards</td>
</tr>
<tr>
<td>$T^{RAIL}$</td>
<td>Transportation Cost per ton by RAIL</td>
</tr>
<tr>
<td>$I^{\text{Normal}}$</td>
<td>In-transit Inventory Cost per ton influenced by the Lead-Times</td>
</tr>
<tr>
<td>$I^{\text{Ecologic}}$</td>
<td></td>
</tr>
<tr>
<td>$F^{\text{Normal}}_{Dc}$</td>
<td>Fixed Opening Cost of DC in Normal Standards</td>
</tr>
<tr>
<td>$F^{\text{Ecologic}}_{Dc}$</td>
<td>Fixed Opening Cost of DC in Ecological Standards</td>
</tr>
<tr>
<td>$E^{\text{Normal}}_{Dc}$</td>
<td>Energy Consumption Cost per ton handled at DC in Normal Standards</td>
</tr>
<tr>
<td>$E^{\text{Ecologic}}_{Dc}$</td>
<td>Energy Consumption Cost per ton handled at DC in Ecological Standards</td>
</tr>
<tr>
<td>$H^{\text{Normal}}_{Dc}$</td>
<td>Handling Capacity at DC in Normal Standards</td>
</tr>
<tr>
<td>$H^{\text{Ecologic}}_{Dc}$</td>
<td>Handling Capacity at DC in Ecological Standards</td>
</tr>
<tr>
<td>$CO^{2A}_{LTL}^{\text{Normal}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr by LTL truck</td>
</tr>
<tr>
<td>$CO^{2A}_{LTL}^{\text{Ecologic}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr by LTL truck</td>
</tr>
<tr>
<td>$CO^{2A}_{FTL1}^{\text{Normal}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr by FTL truck Euro1</td>
</tr>
<tr>
<td>$CO^{2A}_{FTL1}^{\text{Ecologic}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr by FTL truck Euro1</td>
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<td>CO2+Air Pollutants emission produced per ton/gr by FTL truck Euro3</td>
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<td>$CO^{2A}_{FTL3}^{\text{Ecologic}}$</td>
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<tr>
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<td>CO2+Air Pollutants emission produced per ton/gr by FTL truck Euro5</td>
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<tr>
<td>$CO^{2A}_{FTL5}^{\text{Ecologic}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr by FTL truck Euro5</td>
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<tr>
<td>$CO^{2A}_{RAIL}^{\text{Normal}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr in by RAIL</td>
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<td>$CO^{2A}_{RAIL}^{\text{Ecologic}}$</td>
<td>CO2+Air Pollutants emission produced per ton/gr in by RAIL</td>
</tr>
<tr>
<td>$CO^{2}_{Dc}^{\text{Normal}}$</td>
<td>CO2 produced per ton/gr at DC in Normal Standards</td>
</tr>
<tr>
<td>$CO^{2}_{Dc}^{\text{Ecologic}}$</td>
<td>CO2 produced per ton/gr at DC in Ecologic Standards</td>
</tr>
</tbody>
</table>

Decision Variables:

- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from PW to Regional Dealer ($Rd = 1, 2, 3, 4, 5, 6$) by LTL trucks
- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from PW to DC ($Dc = 1, 2, 3$) by FTL-Euro1 trucks
- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from PW to DC ($Dc = 1, 2, 3$) by FTL-Euro3 trucks
- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from PW to DC ($Dc = 1, 2, 3$) by FTL-Euro5 trucks
- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from PW to DC ($Dc = 1, 2, 3$) by RAILCAR
- $Q^{\text{Normal}}_{PWDc}$ = qty. (tons) of products transported from DC ($Dc = 1, 2, 3$) to RD ($Rd = 1, 2, 3, 4, 5, 6$) by LTL trucks
- $Y^{\text{Normal}}_{Dc}$ = 1 if Distribution Centre in Normal Standards is opened, and = 0 otherwise ($Dc = 1, 2, 3$)
- $Y^{\text{Ecologic}}_{Dc}$ = 1 if Distribution Centre in Ecological Standards is opened, and = 0 otherwise ($Dc = 1, 2, 3$)
Objective Function 1. (Minimization the Total Cost of Distribution System)

Min \( Z_1 \) (\( a + b + c + d \))

a) Transportation Cost ($/per ton)

\[
\sum_{Dc=1}^{3} Q^{LTL}_{PWRd} T^{LTL}_{PWRd} + \sum_{Dc=1}^{3} Q^{FTL1}_{PWd} T^{FTL1}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL3}_{PWd} T^{FTL3}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL5}_{PWd} T^{FTL5}_{PWd} + \\
\sum_{Dc=1}^{3} Q^{RAIL}_{PWd} T^{RAIL}_{PWd} + \sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} T^{LTL}_{DcRd}
\]

b) In-transit Inventory Cost influenced by Lead-Time ($/per ton)

\[
\sum_{Dc=1}^{3} Q^{LTL}_{PWRd} I^{LTL}_{PWRd} + \sum_{Dc=1}^{3} Q^{FTL1}_{PWd} I^{FTL1}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL3}_{PWd} I^{FTL3}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL5}_{PWd} I^{FTL5}_{PWd} + \\
\sum_{Dc=1}^{3} Q^{RAIL}_{PWd} I^{RAIL}_{PWd} + \sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} I^{LTL}_{DcRd}
\]

c) Opening Cost of DCs (fixed $)

\[
\sum_{Dc=1}^{3} F^{Normal}_{Dc} Y^{Normal}_{Dc} + \sum_{Dc=1}^{3} F^{Ecologic}_{Dc} Y^{Ecologic}_{Dc}
\]

d) Energy Consumption Cost in DCs ($/per ton operated)

\[
\sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} E^{Normal}_{Dc} Y^{Normal}_{Dc} + \sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} E^{Ecologic}_{Dc} Y^{Ecologic}_{Dc}
\]

Objective Function 2. (Minimization the CO2+Air Pollutant Emission produced within Distribution System)

Min \( Z_2 \) (\( e + f \))

e) Emission produced in Transportation (gr/per ton transported)

\[
\sum_{Dc=1}^{3} Q^{LTL}_{PWRd} COA^{LTL}_{PWRd} + \sum_{Dc=1}^{3} Q^{FTL1}_{PWd} COA^{FTL1}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL3}_{PWd} COA^{FTL3}_{PWd} + \sum_{Dc=1}^{3} Q^{FTL5}_{PWd} COA^{FTL5}_{PWd} + \\
\sum_{Dc=1}^{3} Q^{RAIL}_{PWd} COA^{RAIL}_{PWd} + \sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} COA^{LTL}_{DcRd}
\]

f) Emission produced at DC operations (gr/per ton operated)

\[
\sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} COA^{Normal}_{Dc} Y^{Normal}_{Dc} + \sum_{Dc=1}^{3} \sum_{DcRd=1}^{6} Q^{LTL}_{DcRd} COA^{Ecologic}_{Dc} Y^{Ecologic}_{Dc}
\]
Subject to:

g) Whole demand of Regional Dealers is satisfied

\[
\sum_{Rd=1}^{6} Q_{PWRd}^{LTL} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{DcRd}^{LTL} = \sum_{Rd=1}^{6} D_{Rd}
\]

h) Product In-Flow towards Distribution Centre is limited with its Handling Capacity

\[
\sum_{Dc=1}^{3} Q_{PWRd}^{FTL1} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{FTL3} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{FTL5} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{RAIL} \leq \sum_{Dc=1}^{3} H_{Normal} Y_{Normal}^{Dc} + \sum_{Dc=1}^{3} H_{Ecologic} Y_{Ecologic}^{Dc}
\]

i) Distribution Centre product In-flow and Out-flow is equal

\[
\sum_{Dc=1}^{3} Q_{PWRd}^{FTL1} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{FTL3} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{FTL5} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{3} Q_{PWRd}^{RAIL} = \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{DcRd}^{LTL}
\]

j) Direct Flow from PW to Regional Dealers is limited by 25% of total flow

\[
\sum_{Rd=1}^{6} Q_{PWRd}^{LTL} \leq 0.25 \sum_{Rd=1}^{6} D_{Rd}
\]

k) Quota for CO2+Air Pollutant emissions

\[
\left[ \sum_{Rd=1}^{6} Q_{PWRd}^{LTL} COA_{PWRd}^{LTL} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{PWRd}^{FTL1} COA_{PWRd}^{FTL1} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{PWRd}^{FTL3} COA_{PWRd}^{FTL3} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{PWRd}^{FTL5} COA_{PWRd}^{FTL5} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{PWRd}^{RAIL} COA_{PWRd}^{RAIL} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{DcRd}^{LTL} COA_{DcRd}^{LTL} + \sum_{Dc=1}^{3} \sum_{Rd=1}^{6} Q_{DcRd}^{LTL} COA_{DcRd}^{LTL} \right] \leq COA^{MAX}
\]

l) Binary constraints

\[
Y_{Normal}^{Dc} \in \{1,0\} \text{ for } Dc = 1, 2, 3 \quad Y_{Ecologic}^{Dc} \in \{1,0\} \text{ for } Dc = 1, 2, 3
\]

m) DC in one location is opened either in Normal or Ecologic Standards

\[
Y_{Normal}^{Dc} + Y_{Ecologic}^{Dc} \leq 1 \text{ for } Dc = 1, 2, 3
\]

n) Non-negativity constraint

\[
Q_{PWRd}^{LTL}, Q_{PWRd}^{FTL1}, Q_{PWRd}^{FTL3}, Q_{PWRd}^{FTL5}, Q_{PWRd}^{RAIL}, Q_{DcRd}^{LTL} \geq 0
\]

for \( Dc : 1, 2, 3 \) and for \( Rd : 1, 2, 3, 4, 5, 6 \)
IV. THE SOLUTION APPROACH

It is well-known that there exist multiple non-dominated solutions for a multi-objective optimization problem. Those solutions are called *Pareto optimal solutions* [8]. A Pareto optimal solution is defined as follows: “a solution (call it A) to a multi-objective problem is Pareto optimal if no other feasible solution is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective” [9]. In this paper, we aim to determine eco-efficient frontiers which provides evenly distributed Pareto solutions. It helps the decision makers to select a suitable configuration.

In order to run the linear programming and to find objection function values (Z₁ and Z₂) we use LINDO 6.1 package program. At first we estimate the upper and lower bounds of our second objective function (Z₂), as follows [2]:

Step 1. Run the program for Z₁ excluding Z₂ and constraint (k), and get the initial solution for Z₁

Step 2. Substitute the initial solution Z₂ and assume that the current value of Z₂ is the upper bound of constraint (k)

Step 3. Run the program for Z₂ with all constraints excluding Z₁, get the initial solution for Z₂ which is the lower bound of constraint (k)

Step 4. Set the Pareto optimal set equal to (∅) and the desired number of subsets of Pareto optimal points.

Step 5. Estimate the increment of CO₂ as follows: increment = (upper bound-lower bound)/number of Pareto optimal points.

Step 6. Update constraint (k) as follows:

\[
\begin{align*}
\sum_{Rd=1}^{n} Q_{PWRd}^{LTL} COA_{PWRd}^{LTL} &+ \sum_{Dx=1}^{n} Q_{PWRd}^{FTL} COA_{PWRd}^{FTL} + \sum_{Dx=1}^{n} Q_{PWRd}^{FSTL} COA_{PWRd}^{FSTL} + \sum_{Dx=1}^{n} Q_{PWRd}^{FSTL} COA_{PWRd}^{FSTL} + \\
& \leq \text{(initial upper bound - increment)}
\end{align*}
\]

Step 7. Run the program for Z₁ with the updated constraint (k) and the others

Step 8. Update the subset of Pareto optimal set for (Z₁, Z₂), if all constraints and optimality conditions are satisfied then a solution is found.

Step 9. If the current number of Pareto optimal solutions is less than a desired number of Pareto optimal solutions (in other words, the current upper bound is less than the global lower bound), go to Sep 6.

Step 10. End

V. CONCLUSION

Recently green activities in logistics are being popular due to the increasing environmental consciousness mainly about global warming. Cap and trade regulations along with an increasing consumer and company demand for green products and services constitute two major drivers for motivating corporations to adopt green practices. However, the adoption of green practices usually increases their operational costs. Therefore, the trade-off between “green” and cost-optimal policies is a common challenge for most organizations. To achieve...
such goal, governments and companies must invest on the design and planning optimization of their logistic structures, while accounting for the trade-off between profit and environment impact.

In this context, this paper deals with the design of a multi-objective green distribution network in order to satisfy the customer demands and to respect the environmental requirements. A multi-objective mixed-integer model formulation and resolution through Pareto optimal are proposed as the core of the decision-support tool to reach for sustainable distribution planning using economic and ecological trade-offs. This study mainly focuses on trade-offs between environmental and economic impact of (i) two main transportation modes (i.e. road and rail) (ii) type of on-road distribution vehicles (i.e. FTL heavy trucks and LTL delivery vans) (iii) emission protection level of FTL heavy trucks (i.e. Euro1, Euro3, Euro5). Besides, we considered transit time varying by transport modes and routes as another decisive factor since longer lead-time leads increase on inventory holding cost before final delivery.

To our knowledge, this is the first model that deals green distribution trade-offs from such wide perspective. Besides, we first time include the lead-time factor in the model as another trade-off in transportation mode selection in addition to economic and ecological constraints. The authors of this paper aim to enhance this paper with a numerical example in their next study.

We have also some implications for further studies. While measuring trade-offs between cost and emission performance of trucks, there are certainly some other factors to be considered such as fuel consumption level per km and loading factor of trucks which are directly correlated with each other as well with emission levels produced per ton/km. Noise level of heavy trucks is another important factor about environmental concerns which can be added in ecological constraints.

REFERENCES


