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A concept for warehouse network optimization: Improvement in logistics efficiency

Abstract: Over the last twenty years, there has been a deep change in the energy consumption of freight transport and the economics of logistics and the supply chain. Increasing competition forced supply chain networks to reconsider and restructure their business models in order to increase their sustainability and, consequently, reduce fuel consumption. Companies have turned to optimization models in order to find the best possible supply chain network configuration. This paper presents an overview of the current global energy consumption of the transport sector, in particular the road freight transport sector, and a review of literature on facility location models. Additionally, this paper proposes a conceptual basis for the formulation of a mixed-integer linear programming model that can be applied for the verification of warehouse locations in a supply chain network. The concept of the proposed model is formulated in a way that will lead to cost savings. The model will serve as a decision-support tool for distribution network optimization. The proposed concept includes in its objective function warehousing costs and transportation costs.

Keywords: optimization, mathematical modelling, transport sector

Koncepcja optymalizacji funkcjonowania sieci magazynów – wzrost efektywności systemów logistycznych

Streszczenie: W ciągu ostatnich dwudziestu lat doszło do istotnych zmian w zużyciu energii w sektorze transportu towarowego oraz w ekonomice procesów logistycznych i łańcucha dostaw. Rosnąca konkurencja wymusiła restrukturyzację oraz wzrost efektywności modeli biznesowych ukierunkowanych na zrównoważony rozwój, co w konsekwencji prowadzi do zmniejszenia zużycia paliw. Przedsiębiorstwa zwracają coraz większą uwagę na modele optymalizacyjne, pozwalające na wypracowanie najlepszych konfiguracji sieci łańcucha dostaw. W artykule przedstawiono analizę aktualnego zużycia energii w sektorze transportowym, w szczególności w sektorze drogowego transportu towarowego oraz dokonano przeglądu literatury w obszarze modeli optymalizujących lokalizację obiektów (np. magazynów). Ponadto, w artykule zaproponowano koncepcję sformułowania modelu matematycznego wykorzystującego podejście programowania mieszanego całkowitoliczbowego liniowego, który

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będzie mógł być zastosowany do opracowania i weryfikacji lokalizacjach magazynów. Model ten umożliwi redukcję kosztów prowadzenia działalności w obszarze gospodarki magazynowej. Będzie on służyć jako narzędzie wspomagania decyzji dla optymalizacji sieci dystrybucji. W funkcji celu przedmiotowego modelu uwzględnione zostaną koszty magazynowania oraz koszty transportu.

Słowa kluczowe: optymalizacja, modelowanie matematyczne, sektor transportu

Introduction

Over the last twenty years, a deep change in the energy consumption of freight transport and the economics of logistics and supply chain has taken place. With the rising concern from the general population and national governments over the long-term impact of anthropogenic CO_2 emissions, and the global need for reduction in energy consumption and greenhouse gas emissions (GHG), companies and supply chains have been forced to reconsider and restructure their business models in order to increase their sustainability (Liotta et al. 2015; Wu and Pagell 2011). In this respect, one way for companies and supply chains to increase their sustainability has been to find the best possible supply chain network configuration through Supply Chain Management (SCM) (Melo et al. 2009). A second option has been the apply a well-established research area within Operations Research (OR) to develop Production-Distribution optimization models and decision support tools to minimize different metrics within a production-distribution network.

In 2013, the International Energy Agency (IEA) estimated that the transport sector accounted for approximately 2564 Mtoe or 28% of the total final energy consumption in the world (IEA 2015a). Furthermore, compared to 1973, the final energy consumption of the transport sector doubled and by 2040 it is expected to reach a consumption of 3132 Mtoe (IEA 2015b). The fast growth in fossil fuels consumption, specifically in freight transport, has shown the necessity of new decision support tools that will embrace profitability and also environmental sustainability. Fig. 1 presents the world's final energy consumption by sector type in 2013 and Fig. 2 shows the global energy consumption by sector between 1990 and 2012.

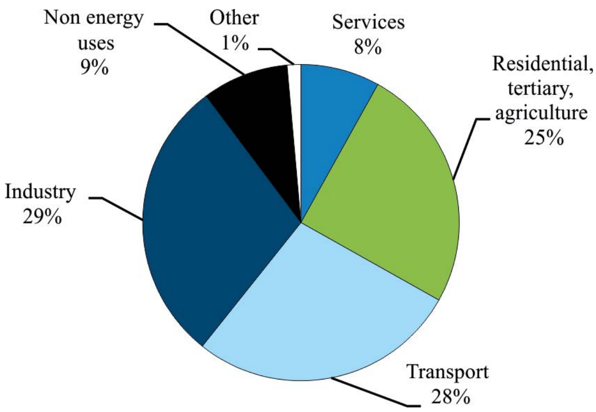

Fig. 1. Global final energy consumption by sector type (2013) Source: IEA 2016

Rys. 1. Konsumpcja energii finalnej w sektorach gospodarczych w świecie

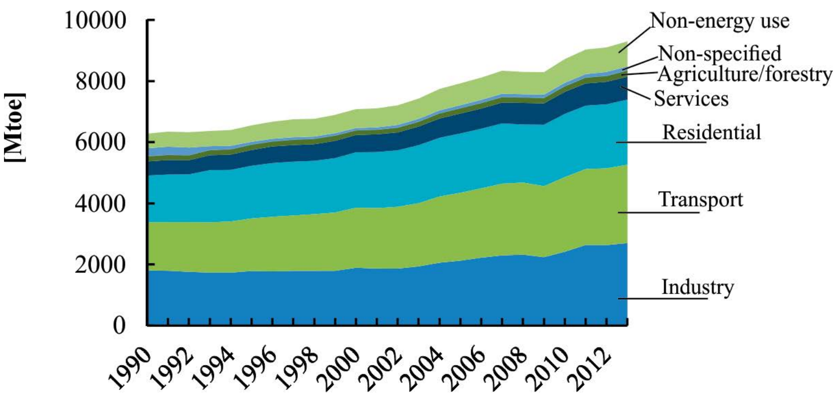

Fig. 2. Final energy consumption by sector type (1990–2013) Source: IEA 2016

Rys. 2. Konsumpcja energii finalnej w sektorach gospodarczych w świecie w latach 1990–2013

In regard to the road freight transport sector, we can observe different energy consumption trends around the world. While in China, India, and other developing countries, energy use in road freight transport has sharply increased, in several EU (European Union) and OECD (Organization of Economic Cooperation Development) countries energy consumption appears to have decreased in the last eight years (Fig. 4). Energy consumption by road freight transport has decreased in EU and OECD countries due to the changes and improvements in efficiency, rather than a reduction in road freight transport services.

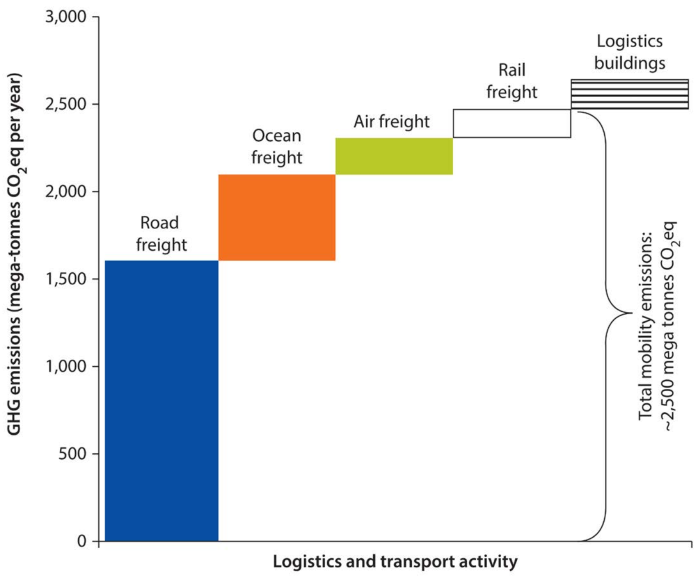

Fig. 3. Emissions from logistic activities (2009)
Source: Kopp et al. 2013

Rys. 3. Emisja w obszarze logistyki w roku 2009

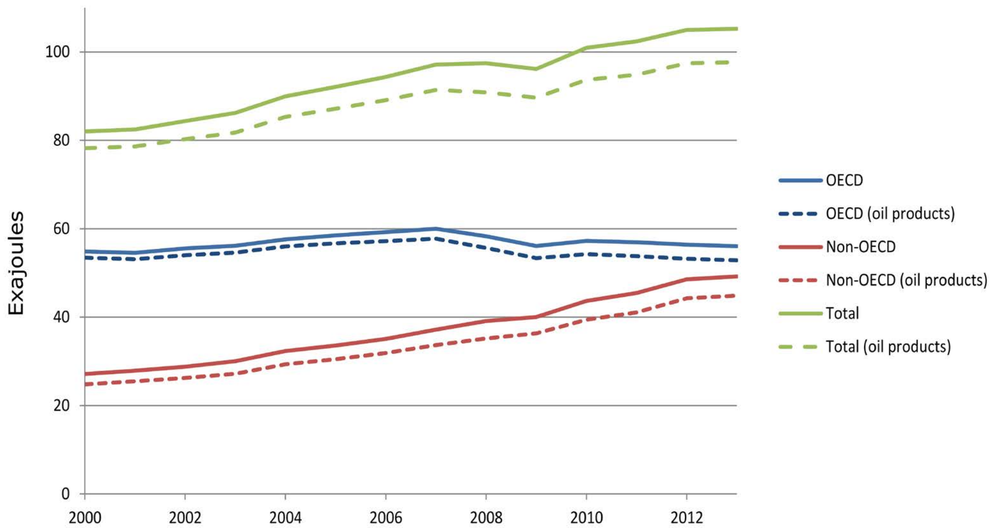

Fig. 4. Transport energy use by OECD and Non-OECD countries (2000–2013)
Source: Cazzola et al. 2015

Rys. 4. Zużycie energii w państwach OECD i Non-OECD w latach 2000–2013

Not only has the environmental concern of GHG emissions (Fig. 3) and energy use (Fig. 5) generated pressure on enterprises to restructure their business models, but also the rising global competition. Multinationals face increasing competitive pressure to find new ways or better methods for operational and organizational improvements. Currently, there

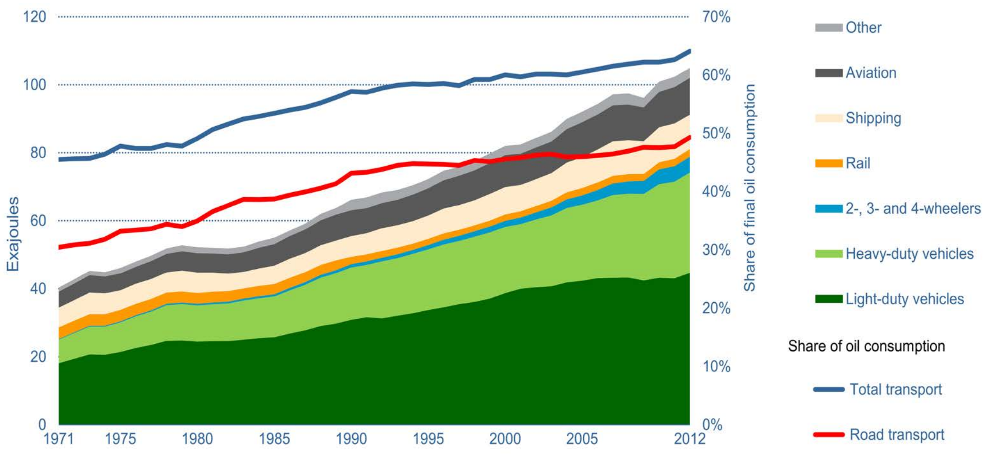

Fig. 5. Energy consumption in transport
Source: Cazzola et al. 2015

Rys. 5. Zużycie energii w transporcie

are a vast number of papers focusing on optimization models for facility locations and personnel scheduling; however, most of them only address the issue of cost optimization. Obviously, this is not a surprise since it is commonly known that industry mainly focuses on profitability, leaving aside the environmental impact and energy intensity assessment from production and distribution network to researchers and policy makers.

Furthermore, several studies have shown that small businesses and even worldwide enterprises tend to resist any reconfiguration in the supply chain network (warehouse network), making a possible reduction in fuel use and CO_2 emissions much more difficult. Wu and Pagell (2011) investigated how organizations balance short-term profitability and long-term environmental sustainability when making decisions under a level of uncertainty. Their results show that organizations usually tend to emphasize on profitability rather than environmental sustainability since the impact of environmental actions are not clear. However, in recent years, leading companies have searched for new ways to cut down fuel consumption, emissions and reduce their environmental impact. These have prompted further studies in OR and SCM and have motivated the development of new optimization tools that not only focus on profitability or cost minimization, but on fuel consumption and greenhouse gas emissions. Moreover, leading companies have seen the beneficial prospect in the medium -long term fuel consumption reduction since it can turn into remarkable operational cost savings.

In this context, the aim of this paper is to propose the conceptual basis for the development of mixed-integer linear programming (MILP) model that can be applied as a support decision tool for freight transport cost optimization and that takes fuel consumption into account. With this scope in mind, to clarify the link between facility locations, fuel consumption and supply chain planning, a literature review on facility locations models is undertaken in section 2. The reminder of the article is organized as follows. Section 3 describes the problem definition and modelling methodology of the optimization model and the paper ends with a summary and conclusions in section 4.

2. Literature review

Over the past three decades, there has been an increasing number of papers published on the subject of facility location and supply chain management. Nowadays, the fast globalization of businesses and the shortening of product cycles have led to an increase in freight transport services. Furthermore, the increase in services has encouraged the need of more robust supply chain management, including better warehouse locations and fuel cost reductions.

In literature, a facility location problem has been described as a "set of spatially distributed customers and a set of facilities to serve customer demands" (Melo et al. 2009). The facility location problem was initially formulated by Hakimi (1964). The main idea at that time was to optimize the location of public facilities such as police stations and hospitals and minimize the distance, travel time or transportation costs.

Since then, the facility location problem has become one of the most studied facility location models. Nowadays, it is commonly referred to in literature as the p-median problem or the k-center problem. The goal of the p-median problem is "locating p facilities to minimize the demand of weighted average distances between demand nodes and the nearest of the selected facilities" (Laporte and Nickel 2015).

The formulation for the p-median problem was proposed by ReVelle and Swain (1970) and has been simplified by Correa et al. (2001) to the following:

- n – total number of vertexes in the graph,
- a_i – demand of vertex i,
- d_{ij} – distance from vertex i to vertex j,
- p – number of facilities used as medians.

Decision variables:

$$x_{ij} = \begin{cases} 1, & \text{if the vertex } i \text{ is assigned to facility } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if the vertex } j \text{ is a facility used as a median} \\ 0, & \text{otherwise} \end{cases}$$

$$Min \sum_{i=1}^{n} \sum_{j=1}^{n} a_i d_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j=1}^{n} x_{ij} = 1, \quad i = 1, 2, \ldots, n \tag{2}$$

$$x_{ij} \le y_i, \quad i, j = 1, 2, \ldots, n \tag{3}$$

$$\sum_{j=1}^{n} y_j = p \tag{4}$$

$$x_{ij}, y_j \in \{0,1\}, \quad i, j = 1, 2, \ldots, n \tag{5}$$

The formulation consists mainly of two parts, objective function and constraints. The objective function, equation (1), which minimizes the sum of the total weighted distances. The first constraint (2) ensures that all demand points are satisfied by exactly one facility site. The second constraint (3) guarantees that demand points are assigned to open facilities. Furthermore, constraint (4) stipulates that exactly p number of facilities must be opened or stablished. Finally, equation (5) restricts the values of the location variables to integer and binary numbers. The graphical solutions for a 5-median and 25-median problem are presented in Fig. 6 and Fig. 7.

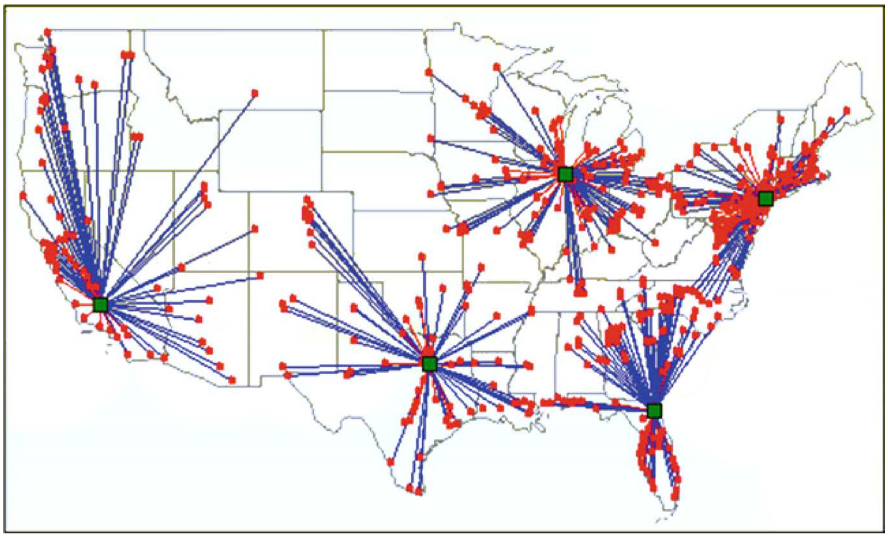

Fig. 6. Graphical solution for a 5-median problem
Source: Laporte and Nickel 2015

Rys. 6. Rozwiązanie graficzne dla problemu 5-median

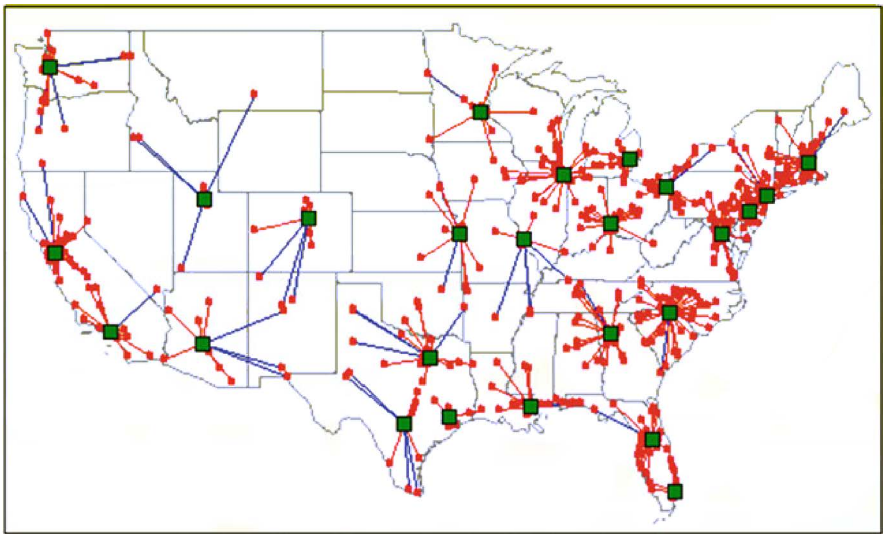

Fig. 7. Graphical solution for a 25-median problem
Source: Laporte and Nickel 2015

Rys. 7. Rozwiązanie graficzne dla problemu 25-median

Over the years, several extensions and modifications of the p-location problem have been proposed, and a variety of models have been developed. Liotta et al. (2015) classified mathematical models depending on the solution approach:

- Mathematical programming techniques – Linear programming models, mixed integer programming models and Lagrangian relaxation models,
- Heuristic techniques,
- Simulations modeling,
- Genetic algorithms.

Moreover, Melo et al. (2009) presented an extensive review on facility location and supply chain management optimization techniques. In their work, facility location models are classified depending on the type of decision variables and supply chain characteristics. Additionally, they are classified based on the nature of the planning horizon, which could be either single or multi-period, and on the type of data, deterministic or stochastic. A recent review by Fahimnia et al. (2013) divided production-distribution models into seven categories: type of optimization, type of products, location of manufacturing plants, transport path, warehouse type and time periods.

Even though extensive literature is available on location and transportation problems, mainly focused on production-distribution problems, there is a small number of papers when it comes to address the issues of facility locations, fuel consumption, and CO_2 emissions simultaneously in road freight. Bauer et al. (2010) addressed the issue of greenhouse gas emissions, intermodal freight transport, and commodity costs, by developing an integer program that minimized GHG emissions on a real-life rail freight transport network.

Additionally, Le and Lee (2011) proposed an integer linear programming model that minimizes cost and the environmental impact of transport activities, purchasing materials and inventory activities. However, the study mainly focuses on a global supply chain network and CO_2 emissions from selected transport modes (road, sea or air).

A more recent study by Liotta et al. (2015) introduced a model that integrates production and transportation networks. Similarly to Le and Lee (2011), the objective function aims to minimize transport costs and CO_2 emissions depending on the shipping mode selected (road, rail, short-sea). It is important to point out that in recent years, models aimed at minimizing CO_2 emissions are part of a combined approach between corporations and governmental agencies to increase global sustainability.

3. Problem definition and Methodology

3.1. Problem definition

Consider the case where a supply chain network owns and operates several warehouses in a specific region. The main region is subdivided into sub-regions and they are treated as independent areas. The warehouses supply a number of commodities to specific demand points that are located in these sub-regions. Moreover, top management has not yet applied any optimization procedure to carry out the assignment of demand points to specific warehouses. Furthermore, warehouses located in sub-region “A” are only allowed to supply commodities to demand points located in the same sub-region. In consequence, if a warehouse is located in sub-region "A" and a demand point is located in sub-region "B", and the distance between "A" and "B" is short, the shipment of commodities between these two facilities is not allowed. Hence, resulting in significant inefficiencies and reducing the company's profits.

The aim of this work is to develop a decision-support tool that could be applied for the verification of warehouse storage locations and optimal assignment of warehouses to demand point. Having said that, the main objective of this exercise is to reduce costs (hence fuel consumption and CO_2 emissions) of the transportation of certain commodities in a supply chain network.

Prior to developing the mathematical model, the following issues need to be addressed:

- No bounds between sub-regions – all sub-regions are aggregated as one region.
- Inclusion in the objective function the following elements: warehousing costs, distribution costs, transportation costs.
- Incorporation of key constraints, such as: maximum shipping distance from a warehouse to a demand point.

3.2. Modelling the distribution network

For the formulation of the model, which aims to optimize costs and restructure a distribution network, there are key elements that need to be defined. Firstly, it is necessary to identify the time horizon, also referred to as the planning horizon. Time horizon can normally range from days to years. Due to the nature of the model, developed as a decision support tool for strategic planning and for which the results are expected to be of assistance for long term decisions, the time horizon in our study is 5 years with a resolution of one week.

Secondly, it is imperative to identify the decision variables of the model. Decisions variables influence the performance of the system, either by maximizing or minimizing an objective function (Winston 2004).

For our model, let us define the following decisions variables:

- Positive variables – non-negative amount of commodities shipped from warehouse X to demand point Y,
- Free variable – total costs,
- Binary variable – binary to indicate if an existing warehouse is closed or it remains open.

In regard to parameters, that can either be fixed or estimated, the following are used:

- Warehouse locations,
- Demand points locations,
- Distances between warehouses and demand points,
- Commodity demand (quantity) for each demand point,
- Inventory level at each warehouse,
- Upper level limit on total throughput for each demand point,
- Shipment cost ($/km), warehousing cost,
- Maximum distance between warehouses and demand points.

In essence, constraints reflect the numerical relations in a quantitative way and in terms of variables, parameters and constants. They are restrictions on the values of decisions variables (Winston 2004). Constraints are postulated as follows:

- Supply constraint – The total amount of commodities shipped from a warehouse to a demand point cannot exceed the warehouse's inventory level,
- Demand constraint – Quantity demand in a demand point cannot exceed the available inventory from the supplying warehouse,
- Throughput constraint – Total volume of commodities from a warehouse to a demand point remains between the allowed throughput level,
- Allocation constraint – A demand point can only be served by one warehouse in the same region.

Formulation of the objective function. The objective function can be either maximized or minimized. The objective function in the model is essentially the sum of warehousing, transportation and distribution costs of all the commodities. Obviously, the objective function is assumed to be minimized.

After formulating the model, there are different stages that are to be followed:

- Gathering data and scenario formulation: the collected data that are used for parameters, constraints and objective function coefficients; furthermore, the scenario is formulated on the basis of the fundamental concept,
- Obtaining an optimal solution: After the development of the model (in a modelling system such as GAMS, AIMMS, AMPL or LINDO), mathematical algorithms (such as CPLEX, or GUROBI) are applied to solve it numerically,
- Sensitivity analysis: Validity check of the model by comparing its output to historical data and investigating it accuracy,
- Testing and implementing the solution: Once the model is tested and validated, the model can be used to optimize a real supply chain network.

Once all the aforementioned steps are completed and the model robustness is positively tested the model is capable of being applied to solve the actual problem.

Conclusions

This paper presents an overview of the current global energy consumption of the transport sector, in particular the road freight transport sector. In developing nations, energy use in road freight transport has sharply increased, while in many developed nations for the last eight years energy consumption has decreased. In OECD and EU countries, improvements in energy efficiency have been one of the most important drivers for the reduction in road transport sector energy intensity and greenhouse gas emissions. Recently, the rising concern of the long-term impact of CO_2 emissions and the increasing competitive pressure between multinational corporations have prompted the development of new methods for optimization of distribution networks. Minimization of GHG emissions and fuel consumption has become part of a combined approach used by industry to increase their sustainability.

In this paper, a separate section is dedicated to the review of literature on facility location problems, specifically p-median problems, and most recent optimization models that integrate emissions, fuel consumption, costs and production-distribution networks. Moreover, in this article a conceptual basis for the formulation of a mixed-integer linear programming model is proposed. The proposed concept will be further used for the verification of warehouse locations in a supply chain network. In the future, the concept of the model will be improved and extended to include multiple transportation modes, production plants, intermediate distribution centers. Additionally, in order to provide a more realistic approach to a real-world application, constraints that require specialized formulations may be included.

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