t. LXXV ▪ nr 4/2023 ▪ DOI 10.33226/1231-2037.2023.4.5

Dr Paweł Ślaski
Military University of Technology (Poland)
ORCID: 0000-0002-1950-9910
e-mail: pawel.slaski@wat.edu.pl

Eco-efficiency of the transportation process in the context of reducing greenhouse gas emissions – case study[1]

Ekoefektywność procesu transportowego w kontekście redukcji emisji gazów cieplarnianych – studium przypadku

Abstract

Global warming is one of the most discussed issues in the context of climate change and refers to the steady increase in the Earth's average air temperature. The main cause of the changes affecting the environment is human activity. The most important task is to reduce atmospheric emissions of greenhouse gases, and one of the most important elements is to change the direction of energy policy – moving away from traditional fossil fuels to zero-carbon energy sources, and according to the author of the publication, systemic changes in the transportation process are also necessary. The article proposes a mathematical model of the eco-efficiency of the transportation process in terms of reducing CO_2 emissions into the environment. A detailed analysis of delivery costs was carried out, which in turn led to measurable results of the model in the form of optimal parameters of the studied process (frequency of deliveries and economic size of deliveries) with minimal costs. Existing studies in the field of reducing greenhouse gas emissions from road transport often ignore input data, which is incompatible with a systemic approach. The solutions used in this study integrate both input and output parameters, taking into account economic and environmental aspects, and reflecting diverse global policy practices. The model represents a kind of reengineering of the transportation process and is flexible enough to be applied to most modes of transportation, mainly those that generate the highest CO_2 emissions (road transport).

Keywords:
eco-efficiency, carbon footprint, consolidation, group material inventory management

Streszczenie

Globalne ocieplenie jest jednym z najczęściej dyskutowanych zagadnień w kontekście zmian klimatu i odnosi się do stałego wzrostu średniej temperatury powietrza na Ziemi. Główną przyczyną zmian wpływających na środowisko jest działalność człowieka. Najważniejszym zadaniem jest ograniczenie emisji gazów cieplarnianych do atmosfery, a jednym z najistotniejszych elementów jest zmiana kierunku polityki energetycznej – odejście od tradycyjnych paliw kopalnych na rzecz zeroemisyjnych źródeł energii. Zdaniem autora publikacji konieczne są również systemowe zmiany w procesie transportu. W artykule zaproponowano matematyczny model ekoefektywności procesu transportowego pod kątem redukcji emisji CO_2 do środowiska. Przeprowadzono szczegółową analizę kosztów dostaw, co z kolei doprowadziło do wymiernych wyników modelu w postaci optymalnych parametrów badanego procesu (częstotliwość dostaw i ekonomiczna wielkość dostaw) przy minimalnych kosztach. Rozwiązania zastosowane w tym badaniu integrują zarówno parametry wejściowe, jak i wyjściowe, biorąc pod uwagę aspekty ekonomiczne i środowiskowe oraz odzwierciedlając różnorodne globalne praktyki polityczne. Model jest wystarczająco elastyczny, aby można go było zastosować do większości rodzajów transportu, głównie tych, które generują najwyższą emisję CO_2 (transport drogowy).

Słowa kluczowe:
ekoefektywność, ślad węglowy, konsolidacja, grupowe zarządzanie zapasami materiałów

JEL: C61, C65, C67

creative commons Uznanie autorstwa 3.0 Polska

Introduction

For several decades, the issue of global warming has become a serious problem and challenge for the whole world, and this no longer means just higher air temperatures. The climate is giving us increasingly clear signals and communicating information that proves the necessity of taking decisive steps to halt the negative changes. To stop climate change is a crucial task, the success of which depends not only on political and economic decisions. The most important task is to reduce greenhouse gas emissions into the atmosphere. Therefore, one of the important elements is a change in the direction of energy policy – a shift from traditional fossil fuels towards zero-carbon energy sources.

As part of the literature research, resolutions and declarations related to climate policy actions were analysed. This includes the 1997 Kyoto Protocol (UN, 1997) and the 2015 Paris Agreement adopted at the twenty-first session of the Conference of the Parties (UN, 2015). The literature study also covered European Union initiatives. The most important EU initiative described in the European Commission's Communication of December 11, 2019 is the European Green Deal (European Commission, 2019). The next section of the study discusses the impact of transportation on greenhouse gas emissions. For this purpose, the following documents were analysed: Emissions Gap Report 2020 (UNEP, 2020a) and Strategy for Sustainable and Smart Mobility – European Transport on the Road to the Future (European Commission, 2020).

The literature study in this section also included considerations of electromobility and the mechanisms between transportation electrification, the economy, energy and climate change (Zhang & Fujimori, 2020; Szaruga & Załoga, 2022a). The issue of the carbon footprint and its impact on people's life-styles and the life cycle of motor vehicles was also addressed (Hammond, 2007; Werdmann & Minx, 2008; Jursova et al., 2019; Zhang, 2021).

When analysing the literature, it is important to mention carbon footprint analysis and eco-efficiency. Hammond (2007) argues that "the property that is often referred to as carbon footprint is actually the 'weight of carbon' in kilograms or tons per person or activity." Werdmann (Werdmann & Minx, 2009) describes how people's lifestyles affect the size of the carbon footprint. A study of Jursova et al. (2019) analysed the carbon footprint of electric vehicle life cycles (car production, battery production, road construction, car use, maintenance and disposal of all components) and battery charging in the Czech Republic, taking into account trends in electric vehicle battery charging between 2015 and 2050. Carbon footprint indicators were derived from life cycle assessment (LCA) using the Intergovernmental Panel on Climate Change (IPCC) method. The total carbon footprint has direct and indirect impacts on human activities and is expressed as a reference unit of kg CO_2, which is calculated based on the global warming potential.

Eco-efficiency has been defined as the overall goal of achieving a reduction in environmental impact. Leaving the normative part of the concept aside, the empirical part refers to the alignment between environmental impact and economic cost or value (Huppes & Ishikawa, 2008).

European Green Deal – impact of transport

On December 9, 2020, following the publication of the Report (European Commission, 2020), a transport strategy was developed, entitled "Sustainable and Smart Mobility Strategy – Putting European Transport on Track for the Future". Currently, transport-related emissions account for around 25% total greenhouse gas emissions in the EU. The European Union assumes that by 2050 Europe is to be the first climate-neutral continent, but in order to achieve this goal, major changes must also be made in transport.

The goals set by the EC for 2050 in the field of sustainable, intelligent and resilient mobility show that the transport transformation in the coming years should be based on vehicles powered by alternative fuels, in particular electricity. It is electric vehicles, which mainly create electromobility, that are supposed to contribute to improving air quality on the one hand, and to stimulate economic development and increase energy security on the other (European Commission, 2020).

In the context of global climate change, the author of the publication focused his research on road transportation, which was a significant contributor to the EU's greenhouse gas emissions in 2019. The author believes that the actions leading to transport based on electromobility are incomplete because the energy used to drive vehicles comes from fossil fuels, and most of the climate pollution is caused by the combustion of coal, oil and gas. Research should also focus on systemic and organizational changes in transport. Consolidation of loads and organization of "large" deliveries should be pursued. Thanks to the scale effect in transport, the frequency of deliveries is reduced, and thus the costs of transport and storage of goods are reduced (economic effect). Such systemic changes also result in a reduction in CO_2 greenhouse gas emissions (ecological effect).

A critical analysis of the literature led the author to pose the following conclusions:

- Efforts by national governments to reduce CO_2 emissions and introduce electromobility in automobile transport are half-hearted efforts, if only fossil fuels (mainly lignite) are still used to generate electricity.
- Also missing are systemic solutions for organizing mainly large-scale automobile freight transport.

It also led the author to formulate the following research questions:

- What measures should be taken to make the global economy climate-neutral?
- Does the energy and climate package (European Green Deal) adopted by the European Council lead to a conflict of goals (zero-carbon and closed-loop economy), and to what extent is it possible to achieve synergies?
- Are the actions of the European Union countries, related to reducing greenhouse gas emissions by 90% by 2050 in the field of mobility in all transport sectors, sufficient?

The author of the publication believes that if the goal of the closed-loop economy is to reduce the consumption of resources, including non-renewable energy carriers of organic origin, which are burned in various technological processes, that the result will be a reduction of greenhouse gas emissions. However, in the long term, the focus on climate targets set by agreements and protocols (Kyoto, Paris) may have a negative impact on the shape of the closed loop. Battery-supplied electric vehicles (BEVs) are an example. Their manufacture requires increased consumption of so-called rare earths, the recycling of which is very difficult because of the complexity of battery cell decomposition processes to recover raw materials and prepare them for reuse. At the same time, elimination of internal combustion engines does not result in a reduction of CO_2 emissions, but instead only in a change of their location to regions where coal-fired power plants are located.

These findings constitute a research gap, which the author would like to partially fill in the presented article. Therefore, the main objective of the article is to develop a model of the transport process in the context of CO_2 reduction and logistics cost reduction. Road transport from supplier to customer within the selected enterprise will be analysed. The developed model is not a comprehensive model and can be used for transport systems at the national level.

The mathematical model developed here is the author's solution to the problem of organizing the transportation of material groups. The objective function is a key element of the model and is an analysis of inventory costs, which are described in detail in by Smyk (2021, pp. 2–11). The purpose of the model, which is described based on the data in the case study, is to come up with a proposal for improving the transportation process after the consolidation of assortment groups in the supply chain. The case study describes two ways of ordering goods:

- classic, based on the EOQ model;
- the author's, based on ordering assortment groups after consolidation.

A comparative analysis of the two ordering methods showed, in the author's model, optimal delivery frequencies with minimal inventory costs. According to the author, the model developed fits into the problem of CO_2 reduction as the minimum number of deliveries involves less fuel consumption (than in the case of classic EOQ ordering), and thus reduces costs.

Materials and methods

The model is presented in the form of a SIPOC diagram, which defines the stages of the supply process design. The SIPOC (suppliers–input–process–output–consumer) diagram consists of three stages: defining the purpose of the model, answering how to transform measurable inputs into outputs, and analysing the input parameters to the model.

The publication develops a mathematical model of supplier–input–output–consumer in the local fruit and vegetable industry. A detailed analysis of the fruit and vegetable industry's commodities, the size of assortments, their type and the supply system in the supply chain were established on the basis of an interview with the head of the enterprise of the industry under study[2]. Basic data on the annual demand for selected types of goods, unit prices of goods, transportation costs and capital costs of holding inventory in the warehouse – stock holding ratio – are summarized in Table 1.

The construction of the model concerns the determination of the extremum of the objective function using differential calculus. For this purpose, Fermat's theorem on the necessary condition for the existence of a local extremum at the point x_0 of a function $f(x)$ differentiable at this point was used.

If a function is differentiable at a point $x_0 \in (a, b)$ and $f(x_0) = \max\{f(x): x \in (a, b)\}$ lub $f(x) = \min\{f(x): x \in (a, b)\}$ then $f'(x_0) = 0$.

Assumptions and structure of the model

The model developed pertains to the transport of assortment groups in the supply process of various goods, and its verification is possible both in road and rail transport. The assumptions of the model are related to the analysis of the unit costs of material stocks, which include the unit cost of creating (orders) and the unit costs of maintaining stocks. It is assumed that the unit costs of creating (ordering) the inventory are defined as the sum of transport costs and expenses incurred by the procurement department for the development and delivery (wages, energy, media, etc.). One should add the costs related to maintaining stocks after deliveries to the costs of creating stocks (orders) (Ślaski, 2021).

The output data of the model also constitute the determination of the objective function, which concerns the analysis of the cost of material stocks on a budget year basis, and its form determines the following research problem: "How to optimally deliver a variety of goods in the procurement process to minimize inventory costs and secure the recipient's needs?"

The analysis of the input data of the model includes the determination of the annual demand for the assortment, the purchase price of the assortment, and unit costs of material stocks.

The research results based on the case study proved that, when transporting various goods, it is better to use "larger deliveries" after consolidating the loads. Such a delivery system reduces logistics costs (mainly transport and storage), reduces the number of deliveries per year, which reduces CO_2 emissions.

Results

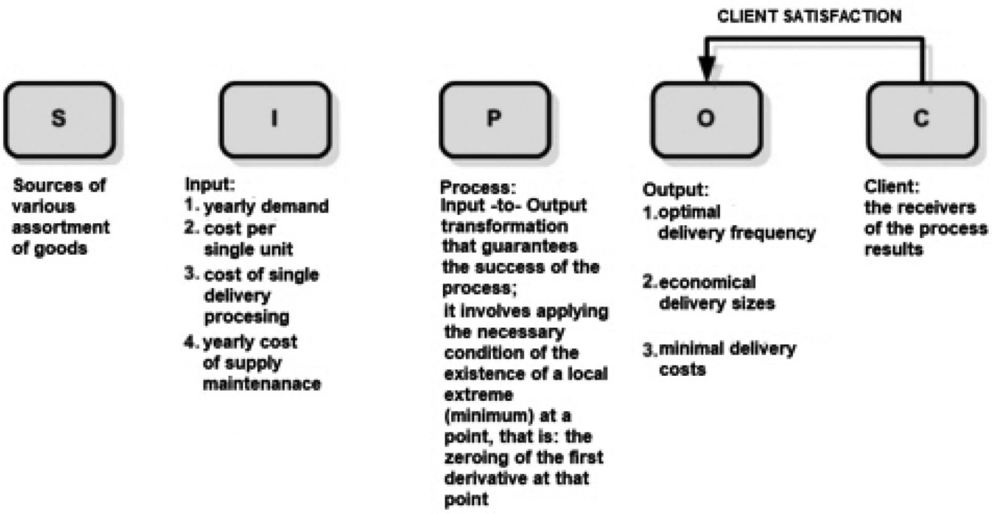
Model of eco-efficiency of the transport process in the context of CO_2 reduction

When carrying out a comprehensive assessment of the transport process, economical, technological and environmental issues should be taken into account at the same time (Simons & Cheung, 2016). This approach is possible thanks to the eco-efficiency analysis, which has been defined by the World Business Council for Sustainable Development (WBCSD) as the provision of products and services at a competitive price that meet human needs and improve the quality of life, reducing the impact on the environment and resource consumption throughout the life cycle (Theißen et al., 2014; Thompson et al., 2020).

The goals set out in the strategy for sustainable and smart mobility, mainly related to the introduction of regular public transport and the doubling of freight rail traffic, became the reason for developing an eco-efficiency model for the transport process. The structure of the model is related to the analysis of the process, in which the following stages can be distinguished, i.e:

- determination of input parameters to the model;
- transformation of inputs into outputs;

Figure 1
The SIPOC model of the transport process in the context of reducing CO_2 emissions



Source: own study.

- analysis of output data;
- supplier sources of various assortment of goods;
- client as a receiver of the process results (Figure 1).

The transformation (solving the problem) is based on determining the extremum of the objective function and solving the decision task of the form (Dineen, 2014; Dziubiński & Świątkowski, 1980):

$$f(x) = min\{f(x)|x \in D\} \quad (1)$$

with the sufficient condition of existence of a local extreme:

$$f'(x_0) = 0. \quad (2)$$

Description of the mathematical model

The objective function has the form:

$$f(x) = ibc \cdot x + \frac{1}{2} \cdot \sum_{i}^{n} \frac{d_i \cdot p_i}{x} \cdot srw \to min \quad (3)$$

a necessary condition for the existence of an extreme

$$\frac{df(x)}{dx} = 0.$$

Hence

$$f'(x) = ibc - \frac{1}{2} \cdot \sum_{i=1}^{n} \frac{d_i \cdot p_i}{x^2} \cdot srw = 0 \quad (4)$$

$$ibc - \frac{1}{2} \cdot \sum_{i=1}^{n} \frac{d_i \cdot p_i}{x^2} \cdot srw = 0 \quad (5)$$

$$ibc = \frac{1}{2} \cdot \sum_{i=1}^{n} \frac{d_i \cdot p_i}{x^2} \cdot srw \quad (6)$$

$$x^2 = \frac{1}{2} \cdot \frac{1}{ibc} \cdot srw \cdot \sum_{i=1}^{n} d_i \cdot p_i \quad (7)$$

$$x = \sqrt{\frac{1}{2} \cdot \frac{1}{ibc} \cdot srw \cdot \sum_{i=1}^{n} d_i \cdot p_i} \quad (8)$$

where:
ibc – inventory building costs – unit cost of creating (ordering) inventory;
x – decision variable number of deliveries;
srw – stock holding ratio in the warehouse ;
d_i – annual demand of the assortment;
p_i – purchase price of the assortment;
n – number of assortments.

The key in the model is the objective function, which consists of two parts. The first part includes the total annual costs of creating (ordering) inventories and is the product of the decision variable (number of developed and completed deliveries) and unit costs of creating (ordering) inventories. The second part concerns the total costs of maintaining inventory of assortment groups, which is defined as the product of the average delivery value of assortment groups (half of the delivery value) and the inventory maintenance ratio (the empirical ratio expresses the freezing of the company's capital in inventories), and is a percentage of the value of inventory.

For the model developed in this way, the economic quantities of deliveries of individual assortment groups are determined from the following formula:

$$es_i = \frac{d_i}{x} \quad (9)$$

where:
es_i – economic size of the assortment.

Verification of the developed model can be carried out on the example of each type of transport, in the intermodal system of transporting a consolidated load, e.g. using 20' or 40' containers. When consolidating goods in an LCL container (less than container load – LCL/LCL), however, one should remember about a few procedural steps. First of all, shipments should be properly sorted and grouped in terms of their type, transport requirements and the possibility of combining them in one container.

Case study – assumptions and limitations

The case study concerns the implementation of deliveries from suppliers of the fruit and vegetable industry supplying the local market[3]. The deliveries cover five assortment groups of the analysed industry. The basic limitation of the examined case is the use of a 20' container in which a variety of cargo is transported after consolidation.

The following factors were also taken into consideration:

- unit cost of delivery (*ibc*) over a distance of 100 km from suppliers to the recipient (costs of order processing, fuel consumption, labour and vehicle operation)[4] ,
- unit costs of "frozen capital" of inventory (*srw*),
- purchase price of an assortment unit (p_i),
- annual demand for a given assortment (d_i).

The case involved two methods of:

1. Deliveries from suppliers directly to the recipient and determination of delivery parameters using the classic model of the Economic Order Quantity EOQ (Figure 2).
2. Deliveries from suppliers after consolidation of loads by the logistics operator to the recipient using the developed mathematical model (Figure 3).

Table 1 contains the input data for model verification and the results after verification. Sample calculations were performed for the data.

Method one. Deliveries from suppliers directly to the recipient and determination of delivery parameters using the classic model of the Economic Order Quantity EOQ (Figure 2). The analysis was carried out for a selected group of assortments (vegetables). Data were entered into the formula for EOQ (Table 1):

$$EOQ_i = \sqrt{\frac{2 \cdot d_i \cdot ibc}{srw \cdot p_i}} = \sqrt{\frac{2 \cdot 14.5 \cdot 1100}{0.3 \cdot 2500}} = 7. \quad (10)$$

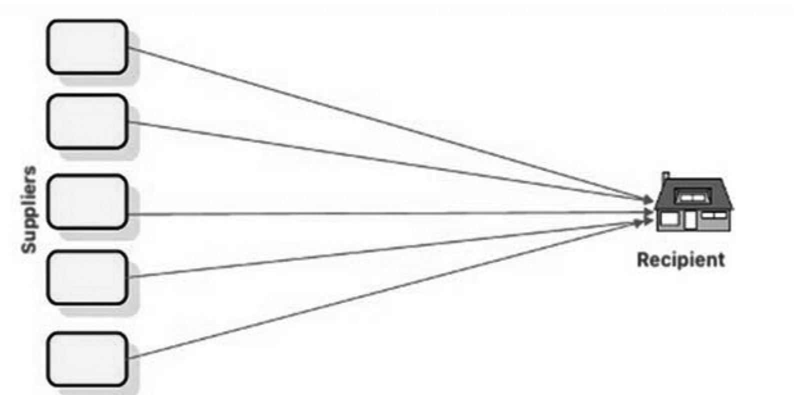
Calculation of the economic volumes of EOQ of the other groups is performed analogously. After calculating the economic volumes of EOQ, it is necessary to calculate the delivery costs for each assortment group. For the group (vegetables), these costs are:

$$f(x) = \frac{d_i}{EOQ_i} \cdot ibc + \frac{EOQ_i}{2} \cdot srw \cdot p_i =$$

$$= \frac{14.5}{7} \cdot 1100 + \frac{7}{2} \cdot 0.3 \cdot 2500 = 4891 \text{ PLN}. \quad (11)$$

Figure 2

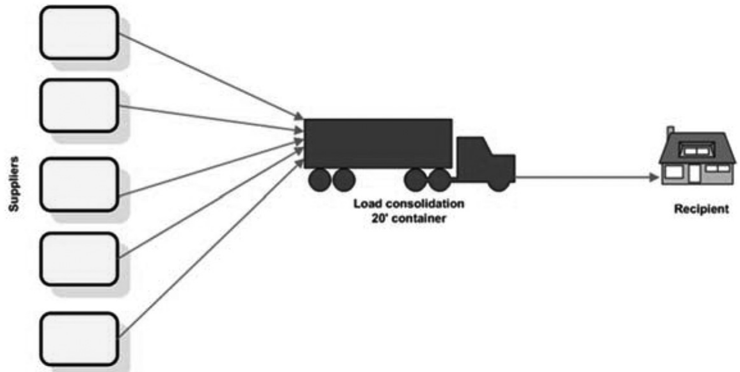
Deliveries from suppliers directly to the recipient (according to the EOQ model)



Source: own study.

Figure 3

Deliveries from suppliers after consolidation directly to the recipient (according to the developed mathematical model)



Source: own study.

Table 1
Summary of test results for analysed cases

No.	Product	d_i [t]	p_i [PLN]	ibc [PLN]	srw	EOQ [t]	es_i [t]	X(number of deliveries)		Inventory costs [PLN]	
								for EOQ	for model	for EOQ	for model
1.	Vegetables (onions, potatos)	14.5	2500	1100	0.3	7	3	10	5	22,513	10,633
2.	Legumes (beans, peas)	7.9	1300	1100	0.3	7	2				
3.	Fruit (apples, pears)	11.0	3500	1100	0.3	5	2				
4.	Citrus fruits (lemons, oranges)	10.5	7000	1100	0.3	3	2				
5.	Cereals (wheat, rye)	15.8	870	1100	0.3	12	3				

Source: own study.

The reader will want to check the costs for the other groups, using the identical formula (11). After adding up the costs for all groups, one gets:

$$\sum f(x) = 22513 \text{ PLN.}$$

Method two. Deliveries from suppliers after consolidation of loads by the logistics operator to the recipient using the developed mathematical model (Figure 3). Insert the data from Table 1 into equation (8) decision variable number of deliveries.

$$x = \sqrt{\frac{1}{2} \cdot \frac{1}{ibc} \cdot srw \cdot \sum_{i=1}^{5} d_i \cdot p_i} =$$

$$= \sqrt{\frac{1}{2} \cdot \frac{1}{1100} \cdot 0.3 \cdot 172266} = 5 \tag{12}$$

$$\text{where} \sum_{i=1}^{5} d_i \cdot p_i = 172266 \text{ PLN.}$$

Then from equation (3), the cost of delivery is calculated:

$$f(x) = ibc \cdot x + \frac{1}{2} \cdot \sum_{i=1}^{5} \frac{d_i \cdot p_i}{x} \cdot srw \rightarrow min$$

$$f(x) = 1100 \cdot 5 + \frac{1}{2} \cdot \frac{172266}{5} \cdot 0.3 =$$

$$= 10633 \text{ PLN.} \tag{13}$$

The final step in the methodology is to determine from equation (9) the economic sizes of each assortment group:

$$es_i = \frac{d_i}{x} = \frac{14.5}{5} = 3. \tag{14}$$

The calculation was made for the assortment group (vegetables). The reader will want to check, in the same way, how much the economic volumes are for the other assortment groups.

Discussion

When analysing the energy transformation of transport, attention should be paid to the method of obtaining electricity. Currently, the main way is by combusting fossil fuels: coal, oil and natural gas. About 80% of energy is obtained from these sources, which results in global warming, the catastrophic effects of which, in the form of hurricanes, melting glaciers, floods and fires, are increasingly experienced. It is therefore necessary to change and replace fossil fuels with renewable alternative energy sources. Obtaining energy from wind, water, the sun, geothermal energy, as well as from biomass and nuclear fuels will have a positive impact on the environment and global warming (Ellabban et al., 2014).

The sun is the greatest natural energy resource on Earth. Although it cannot be used continuously, yet the winds converted from solar energy, that blow along the seashores, can provide a lot of energy. Biomass, which, similarly to winds, draws energy from the sun, gives off energy during combustion and does not cause harmful emissions.

Another unlimited source of energy is hydrogen obtained from water, which can be used to generate electricity in fuel cells. Nuclear energy is a special type of energy because, while not being generated from renewable sources, it is certainly not as harmful as fossil fuels. In addition to renewable energy, selected systems should also be included in the fight against climate change, i.e. the European CO_2 emissions trading system, the carbon tax system for imported goods, and perhaps also the transport system described in the developed model. We should also mention the potential of forests, which will not save us from a climate catastrophe, but will give us more time to reach the zero-emission world (Witkiewicz, 2021).

Humanity needs energy to live, but it should be energy obtained in the manner described above, otherwise it will end its life on Earth in a short time. Undoubtedly, human influence on the climate is the main cause of global warming, as confirmed by research published in Environmental Research Letters. Benjamin Houlton, dean of the College of Agriculture and Life Sciences at Cornell University (USA), summarized the research as follows (quote): "It is essential to recognize the central role of greenhouse gas emissions so that we can quickly mobilize new solutions as we are already witnessing the devastating impact of climate-related disasters on businesses, people and the economy in real time".

Conclusions

The author believes that the program to decarbonize the economy should go in the direction of developing technologies to produce hydrogen (H_2) as an energy carrier, e.g. as fuel in transportation processes. Decarbonization of the transportation sector may be possible by using electric vehicles as a sustainable and efficient alternative to traditional diesel and gasoline vehicles. Therefore, the author believes that research should move toward the zero-carbonization of transportation, replacing fossil fuels for energy extraction with renewable sources (wind, nuclear, biomass, solar, wind). Changes should also apply to the organization of transportation itself (cargo consolidation, "large transports"). Such measures will help reduce CO_2 emissions and lower transportation costs.

Existing research in the field of reducing greenhouse gas emissions from road transport often ignores input data, which is inconsistent with systemic approach. The solutions used in this study integrate both input and output parameters, taking into account economic and environmental aspects, and reflecting the diverse practice of global policy.

The model constitutes a kind of reengineering of the transport process and is so flexible that it can be used in most types of transport, mainly those that generate the highest CO_2 emissions (road transport). As a result of the conducted analyses, the following conclusions were drawn. In the first case, in the Economic Order Quantity (EOQ) model, the costs of inventory (delivery, transport) and the cost of inventory at the recipient's warehouse amounted to PLN 22,513. The total frequency (number of deliveries) from individual suppliers was 10. In the second case, using a proprietary mathematical model, the total inventory costs amounted to PLN 10,633, while the frequency of deliveries after consolidation was 5. The results of both analyses, including economic figures for both methods (EOQ and es_i) are presented in the Table 1. It should be observed that the emission of CO_2 greenhouse gases in the first case amounted to 140,000 grams of CO_2, and in the second – 70,000 grams of CO_2, which is 50% less on the same route.

The developed mathematical model for the realization of the transport of goods in the chain has its limitations, but after adapting to a specific environment, defining the assumptions, limitations and input parameters of the model, it can be implemented to both manufacturing companies and the economy of the TSL industry.

Notes/Przypisy

[1] **Pamięci Mariusza Gorzki.**
[2] Small enterprise, employing less than 50 persons, with annual total assets of less than EUR 10 million.
[3] Local market – the totality of purchase-sale transactions concluded on the territory of a municipality of the Łódź province.
[4] Data obtained from the company.

References/Bibliografia

Dineen, S. (2014). *Multivariate Calculus and Geometry*. Third edition. Springer.
Dziubiński, I., & Świątkowski, T. (Eds.). (1980). *Poradnik matematyczny*. PWN.

Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, *39*, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

European Commission, Secretariat General (2021). *Communication from the Commission to the European Parliament, Council, the European Economic and Social Committee and the Committee of the Regions EMPTY: "Ready for 55": achieving the EU's 2030 climate target on the road to climate neutrality* (availability: 2.02.2022).

European Commission. (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the Economic and Social Committee Economic and Social Committee and the Committee of the Regions. European Green Deal*. Brussels COM (2019), 640.

European Commission. (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Economic and Social Committee and the Committee of the Regions. Strategy for Sustainable and Smart Mobility – European Transport on the Road to the Future*. Brussels (availability: 9.12.2020).

European Commission. (2021). *GHG emissions of all world countries – 2021 Report*. https://edgar.jrc.ec.europa.eu/report_2021

Ghosh, A. (2020). Possibilities and challenges for the inclusion of the electric vehicle (EV) to reduce the carbon footprint in the transport sector: A review. *Energies*, *13*(10), 2602. https://doi.org/10.3390/en13102602

Hammond, G. (2007). Time to give due weight to the 'carbon footprint' issue. *Nature*, *445*(7125), 256. http://dx.doi.org/10.1038/445256b

Huppes, G., & Ishikawa, M. (2008). Eco-efficiency and its xsTerminology. *Journal of Industrial Ecology*, *9*(4). https://doi.org/10.1162/108819805775247891

Jursova, S., Burchart-Korol, D., & Pustejovska, P. (2019). Carbon footprint and water footprint of electric vehicles and batteries charging in view of various sources of power supply in the Czech Republic. *Environments*, *6*(3), 38. https://doi.org/10.3390/environments6030038

Koide, R., Lettenmeier, M., Akenji, L., Toivio, V., Aryanie, A., Khodke, A., Watabe, A., & Kojima, S. (2021). Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research. *Sustainability Science*, *16*, 2087–2099. https://doi.org/10.1007/s11625-021-01018-6

Secretariat of the Convention on Biological Diversity. (2020). *Global Biodiversity Outlook 5*.

Simons, P. J., & Cheung, W. M. (2016). Development of a quantitative analysis system for greener and economically sustainable wind farms. *Journal of Cleaner Production*, *133*, 886–898. https://doi.org/10.1016/j.jclepro.2016.06.030

Ślaski, P. (2021). *Zapasy materiałowe w systemie bezpieczeństwa narodowego*. Wojskowa Akademia Techniczna.

Smyk, S. (2021). Koszty logistyki jako determinanta współczesnych procesów logistycznych. *Gospodarka Materiałowa i Logistyka*, (4).

Szaruga, E., & Załoga, E. (2022a). Environmental management from the point of view of the energy intensity of road freight transport and shocks. *International Journal of Environmental Research and Public Health*, *19*, 14417. https://doi.org/10.3390/ijerph192114417

Szaruga, E., & Załoga, E. (2022b). Qualitative-Quantitative warning modelling of energy consumption processes in inland waterway freight transport on river sections for environmental management. *Energies*, *15*, 4660. https://doi.org/10.3390/en15134660

Theißen, S., Spinler, S., & Huchzermeier, A. (2014). Reducing the carbon footprint within fast-moving consumer goods supply chains through collaboration. The Manufacturers' Perspective. *Supply Chain Management*, *50*(4), 44–61.

Thompson R. G., Nassir, N., Frauenfelder, P. (2020). Shared freight networks in metropolitan areas. *Transportation Research Procedia, 46*, 204–211.

UN. (1997). *Kyoto Protocol to the United Nations Framework Convention on Climate Change conference of the Parties Third Session Kyoto*. Agenda item 5 FCCC/CP/1997/L.7/Add.110

UN. (2015, 12 December). *Adoption of the Paris Agreement*. Fccc/Cp/2015/L.9/Rev.1.

UNEP. (2020a). *Emissions Gap Report 2020. United Nations Environment Programme*. https://www.unep.org/emissions-gap-report-2020

UNEP. (2020b). *Global Environment Outlook Geo-6 Healthy Planet. Healthy People*. Cambridge University Press. https://doi.org/10.1017/9781108627146

Werdmann, T., & Minx, J. A. (2007). *Definition of 'Carbon Footprint'*. ISA UK Research Report 07-01.

Witkiewicz, Z. (2021). Co po węglu? *Głos Akademicki*, (9–10), 34.

Zhang, R., & Zhang, J. (2021). Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. *Transport Policy*, *110*, 28–36.

Zhang, R., Fujimori, S. (2020). The role of transport electrification in global climate change mitigation scenarios. *Environmental Research Letters*, *15*(3). https://doi.org/10.1088/1748-9326/ab6658

Dr Paweł Ślaski

Researcher at the Institute of Logistics at the Military University of Technology in Warsaw. He graduated from the Military University of Technology in 1990 and received his PhD in Economics and Management Sciences in 2007. He conducts research in the areas of design and optimization of logistics processes in supply chains and material inventory management in logistics systems.

Dr Paweł Ślaski

Pracownik naukowy w Instytucie Logistyki Wojskowej Akademii Technicznej w Warszawie. W 1990 r. ukończył studia w Wojskowej Akademii Technicznej, a w 2007 r. uzyskał stopień doktora nauk ekonomicznych i nauk o zarządzaniu. Prowadzi badania w obszarach projektowania i optymalizacji procesów logistycznych w łańcuchach dostaw oraz zarządzania zapasami materiałowymi w systemach logistycznych.