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ORIGINAL PAPER

SUSTAINABLE SUPPLY CHAINS MODELING

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ABSTRACT. Background: Although existing studies have highlighted the importance of modeling sustainable supply chains, there is a scarcity of research that integrates environmental, social, and economic dimensions simultaneously. Accordingly, this paper aims to explore the possibilities of creating and modeling sustainable supply chains in the trefoil of economic, environmental, and social sustainability.

Methods: For creating and modeling optimal sustainable supply chains, we used the mathematical method of dynamic programming. The method of dynamic programming was chosen for the reason that dynamic programming represents a set of special mathematical methods that serve to optimize multi-stage or multi-phase processes.

Results: Minimum costs of the supply chain in the given example are achieved when the problem is solved from an economic perspective or from the perspective of total costs. Solving the problem from an ecological or social perspective increases the costs of the supply chain compared to optimal solutions, by 16.05% if the problem is solved from an ecological perspective and by 14.31% if the problem is solved from a social perspective.

Conclusions: Contemporary sustainable **s**upply chains are forced to include in their logistics network only those participants who can satisfy the principles of integral sustainability, i.e. respecting the economic, ecological and social dimensions.

Key words: supply chains, sustainable development, economic sustainability, ecological sustainability, social sustainability, dynamic programming

INTRODUCTION

"Slowbalisation" [Kandil, Battaïa and Hammami 2020], the COVID-19 crisis [Pupavac, Maršanić and Krpan 2021] and finally the war in Ukraine and the inflation associated with it put supply chain management at the forefront of scientists and logisticians around the world again. This management should be based on the principles of sustainability. Sustainability for the 21st century integrates environmental, social and economic dimensions [Govindan, Jafarian and Nourbakhsh 2015]. Global supply chains as open, dispersed, complex, dynamic, and stochastic systems [Zelenika and Pupavac 2008] are in a state of constant transformation and less and less security. New approaches to supply chain modelling put more focus on security and resilience. Managers are increasingly concerned that supply chains should be robust, not just efficient. The costs of such approach would fall on taxpayers, companies, and consumers.

In order to carry out this transformation in an efficient way, it seems appropriate to investigate the possibilities of creating and modelling sustainable supply chains in the framework of economic, ecological, and social sustainability. The scientific contribution of this work comes from the fact that it simultaneously optimizes the supply chain from different aspects of strong sustainability. According to the defined problem and goal of the investigation, a scientific question was set: Does ignoring any dimension of sustainability in the optimization of supply chains can result in unfavourable solutions, i.e., higher costs in the execution of supply chain activities? In order to achieve the aim and purpose of the research and to find answers to the scientific question, numerous scientific methods

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were applied, among which the analysis and synthesis method, the comparative method and the dynamic programming method stand out.

THEORETHICAL FRAMEWORK AND RESEARCH PROBLEM

Supply chains connect producers, processors, and suppliers, through traders and intermediaries (freight forwarder, agents, distributors, and carriers) with customers. Inside the supply chain, constant flows of information, products, and money take place. A typical supply chain is a network [Joshi 2022]. By analyzing individual stages in the execution of the business venture of supply chains and their participants, it is possible to determine some of the more important features of supply chains, such as: 1) every participant in the supply chain, apart from their own, should be guided by the common interest of the supply chain and, by rationalizing their operations, contribute to the rationalization of the operations of the entire supply chain; 2) supply chains can have different numbers of participants, different sizes and economic strengths; 3) participants within the supply chain can be permanent, occasional, or temporary; 4) supply chain participants can be local, national, regional, and/or global, 5) a supply chain is only as strong as its weakest link (participant); 6) the work of participants within the logistics chain must be synchronized and coordinated with market requirements.

An efficiently created supply chain is one that delivers the required product (service) to the right place, at the right time, in the right quantity, and at the right price. The profitability of the supply chain is determined from the function of the total profit that is shared between all active participants in the supply chain. Creating a supply chain starts with choosing the appropriate strategy: global, pan-European, regional, national, local. After that, it is necessary to make the optimal choice of supply chain participants and work on their competitive performance. Disruptions in supply chains caused by the COVID-19 crisis and the war in Ukraine have forced global supply chain leaders to change the paradigm of creating supply chains. Namely, an increasing number of managers of global supply chains decide on at least two suppliers of raw materials, on increasing stocks within the supply chain, regionalization of supply chains, and nearshoring. Nearshoring is a tactic that allows companies to move their operations to the closest country [Diaz 2021]. Therefore, the key challenges for supply chain managers are to create an effective and efficient supply chain network that will be robust enough to recover from any disruption and that also needs to have enough vigilance to provide the same sustainability in a disruption state. Adapting to these unanticipated disturbances, supply chain systems could abandon their sustainability goals.

Many scientists have investigated the modeling of sustainable supply chains in recent works [Mota 2018; Panigrahi, Bahinipati and Jain, 2019, Ghadimi, Wang and Lim, 2019, Zimon, Tyan and Sroufe 2019, Hoffa-Dabrowska and Grzybowska 2021]. Analysis of the literature demonstrates that the effectiveness of the supply chain is assessed not only in terms of business, but also in terms of its effects on the environment and the social system [Kot 2018]. According to Pagell and Shevcehenko [2014], a sustainable supply chain had “no harm on social or environmental systems while maintaining economic viability.” The supply chain is entirely sustainable, it will not have a negative impact on social or ecological systems, and it will generate long-term profits [Niño-Amézquita, Legotin and Barbakov 2017, Yang and Černevičiūtė, 2017, Abdel-Basset et al. 2020]. Mari, Lee and Memon [2014] point out that "increasing regulations for carbon and waste management are forcing firms to consider their supply chains from ecological and social objectives". Sustainable supply chains should be based on sustainable practices such as ethical sourcing, green purchasing, environmental purchasing, and logistics social responsibility [Agrawal et al. 2015, Ghadimi et al. 2017, Sarkis and Zhu, 2017].

DATA AND METHODOLOGY

Let’s say that for a product to be manufactured and delivered at the demand location within the supply chain, certain production and logistic activities need to be done and which can be classified into five phases (I-V): x_1 (procurement of raw materials), x_2 (production), x_3 (warehousing and land transport), x_4, (maritime transport), x_5 (selling), and for which within the global logistic system it is possible to engage 23 different participants: f_1, f_2, f_3...,f_{23}. A logistic operator is familiar with the engagement schedule of participants within the supply chain in carrying out single phases of the logistic undertaking (cf. Table 1).

Table 1. Production phases within the supply chain and potential supply chain participants

Phases of logistic process	Potential supply chain participants	Costs of each phase within the supply chain (in 000 €)			
1	2	3			
		Economic	Environmental	Social	Total
I. Delivery of raw materials Incoterms EXW - Ex Works	f_1– Russia f_2 – Finland f_3 – Egypt	**10** 12 14	(35×0.03)=1.05 (25×0.03)=**0.75** (40×0.03)=1.20	(5)=2.5 (1)=**0** (10)=7	13.55 **12.75** 22.20
II. Production	f_4 – Czech f_5 – Romania f_6 – Poland f_7 – Slovakia	32 **22** 26 24	(32×0.03)=0.96 (40×0.03)=1.2 (25×0.03)=**0.75** (30×0.03)=0.9	(1)=**0** (10)=11 (5)=6.5 (5)=6	32.96 34.20 33.25 **30.90**
III. Warehousing and land carriage (railway operator, road transport operator)	f_8 – national railway operator f_9 – ABC Logistics	**6** 7	(0.7×0.03)=**0.021** (4.5×0.03)=0.135	(1)=**0** (5)=1.75	**6.021** 8.885
IV. Sea shipping (ship operators)	f_{10} - Global Alliance f_{11} - Grand Alliance f_{12} - Maersk-Sealand	8 **6** 9	(31.2×0.03)=0.936 (30.0×0.03)=**0.9** (33.0×0.03)=0.99	(5)=2 (5)=**1.5** (5)=2.25	10.936 **8.40** 12.24
V. Distribution (distributors in North America)	f_{13} – East Coast f_{14} – West Coast f_{15} – Canada	10 **9** 12	(2.8×0.03)=**0.084** (3.1×0.03)=0.093 (3.5×0.03)=0.105	(5)=2.5 (5)=**2.25** (5)=3.0	12.584 **11.343** 15.105
I., II.	f_{16} – Austria	30	(65×0.03)=1.95	(5)=7.5	39.45
II., III.	f_{17} – Switzerland	36	(40×0.03)=1,2	(1)=0	37.20
I., II., III.	f_{18} – GB	42	(75×0.03)=2.25	(5)=10.5	54.75
II., III., IV.	f_{19} – Croatia	40	(60×0.03)=1.8	(5)=10	51.80
III., IV., V.	f_{20} – Germany	28	(28×0.03)=0.84	(1)=0	28.84
III., IV.	f_{21} – Italy	22	(30×0.03)=0.9	(5)=5.5	28.40
IV., V	f_{22} – USA f_{23} – USA	20 18	(25×0.03)=0.75 (22×0.03)=0.66	(5)=5 (5)=4.5	25.75 **23.16**

Source: Own work

The assumption is that the supply chain produces and delivers 100 tons of goods per month. Economic, environmental, and social costs are arbitrarily estimated. Economic costs are the cost price of each stage within the supply chain. Environmental costs refer to pollution of rivers, air, environment, waste, and are expressed in monetary units in such a way that their cost is estimated at 30 EUR/t CO_2. The ecological costs of transport were estimated so that the CO_2 emission of truck transport is 150 g-CO_2/tkm, sea transport 39 g-CO_2/tkm and rail transport 20 g-CO_2/tkm [Niwa, 2009]. Social costs are estimated as a percentage of economic costs depending on whether there is a high (10), medium (5) or low (1) risk of unacceptable business behaviour within any supply chain participant. Unacceptable business behaviour means poor working conditions for employees, the use of child labour, or the practice of forced labour within the supply chain. If the public becomes aware of the practice of unacceptable behaviour within any participant in the supply chain, it can have adverse effects throughout the supply chain. Thus, the social costs were estimated for the existence of a high risk of unacceptable behaviour at 50% of the economic costs, the existence of a medium risk at 25%, and the existence of a low risk without costs for the respective supply chain participant.

Accordingly, in the continuation of this scientific discussion, using the mathematical method of dynamic programming, the supply chain was optimized from an economic, ecological, and social point of view, and the supply chain was optimized taking into account all three points of view, that is, from the point of view of total costs. The method of dynamic programming was chosen for the reason that dynamic programming represents a set of special mathematical methods that serve to optimize multi-stage or multi-phase processes. A large number of different problems from supply chain management can be presented in the form of multi-stage processes, which can be solved by applying the dynamic programming method.

MATHEMATICAL MODEL

It is possible to present the described production process within the supply chain by means of mathematical relations in the following way:

$x_i f_j = 1, i = 1, 2, ..., n; \qquad j = 1, 2, ..., m$

if in the production phase within the global logistic chain x_i services of a potential logistic chain participant f_j are used.

$$\left(\sum_{i=1}^{k-(r-1)} x_{i+r-1}\right) f_j = k-(r-1), k\epsilon[1,n], r\epsilon[1,n]\ k>r, j=1,2,\dots,m \qquad (1)$$

if in the k-(r-1) of the production phases within the global logistic chain and specifically from r, including the production phases r and k, services of a potential logistic participant f_j are used.

$x_i f_j = 0, \qquad i = 1, 2, ..., n; \qquad j = 1, 2, ..., m$

if for the production phase x_i services of a potential logistic participant f_j are not used.

Except for the aforementioned, the following requirements arising from the very nature of the problem should be taken into account.

$$\sum_{i=1}^{n} (x_i = n)$$

This means that the selected logistic production process within the global logistic chain has to be complete, i.e., it has to comprise all n phases.

$f_j = 1, j = 1, 2, ..., m,$

if in the selected logistic process the services of a potential global logistic chain participant f_j are used, and

$f_j = 0, j = 1, 2, ..., m,$

if in the selected logistic process the services of a potential global logistic chain participant f_j are not used.

Based on the data in Table 1 it is evident that some of the potential global logistic chain stakeholders could be engaged in several production phases within the logistic chain. Such conditions can be defined with the pair (x_i, f_j), i = 1,2, ..., n; j = 1,2, ..., m, which means that with this pair it can be defined whether during a single phase of the execution of the logistic process a potential participant f_j will be engaged or if his engagement is not possible in the given phase. If the potential participants in the logistic chain f_j, j = 1,2, ..., m are allocated to every phase of the execution of the logistic process x_i, i = 1,2, ..., n, all possible conditions of the services production within the logistic chain will be obtained that can be marked with L.

Now, the optimal selection of participants can be set in the following way: from all *m* possible (potential) supply chain participants, those meeting all requested requirements are to be selected so that the criterion function

$$z^* = \sum_{(x_i, f_j) \in L} c(x_i, f_j) \tag{2}$$

with restrictions:

$$x_i f_j \leq 1, i = 1, 2, ..., n; j = 1, 2. ..., m,$$

$$\left(\sum_{i=1}^{k-(r-1)} x_{i+r-1} \right) f_j \leq k-(r-1), k \epsilon [1,n], k > r, j = 1,2, \ldots, m \tag{3}$$

$$\sum_{i=1}^{n} x_i = n$$

$$f_j = \{^0_1 \; j = 1,2, ..., m.$$

assumes maximum or minimum value. For the criterion function, the following can be taken: production costs within the logistic chain, time needed for executing production within the logistic chain, engagement of capacities needed for executing production within the logistic chain, engagement of people needed for production within the logistic chain (...).

Taking into account specific features of logistic processes and in order to bring the goods to the delivery point by appropriate transport means without unnecessary retentions and execution of additional logistic activities, it seems appropriate to describe the logistic process with the oriented network. Such networks are quite suitable for modelling practical logistic problems where solving the problem comes down to defining an extreme (shortest or longest) way.

In the oriented network G = (N, L), whose set of nodes N = $\{1,2,\ldots,n\}$, and branches (i, j) ∈ L, where is always $i < j$, based on the optimality principle, to define the shortest way between two nodes, for example 1 and n, it is possible to write the following recursive equation.

$$f(j) = \min_i \{ f(i) + c_{ij} \} \; j = 2,3, ..., n \tag{4}$$

whereby

$$f(1) = 0.$$

RESARCH RESULT AND DISCUSION

Based on the data from Table 1, it is evident that in order to design an optimal network from an economic, ecological, social, or total cost aspect, it is not necessary to consider all potential participants, but only some of them. Thus, for example, in the second phase of the supply chain, out of four potential producers, namely f4 from Greece, f5 from Romania, f6 from Poland, and f7 from Slovakia with different production costs, the producers with the lowest costs will be selected. Thus, producer f2 will be selected from the economic point of view, producer f3 from the environmental point of view, f1 from the social point of view, and producer f4 will be selected from the point of view of total costs (economic, ecological, and social). With such an approach, it is possible to eliminate non-competitive participants in the supply chain, depending on the point of view from which the optimization is approached: economic, ecological, social or from the point of view of total costs. Once the non-competitive potential participants of the supply chain are eliminated, it is possible to approach the design of the appropriate supply chain network and to solve the problem thus posed.

The following shows the supply chain network from an economic point of view (cf. figure 1) and the supply chain network from the point of view of environmental costs (cf. figure 2).

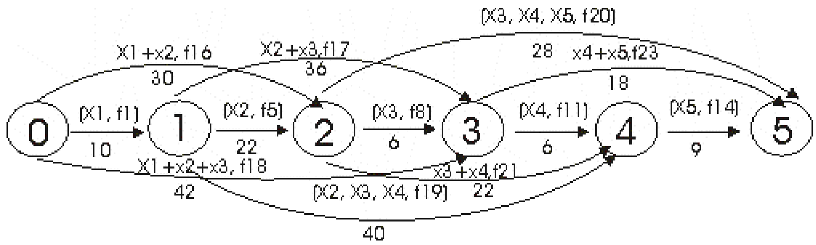

Fig. 1. Logistic network of potential qualified global supply chain participants from economic aspects
Source: Own work

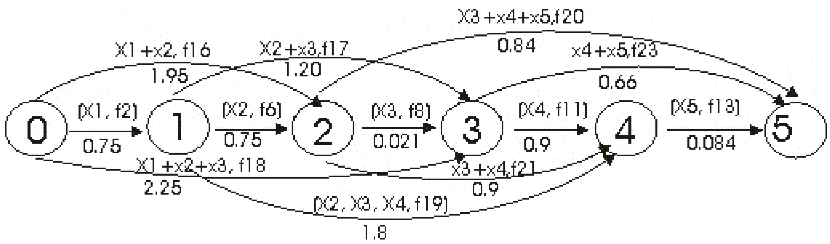

Fig. 2. Logistic network of potential qualified global supply chain participants from ecological aspects

Source: Own work

Above every branch of the logistic network (cf. *Figure 1* and *Figure 2*) a logistic chain phase is entered, as well as potential participants for carrying out a certain activity within the global logistic chain, and under the branches of the logistic network costs for carrying out a certain phase within the logistic chain are entered.

In the following, the problem of the shortest path in the network is solved from an economic point of view by applying the dynamic programming method. Other problems were solved according to the same principle, and the description of their solution is omitted. By applying the recursive expression, the following is obtained.

f(0) = 0 i f(1) = 10, and then

$$f(2) = \min \begin{cases} f(0) + c(x1 + x2, f16 = 0 + 30 \\ f(1) + c(x2, f5 = 10 + 22 \end{cases} \} = 30$$

$$f(3) = \min \begin{cases} f(0) + c(x1 + x2 + x3, f16 = 0 + 42 \\ f(1) + c(x2 + x3, f17 = 10 + 36 \\ f(2) + c(x3, f8) = 30 + 6 \end{cases} \} = 36$$

$$f(4) = \min \begin{cases} f(0) + \infty = 0 + \infty = \infty \\ f(1) + c(x2 + x3 + x4, f19) = 10 + 40 \\ f(2) + c(x3 + x4, f21) = 30 + 22 \\ f(3) + c(x4, f11) = 36 + 6 = 42 \end{cases} \} = 42$$

and finally

$$f(5) = \min \begin{cases} f(0) + \infty = 0 + \infty = \infty \\ f(1) + \infty = 10 + \infty = \infty \\ f(2) + c(x3 + x4 + x5, f20 = 30 + 28\} = 51 \\ f(3) + c(x4 + x5, f13) = 36 + 18 \\ f(4) + c(x5, f14) = 42 + 9 \end{cases}$$

which means that the length of the shortest way p*, i.e. the minimum value of the function of the target z* = d(p*) = 51, and this way is p* = (**0,2,3,4,5**). It means that in the global supply chain in the first and second execution phase the participant f_{16} will be involved, in the third phase the participant f_8, and in the fourth phase within the global supply chain the participant f_{11} will be involved and in the last phase the participant f_{14}. These active participants form a supply chain that will ensure the execution of the business venture at minimal economic costs in the amount of €51,000. The optimal supply chain formed from an economic point of view will have its associated ecological (€2,964) and social costs (€11,250), and the total costs of the supply chain formed from an economic point of view will amount to €65,214. An overview of other optimal solutions is given in Table 2.

Table 2. Overview of optimal solutions

Optimization by aspects	Optimal way on network	Supply chain participants	Economic costs (000 €)	Environmental costs (000 €)	Social costs (000 €)	Min total costs (000 €)
Economic	0,2,3,4,5	f16,f8,f11,f14	51	2.964	11.25	65.214
Environmental	0,1,2,3,5	f2,f6,f8,f23	62	2.181	11.5	75.681
Social	0,1,2,5	f2,f4,f20	72	2.55	0	74.55
Total costs	0,2,3,4,5	f16,f8,f11,f14	51	2.964	11.25	65.214

Source: Own work

Based on the data in Table 2, it is clear that the minimum costs of the supply chain in this example are achieved when the problem is solved from an economic perspective or from the perspective of total costs. The reasons for this should be the high economic costs within the supply chain, which highlights the importance of economic sustainability. Solving the mentioned problem from an ecological or social perspective increases the costs of the supply chain compared to optimal solutions by 16.05% if the problem is solved from an ecological perspective and by 14.31% if the problem is solved from a social perspective. It is also evident that it is possible to form a supply chain without social costs. The importance of optimizing supply chains is also confirmed by the data in Table 3, which contains an overview of the most unfavorable solutions. From experience, the most unfavorable solutions were obtained by solving the functions at their maximum.

Table 3. Overview of the most unfavorable solutions from experience

Solution by aspects	Way on network	Supply chain participants	Economic costs (000 €)	Environmental costs (000 €)	Social costs (000 €)	Max total costs (000 €)
Economic	0,1,2,4,5	f3,f,4,f21,f15	80	3.165	15,5	98.665
Environmental	0,2,3,4,5	F16,f9,f12,f15	58	3.645	14.5	76.145
Social	0,1,2,4,5	f3,f5,f21,f15	70	3.405	26.5	99.905
Total costs	0,1,2,4,5	f3,f,5,f21,f15	70	3.405	26.5	99.905

Source: Own work

Based on the data from Table 3, it is clear that the most unfavorable solution obtained when the function is solved at its maximum is 51.97% higher than the optimal solution from the perspective of total costs. The optimal supply chain optimized only from the economic perspective is more favorable by 51.29%, from the ecological perspective by 0.06%, and from the social point of view by 34.01%. Also, from Table 3, it is clear that all optimal solutions obtained are more favorable according to any criterion of sustainability than those solutions that ignore sustainability from any perspective, thus proving the set hypothesis.

CONCLUSION

Supply chains for the 21st century are forced to include in their logistics network only those participants who can satisfy the principles of integral sustainability, i.e. respecting the economic, ecological and social dimensions. Such an approach emphasizes that supply chains do not have only one goal, the creation of economic value, but that it is necessary that they emphasize the creation of ecological and social value as their priority goals. This means that the supply chain network should be cleaned as much as possible of those participants who cannot meet the requirements of integral sustainability. Participants in the supply chain who are unable to meet these requirements can seriously impair its competitiveness or, due to non-compliance with environmental and/or social requirements, contaminate the entire supply chain network. In order to ensure the competitiveness of the supply chain and avoid possible scandals, it is necessary to create and optimize a sustainable supply chain. The results obtained point to the conclusion that all optimal solutions obtained according to any criterion of sustainability are more favorable than those solutions that ignore sustainability from any perspective. The implications of this approach are to create robust and efficient supply chains. The main shortcoming of this work stems from the fact that the creation and modeling of a sustainable supply chain were dominated by an economic perspective. In future research, all three components of sustainability should be treated equally.

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