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The Evolution of Linear Programming Utilization in Supply Chain Management: Pre-pandemic and Pandemic Period Comparison

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Abstract

The COVID-19 pandemic has brought new challenges in the 21st century, which must be faced not only by companies but also by their entire supply chains. This research study aimed to examine the implications of this pandemic through the changes in the application of linear programming to optimization in supply chain management. This study was carried out on two sample files consisting of Slovak manufacturing enterprises during the pre-pandemic and pandemic period. There were two main criteria of selection. Firstly it was the orientation of business activities of the company and secondly, it was the size since only medium-sized and large-sized enterprises were examined. The representativeness of both sample files was confirmed by the application of Pearson´s chi-squared test (χ2 - test) due to the above criteria. The findings of this research imply both academia and business practice. It was discovered that the utilization of linear programming methods in supply chain management increased during the pandemic. The decrease in the number of customers was experienced by the higher percentage of companies that had not utilized linear programming before the outbreak of the pandemic. Resource allocation was the application with the largest representation during both surveys, even though there was a slight decrease in 2021. An increase in the number of companies that applied these methods was recorded in waste management, distribution plans, and financial management.

Keywords: *COVID-19, Linear programming, Supply chain management, Optimization*

1. Introduction

When the new coronavirus COVID-19 appeared in 2019 and began to spread around the world, few experts expected its consequences to be so long-lasting and so severe. In modern history, it is difficult to find examples of similar disturbances or crises that could serve as a model for predicting future trends. Supply chain managers, therefore, have to rely only on theoretical models and unreliable data.

Examples from some recent disasters and subsequent research studies could also serve as prediction models. One of the main negative events of the 21st century before the outbreak of COVID-19 was the catastrophe of the Fukushima Daiichi nuclear power plant. In addition to renewal costs, this has had other consequences for the local economy and international supply chains. In particular, consumers initially reacted negatively to agricultural products from Fukushima Prefecture following the Fukushima incident, which resulted in economic loss due

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to reputation damage [20][2]. However, after catastrophic supply chain interruptions, positive effects may also occur over time, such as the reform of the electricity market in Japan after Fukushima [13]. The lesson from these case studies is that if the supply chain is built as resilient as possible with a special focus on optimization and continuous improvement it can survive even major disruptions such as global pandemics and economic crises [25][31].

These examples have a lot in common, especially the need to optimize supply chains to provide individual companies with the necessary tools for process sustainability. In addition, rapid supply chain response has been identified in the past as one of the key components of their survival. However, what is still lacking in the current body of knowledge provided in the literature is an evaluation of how the various supply chain optimization methods are used in response to the disturbances caused by this crisis. This study seeks to provide answers to this question by examining the effects of the COVID-19 pandemic on the scope and ways of using linear programming in supply chain management. In this paper, we also deal with the consequences of a pandemic on chains, depending on the scope of the application of linear programming.

2. Related works

To be able to adapt to development trends and dynamic changes, it is important to focus on production, quality, economic efficiency, achieving and increasing technical and quality requirements, which are constantly changing in a competitive environment of modern supply chains [10]. The transformation of inputs into outputs must take place as efficiently as possible which requires the cooperation of all nodes of the supply chain. In terms of individual company goals, this means that in the production process it is necessary to achieve maximum profit with limited resources of raw materials and energy, minimize production costs, and shorten the average production time while respecting the limiting conditions [17], [15]. Other authors [24] also emphasize the need to develop and increase the efficiency of the supply chain processes. One way to achieve this is to apply optimization methods throughout the supply chain. According to Paksoy et al. [21] optimization should be a search for opportunities to achieve the best results in given conditions. Other authors [34] present optimization as such, harmonization of system resources with resource requirements, so that the monitored criterion acquires an extreme value (maximum or minimum). This means that after identifying processes, the managers should determine the values of performance indicators based on the chosen strategic goals of not just individual companies but the whole supply chain. Optimization of supply chains is therefore a more complex and continuous task [7][11][27]. Various methods currently exist and are utilized for optimization. One of the oldest of them is linear programming methods.

The field of linear programming is one of the most widespread and most elaborate areas of mathematical programming which focuses on finding optimal solutions to problems with constraints. The theory of linear programming has been solved for a long time and for that reason it is also elaborated in detail. However, its practical application is more complicated. Great progress has been made in the area of solving linear systems in the context of optimization problems [23]. However, a gap still exists in the application of these methods in supply chain management. In the modern literature, there are few examples of linking the application of linear programming and optimization of supply chain activities or processes to cope with adverse disruptions from the external environment, such as the pandemic crisis [22][28][32]. Modern supply chains are very complex, and recent lean practices have resulted in these networks becoming more vulnerable. Various methods have been created to make supply chains more resilient and consequently more adaptable to changing environments [5][8][15]. What remains to be explored are the effects of the 21st century pandemic on supply chain operations.

Currently, the impacts of the COVID-19 pandemic on global supply chains are still being evaluated. Some authors [19] discovered that the Chinese suppliers proved to be highly resilient in terms of speed and level of recovery. As such, they managed to prevent the significant decrease in supply chain performance during the crisis [1][5]. Such examples provide a source of optimism for the innovation of supply chain resilience worldwide. Linton et al. [18] also emphasized the need to constantly optimize supply chains to build their resilience to avoid the COVID-19 like disruptions in the future. This research study aims to provide a closer look at whether the linear programming application in supply chain management changed during the pandemic. The comparison of business reality before and during the pandemic enables an understanding of managers' attitudes towards supply chain optimization and how the pandemic possibly affected this outlook.

3. Methods

The main aim of this research study was to examine the evolution of the utilization of linear programming in supply chain management and to compare the situation before and during a pandemic. To achieve this aim data for the research was provided by Slovak manufacturing enterprises via two independent surveys. This method was selected to gain a large amount of data from businesses. Since recent data was necessary to enable comparisons it was not possible to obtain data from any databases. Furthermore, the concept of this research required very specific data that no institution provides. The first survey was conducted in 2014 and the second survey took place in 2021. The same questionnaire was used to collect the data in both periods. It consisted of 16 questions divided into 3 categories. The first set of questions was focused on exploring various aspects of applications of optimizing methods. The second part of the questionnaire involved questions designed to gain data about linear programming utilization. This part of the questionnaire was only completed by those companies which at the time of research used these methods. The last part of the questionnaire focused on the collection of data on the characteristics of enterprises. Companies were asked to provide information about their size (the number of their employees), supply chain characteristics, and, in the second inquiry, the impact of the pandemic on their supply chain.

Research sample files were created as a representative sample of the corresponding base file. Both sample files consisted of Slovak enterprises classified by the national SK NACE classification as manufacturing companies. Furthermore, the criterion of enterprise size was also considered. In terms of this criterion, the focus of this research was only on medium and large companies, since the general assumption was that they use methods of linear programming to a greater extent than small companies. The decisive criterion was set according to the European Standard No. 2003/361/EC. The representativeness of both sample files was examined by the structure of base files provided by the Slovak Statistical Office at the time of the research.

The research was carried out on an initial file consisting of 1450 Slovak manufacturing companies. The individual companies were selected randomly and chosen respondents were addressed by email. In 2014 the questionnaire was fulfilled by 274 Slovak companies which represent an 18.9 % return. In 2021 the sample file consisted of 312 manufacturing companies. The structure of both sample files and their corresponding base files are provided in [Table 1].

Table 1. Structure of sample files and base files

2014				
Number of employees	Base file		Sample file	
	Number of companies	Percentage	Number of companies	Percentage
51 – 250	1641	72.35%	199	72.63%
over 251	627	27.65%	75	27.37%
Total	2268	100.00%	274	100.00%
2021				
Number of employees	Base file		Sample file	
	Number of companies	Percentage	Number of companies	Percentage
51 - 250	1781	72.40%	226	72.44%
over 251	679	27.60%	86	27.56%
Total	2460	100.00%	312	100.00%

Using the statistical testing method, the level of representation of both sample files of manufacturing companies was confirmed by the application of Pearson´s chi-squared test ($\chi 2$ - test), which is also known as the ‘goodness-of-fit’ test. This test was selected because other researchers had previously successfully used it for this very purpose [33]. It was performed at a significance level of 95%. According to the results of performed tests, both sample files are representative samples of the corresponding base file. To further examine the impact of the pandemic on the utilization of linear programming in supply chain management in Slovak companies and to achieve statistically valuable results, five hypotheses were formulated:

H1: The utilization of linear programming methods in supply chain management increased during the pandemic.

H2: The majority of manufacturing companies that had utilized the methods of linear programming before the pandemic experienced no decrease in revenues during the pandemic.

H3: The majority of manufacturing companies that had utilized the methods of linear programming before the pandemic experienced no decrease in the number of suppliers during the pandemic.

H4: The majority of manufacturing companies that had utilized the methods of linear programming before the pandemic experienced no decrease in the number of customers during the pandemic.

H5: The utilization of linear programming for resource allocation in the supply chain increased during the pandemic.

Currently, there are very few research studies that can provide relevant information on how the pandemic impacted the supply chain management of manufacturing companies. Therefore, the formulation of hypotheses was mostly based on research studies in the manufacturing industry from before the pandemic. According to various authors, the utilization of linear programming has a positive effect on increasing performance and resilience [8][19]. Therefore the first hypothesis assumes that linear programming utilization in supply chain management increased during the pandemic which is the main topic of this research study and as such an innovative issue that has not yet been tested. Furthermore, the relationship between linear programming utilization and economic benefits was examined in depth before the pandemic and its existence was confirmed by the findings of many research studies [9][12][16][29]. In this research, we go beyond this confirmed relationship and assume that this relationship not only exists but can also help companies reduce the impact of the pandemic. It is similar to the relationship between the application of linear programming and the development of a transparent management system for relationship management in the supply chain [33]. The two hypotheses were therefore aimed at examining the assumption of the impact of linear programming on changes in the number of customers and the number of suppliers. Before the pandemic, several authors explored the possibilities of applying linear programming to optimize processes and activities [3][4][10][30]. One of the demonstrably most important applications is resource allocation. Given the relationship of this application with supply chain management, hypothesis H5 was formulated.

These hypotheses were verified using the program SPSS Statistics. A binomial test was used to test hypotheses H1, H3, and H4. Pearson correlation test was used to test hypothesis H2 and multivariate regression analysis was used to test H5. These tests were selected based on their widespread use in societies worldwide enabling a better understanding of results not just by other researchers, but also by managers in practice who may find inspiration in this research for optimization of their supply chain. The binomial test enables the calculation of the expected increase of linear programming utilization using a statistically significant approach. Pearson correlation test enables to examine the relationship between two observed variables and regression analysis verifies the importance of one specific linear programming application and compares it with other supposedly less significant applications.

4. Results and discussion

This research focused on analyzing the effects of the pandemic on the supply chains of the manufacturing production sector of the economy. To achieve that, the development of the utilization of linear programming in supply chain management was examined which enabled the comparison of the situation before and during a pandemic. A slight increase in the number of manufacturing companies operating in the Slovak Republic can be observed in 2021 in comparison to their number in 2014. However, the internal structure of their size remained almost the same. An increase in linear programming utilization was reported, however, the rise was only slight. According to the data provided in Table 2 almost 43% of all manufacturing companies utilized linear programming in their supply chain management in 2014. In 2021 this number increased by 3.13%. The rise was slightly higher in the segment of large companies (by 4.33%). Hypothesis H1 examined the assumption that the utilization of linear programming methods in supply chain management increased during the pandemic. Both the data provided in [Table 2] and the results of Binomial test verification confirm this statement.

It was further examined how the pandemic affected the revenues of manufacturing companies. Hypothesis H2 examined whether, if companies had implemented linear programming, their revenues did not decrease, unlike companies that had not applied these methods before the pandemic. Figure 1 shows the differences between companies. There was no manufacturing company in Slovakia that reported an increase of revenues of over 75%. The share of companies that had not applied linear programming before the pandemic and recorded a decrease in revenues was 63.08%, which is a lower share than in the segment of companies that had these methods implemented. However, the situation was the opposite of revenue growth. A higher percentage of companies with an increase in revenues during the pandemic were in the group of companies that had linear programming methods applied before the pandemic (17.09%). For companies without implemented linear programming, this share was only 8.92%. The Pearson correlation test was used to verify the hypothesis H2, however according to the data two thirds of companies that applied linear programming experienced a decrease in revenues. Therefore, hypothesis H2 could not be confirmed.

Table 2. Application of linear programming methods structured by the size of companies

Application of linear programming methods in 2014						
	Size of company				Total	Percentage
	Medium-sized companies		Large-sized companies			
Yes	81	40.70%	36	48.00%	117	42.70%
No	118	59.30%	39	52.00%	157	57.30%
Total	199	100.00%	75	100.00%	274	100.00%
Application of linear programming methods in 2021						
Yes	98	43.36%	45	52.33%	143	45.83%
No	128	56.64%	41	47.67%	169	54.17%
Total	226	100.00%	86	100.00%	312	100.00%

Hypotheses H3 and H4 focused on examining the relationship between the application of linear programming and the change in the number of links in the supply chain. It was assumed that companies applying these methods were less affected by the disruptions caused by the pandemic. According to the data provided in [Figure 2] the majority of manufacturing companies that applied linear programming before the pandemic experienced an increase in the number of suppliers (39.32%). Only a little over a quarter of them reported a decrease in suppliers. A binomial test was used to verify hypothesis H3 which focused on the assumption that the majority of manufacturing companies that had utilized the methods of linear programming before the pandemic experienced no decrease in the number of suppliers during the pandemic. This hypothesis was confirmed.

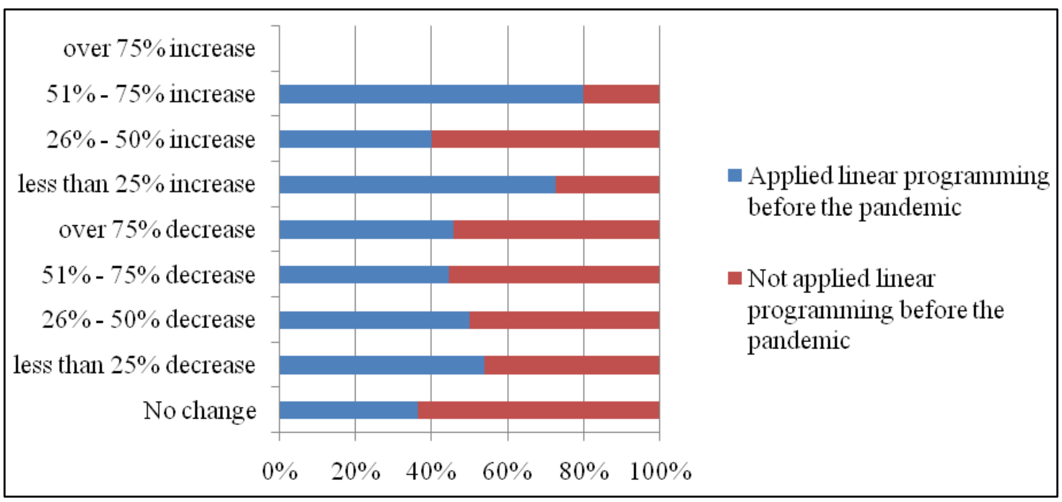

Figure 1. Changes in revenues during the pandemic

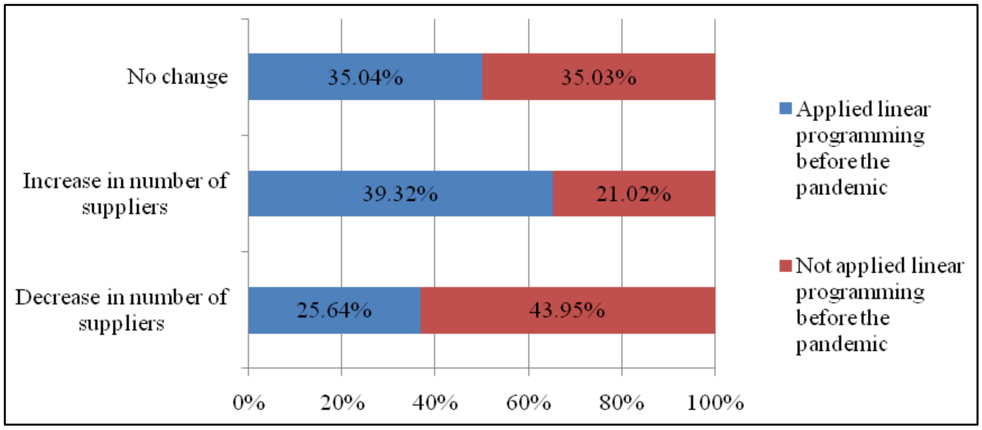

Figure 2. Changes in supply chain structure – suppliers

The situation was however different on the customer side of the supply chain. Nearly half of the manufacturing companies that had utilized linear programming in 2014 reported a decrease in the number of customers [Figure 3]. This number was so close to 50% that the Binomial test performed to verify hypothesis H_4 did not confirm it with any reliable statistical significance. On the other hand, this decrease in the number of customers was experienced by the even higher percentage of companies that had not utilized linear programming before the outbreak of the pandemic.

The last formulated hypothesis H_5 was oriented on resource allocation as the main linear programming utilization. Seven possible linear programming utilizations recognized by scientific literature were presented to supply chain managers during both surveys. According to the data provided in Table 3 resource allocation was the application with the largest representation during both surveys, even though there was a slight decrease in 2021 by 1.32%. A slight increase in the number of companies that applied these methods was recorded in distribution plans and financial management. There was a significant increase during the pandemic in 2021 in waste management (an increase of up to 6.84%). Multivariate regression analysis was used to test and ultimately confirm hypothesis H_5.

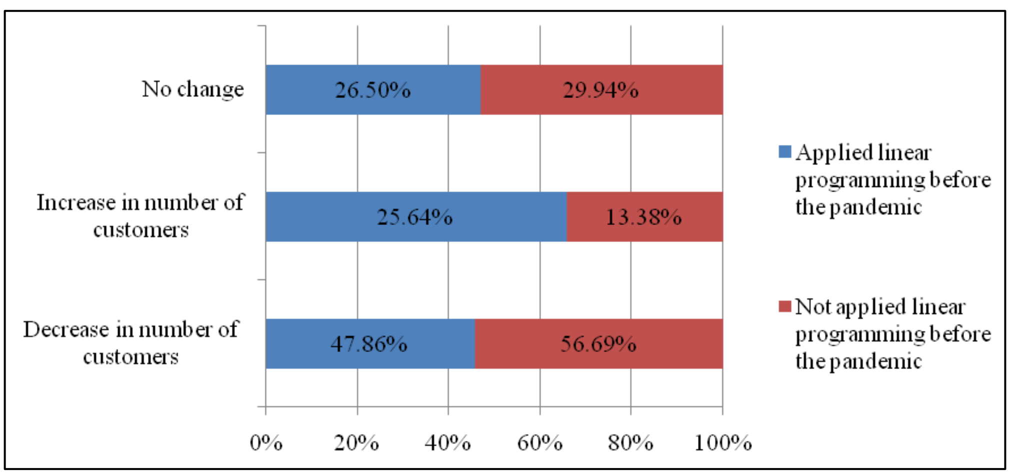

Figure 3. Changes in supply chain structure - customers

Table 3. Types of linear programming utilizations

Linear programming utilization	2014		2021	
	No. of companies	Percentage	No. of companies	Percentage
resource allocation	31	26.50%	36	25.17%
creating the production plan	30	25.64%	31	21.68%
personnel management	16	13.68%	13	9.09%
waste management	1	0.85%	11	7.69%
distribution plans	14	11.97%	23	16.08%
financial management	10	8.55%	14	9.79%
supplier selection	15	12.82%	18	12.59%

5. Conclusions

Supply chains all around the world were significantly affected by the COVID-19 pandemic and consequent economic crisis. The challenges that have been posted by the pandemic persist and their consequences for businesses are not yet sufficiently monitored and characterized in practice. These characteristics are a necessary prerequisite for predicting future market developments, which allows companies to optimize their supply chains and increase their performance. Linear programming is not an innovative way to optimize processes, but in practice, it is little used for processes and activities within the supply chain. In the conditions of the Slovak Republic, this tool was used by less than half of industrial production companies before the pandemic. During the pandemic, this proportion increased only minimally. However, the results of this study show that the involvement of linear programming in the optimization of supply chain processes helps to mitigate the effects of the pandemic.

This study also provides an overview of how possibilities of utilizing linear programming methods to optimize supply chain activities. The most common application has been resource allocation, both before and during a pandemic. At the same time, applications were identified that are not used in practice to a sufficient extent, which also represents an untapped potential for the development of supply chains. One of the most undervalued applications is the selection of suppliers, even though up to 10% of companies that do not use linear programming have seen a decrease in the number of suppliers. Supplier relationship management is one of the basic ways to develop and maintain the performance of entire chains. On the other hand, waste management and distribution plans have been identified as applications that increased in importance during the pandemic. Other research studies also described these areas as areas with potential for post-pandemic development [14][23][26] and linear programming can be an opportunity to better optimize these areas.

The main contribution of this research is the description of the effects of the pandemic on the scale and ways of using linear programming in supply chain management that has not yet been provided. The limit of this study is a narrow focus only on methods of linear programming and only on industrial production companies in the conditions of the Slovak Republic. It's possible that the business reality in Slovakia as described above does not reflect on the business reality in other countries, especially if they were differently impacted by the pandemic and/or the response of the government was dissimilar. However, the findings of this research can still serve as an indication of the situation in similar countries or sectors of the economy. A natural extension of this research is the addition of its focus to other methods of optimizing supply chain processes and activities.

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