
New Application of FMEA Analysis in the Heavy Industry Supply Chain

Submitted 15/04/20, 1st revision 01/05/21, 2nd revision 25/05/20, accepted 25/06/20

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Abstract:

Purpose: The purpose of the publication is to indicate the validity of building industry supply chains and to present a modified FMEA analysis for the heavy industry supply chain.

Approach/Methodology/Design: The research was carried out with reference to companies operating in the heavy metal industry between 2016 and 2020 on a European scale. The presented results concern one aspect of the conducted research related to the identification of key areas and determinants shaping industry supply chains.

Findings: The results obtained determine the specificity of the heavy industry supply chain, where social and societal aspects had the greatest impact on industry supply chains, mainly related to the lack of qualified staff, the increase in labour costs and social benefits and the need to meet staffing needs with foreign human resources.

Practical Implications: The relationships of companies operating in the heavy industry sector, the specifics of the supply chain and the risk factors affecting the companies in question are examined, as well as relating the risk elements to the heavy industry sector.

Originality/Value: The article contains important determinants for the development of the heavy industry explained along with the presentation of an innovative method combining FMEA analysis with the emergence of determinants shaping the industry.

Keywords: Supply, chain/network, management/governance, accidents (industrial, operational, etc.), failures, risk management.

JEL classification: O14, P42, P51.

Paper Type: Research study.

Acknowledgment: Research financed from the NCN research project no. UMO-2012/05 / B / HS4 / 04139.

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1. Introduction

Contemporary economic conditions and globalisation processes influence the way a company is managed and develops. Different regional, cultural and social factors and structures determine the choice of an appropriate decision-making strategy to maintain a company's competitiveness in a given market. The dynamics of change in both cultural and economic issues determine the determinants of change in organisational management (Stajniak and Koliński, 2016). The literature on the subject abounds with many concepts of management, organisation, efficiency, effectiveness, flexibility, ect. attributed to supply chains (Leung *et al.*, 2014; Yang *et al.*, 2021; Christopher and Holweg, 2011). Based on these considerations, a number of contemporary concepts have emerged, such as, rigid supply chains (Gualandris and Klassen, 2018), lean supply chains (Carvalho *et al.*, 2017; Frazzon *et al.*, 2017; Chen *et al.*, 2020), supply chains of continuous replenishment (Parsa *et al.*, 2017), slimmed-down supply chain (Pawlewski, 2018), flexible supply chains (Singh *et al.*, 2017; Radziwon *et al.*, 2014; Kurpjuweit *et al.*, 2021), resilient supply chains (Dubey *et al.*, 2019; Sawyerr and Harrison, 2019; Rajesh 2019), agile supply chains (Wu and Barnes, 2018; Biccocchi *et al.*, 2019), hybrid supply chains (Lin *et al.*, 2014; Tu *et al.*, 2019), multidimensional supply chains (Dendera-Gruszka *et al.*, 2020; Varsei *et al.*, 2014; Panchal *et al.*, 2015), whether triadic supply chains (Swierczek, 2019; Swierczek, 2020; Him and Henderson, 2015).

It is also worth mentioning that the supply chain is inextricably linked with the current world picture. The awareness of the advantages of the supply chain has contributed to the creation of methods supporting its management processes. Globalization forces the expansion of market activity of enterprises on a macroeconomic scale. Therefore, it is necessary to look at the structure of the supply chain from an industry perspective, which is the main idea of this publication.

The purpose of this publication is to indicate the rationale for building industry supply chains and to present an FMEA analysis for a heavy industry supply chain. The research was carried out for companies operating in the heavy metal industry between 2016 and 2020, mainly on a European scale, and covered nine major business entities, including three steel fabricators, three steel trading and manufacturing companies, and three metal products and metal processing companies. The relationships of the heavy industry companies, the specifics of the supply chain and the risk factors affecting the companies in question were examined, as well as relating the risk elements to the heavy industry.

2. Industry Supply Chain - Areas of Analysis and their Determinants

Supply chain transformation involves the adaptation of some of its elements to current market conditions. The ability to adapt to market conditions is extremely important in achieving competitive advantage. Ongoing supply chain changes are closely linked to the ability to anticipate the direction of market changes, to take

appropriate anticipatory actions and to improve supply chain management (Bentyn, 2016). In the implemented supply chain activities, one notices many elements of different concepts, mentioned in the introduction, implemented simultaneously. Managers extremely rarely consider which of the selected supply chain management concepts to apply in a given case. They need quick simple mechanisms to facilitate decision-making processes. They pay special attention to relationships with partners, information flow, flexibility and response time.

The analysis of industry supply chains is an analysis of the individual actors and, above all, of the relationships between them. Four years of research have shown that managing these relationships poses the greatest difficulties for managers. The results of this research have been divided into problem areas such as technological, temporal, locational, economic, political-legal, economic, social, globalisation and ecological. While these areas can be adopted similarly across industries, the determinants that shape these areas will differ. Table 1 summarises the areas of analysis and determinants of the heavy industry supply chain.

Table 1. Industry supply chain - areas of analysis and determinants (own study based on Polak 2009; Dendera-Gruszka et al., 2018; Dorn et al., 2018)

Area	Determinants
Technological	<ul style="list-style-type: none"> – technological progress – technological developments – the increasing role of telecommunications – access to high-speed internet networks – access to new technologies – access to information – quality of information flow – data theft – technological and technical innovation – use of information systems – e-banking – electronic data processing – cloud computing
Temporary	<ul style="list-style-type: none"> – technological developments – development of information technology – information flows – Development of emerging markets – Speed of response to customer requests and requirements – development of competition
Location	<ul style="list-style-type: none"> – reduction of spatial barriers – deterritorialisation – integration – reduction of state sovereignty – density of transport network – density of communication network – access to airports/sea/interland ports

	<ul style="list-style-type: none"> – access to railway stations – access to motorways, national roads – spatial mobility
Economical	<ul style="list-style-type: none"> – dominance of economics – unpredictability of the future – accumulation of wealth – economisation of politics – balance of payments burden – increase in unemployment – lack of skilled labour – the state of world markets – the volume of foreign exchange turnover – average tariffs – market regulation mechanisms – stock exchange quotations – exchange rates – inflation – turbulence on energy markets – economic situation – liberalisation of the markets
Politico-legal	<ul style="list-style-type: none"> – unpredictability of the future – dependence of the economic and political sphere on international capital – weakening of state structures – international legal and social relations – international tax regulations – aid received from public funds – policy of state authorities towards enterprises – changeability of legal regulations – legal regulations on the freedom to conduct business activities – effectiveness of corporate governance mechanisms – economic freedom – changes in economic conditions – tax rates – state fiscal policy – condition of the public finance sector – effectiveness of state control bodies – value of export – value of state investments – changes in political and economic structures of the state – restriction of political and economic sovereignty – political corruption – burden on the state budget – reforms of the tax system – functioning within a customs union or union of nations
Business	<ul style="list-style-type: none"> – standardisation

	<ul style="list-style-type: none"> – unification – integration – fragmentation – formalisation – institutionalisation – innovation of the economy – level of economic growth – uncertainty of market position – uncertainty of market identity – economic volatility – volatility – alignment of price/wage levels – price/wage level – number of multinational corporations and subsidiaries – share of intra-firm flows – degree of concentration of production – export rate – share of output value in global production – level of foreign direct investment – investment projects – consolidation/transformation of the industry – implementation of strategic transactions – changes in the structures of companies – increase in costs – supply and demand developments – competitiveness policy – tightened competition policy – business relationships with clients – smooth communication – commitment to orders – information flow – payment turnover – customer insolvency – payment deadlines – international flows of capital, goods, services and knowledge – value of exports – value of international investments – internationalisation of the company – number of contractors/branches abroad – fragmentation of production – export capacity – international division of labour – changes in production structures and product range – enlargement of sales markets – new jobs – access to international raw material, capital and production
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	<ul style="list-style-type: none"> resources – access to the global labour and sales market
Social	<ul style="list-style-type: none"> – instability of life – unpredictability of the future – impoverishing cultural diversity – commercialisation of consumer culture – deterritorialisation of culture – commercialisation of social relations – links to cultural, territorial and professional communities – social disintegration – increase in social activity – payments for social and welfare benefits – demand and supply of skilled labour – minimum wage levels – increase in labour costs – population movements – foreign language skills
Globalisation	<ul style="list-style-type: none"> – the growing role of non-state, unelected and undemocratic centres of economic power – the concentration of power resulting from hyper-power – the separation of the financial world from the real economy – increasing disparities between individual market segments – uncontrolled privatisation of the sector and public space – centralisation of political and economic decisions – globalisation of social pathologies – social threats and terrorism – universalisation
Organic	<ul style="list-style-type: none"> – rapidly increasing pressure to use green solutions – legal regulations on environmental protection – environmental disasters – natural disasters – natural disasters

Source: Own study based on Polak 2009; Dendera-Gruszka et al., 2018; Dorn et al., 2018.

Determinants influencing the industry supply chains concern each area of activity of the economic entity. Starting from the closest environment of the links comprising the supply chain, through social conditions, ending with the geopolitical situation of the world and globalisation processes. Table 1 presents factors influencing industry supply chains. In an industry supply chain, social factors are extremely important, as extremely culturally different employees may operate the supply chain at different stages of the business. Another important issue is the location of each element of the industry supply chain and its access to transport infrastructure. The operation of industry supply chains depends not only on national legal and fiscal frameworks, but also on international legal, tax and customs standards. The operation of industry supply chains is directly affected by the situation on global markets. The transformation of industry supply chains also takes place in connection with

exchange rate fluctuations and inflation. The pressure from international organisations to protect the environment is also increasingly important in this area.

The research conducted also allowed for the identification of determinants shaping the industry supply chain. The management of the studied business entities indicated the most significant, in their opinion, key elements influencing changes in the industry supply chain. On this basis, an analysis of the dependence between the influence of each factor on the functioning of the studied business entities and an exploration of the dependence of the factors in the perspective of each enterprise was carried out. For this purpose, the dependency graph method was used. In order to develop a risk management model of the industry supply chains, a decision table was drawn up based on the developed dependency graphs. The decision table showed the relationship between the determinants affecting the transformation of supply chains and the corresponding risk factors. These areas of research will be described in another publication.

The identified risk factors were used to carry out a risk management model of transforming supply chains, which is based on FMEA analysis. As is well known, FMEA analysis is used to analyse products or processes. FMEA analysis is a method of identifying and preventing problems related to the analysed process before its execution. It focuses on the prevention of process or product defects, increasing the safety of the process implementation, the financial security of the project, the safety of work and environmental protection (Wyrębek, 2012). FMEA analysis is carried out in the design phase of a process or product in order to avoid major risks and defects in the implementation phase. It is an important technique for identifying and eliminating potential defects and errors in processes and products. The authors decided to use it in a slightly different way.

The research decided to extend its application to the supply chain analysis of a specific industry. The developed FMEA model of industry supply chains includes areas that were selected from all the factors affecting changes in the management of the flow of goods and services. Based on the previously conducted analysis and selection of determinants, an FMEA analysis was conducted for the industry under study. The FMEA analysis covers the previously mentioned areas. The determinants affecting the industry supply chain in the heavy industry were analysed. The FMEA analysis was prepared on the basis of data obtained from the researched business entities - Table 2.

Table 2. *FMEA analysis sheet for the industry under study*

Area	Potential type of defect	Potential effect of the defect	Importance	Potential causes of the defect	Occurrence	Preventive measures	Detection	RPN
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Technological	Incorrect implementation of innovations	Loss of capital	3	Difficulties in implementing innovations	2	Analysis of current machinery and process facilities in terms of innovation implementation. Economic analysis of innovation implementation.	7	42
				Lack of patience of the management regarding the effects of implemented innovations				
	Lack of focus of the organisation on innovation activities	Lack of technological development in the organisation	3	High costs of implementing innovations	2		7	42
	Extension in time of the implementation of innovative investments			Employees' fears connected with the implementation of innovations				
	Lack of interest in new technological solutions							
Temporary	Expansion of emerging markets	Increased competition	7	More attractive offer from an emerging market supplier	5	Winning new customers. Negotiating new rates for the purchase of raw materials. Increasing the number of suppliers.	8	280
		Loss of customers						
	Late response to customer enquiries and requests	Loss of a potential customer	6	Distracted employees. Too little involvement of employees. Employee overload. Employing workers with insufficient skills and experience.	6	8	288	
Lack of response to customer queries and requests	Customer loss	8	3					8
Location	Reduction of spatial barriers	Increased competition	4	Country's accession to the economic union	6	Expanding sales and purchase offer to other countries.	7	168
	Transport network	Lack of access to sea, river and air ports, roads, motorways, railway networks	2	Location of plant in an economically underdeveloped area.	7	Relocation of the company. Attracting suppliers from the company's local environment	5	70
		Lack of an adequate transport or communication network	3		4		4	48
		Poor condition of road network	2		4		4	32
Limited spatial mobility	Lack of a suitable transport fleet	4	Lack of investment by the operator in transport equipment	2	Use of forwarding companies	9	72	
Economic	Lack of skilled labour	Staff shortages	7	Unemployment. Migration of	8	Employment of foreigners	2	112
		Lack of suitable	7		10		1	70

		staff		population. High level of emigration. Ageing of the population. Lack of labour force of working age					
		Employing staff with insufficient qualifications, experience and skills	7		9		3	189	
	Changes in global markets	Financial crisis	5	International economic situation. Conflicts between countries	2	Relocation of production to stable areas of the world	3	30	
	Changes in stock exchange quotations	Loss of potential shareholders	4	Crisis on world stock exchanges. Company bankruptcy. Speculative bubble	3	---	2	24	
	Changes in exchange rates	Decrease in share value	2		2		6	24	
		Inflow of external capital	3		3		5	45	
		Inflation	3		2		5	30	
	Politico-legal	Changes in legal and social relations	Unfavourable legal and social relations	4	Strikes of professional groups. Social policy of the state	5	---	4	80
		Changes in tax rates	Unfavourable tax regulations	5	Burden on the earned income	7	---	3	105
		Changes in tax regulations							
Lack of possibility of assistance from public funds		Lack of funds for enterprise development	2	Lack of public funds for a given area. Lack of classification of entity to receive assistance from public funds. Insufficient pool of public funds. Insufficient argumentation in applying for aid. Lack of an adequate aid scheme.	5	Acquisition of new customers, new production orders	5	50	
		Rejection of an application for funding of an investment	1		7		7	49	
		Insufficient funds to carry out the investment	1		9		8	72	
Changes in economic conditions		Lack of credit capacity	4	Other credit commitments. Loss of production orders. Company indebtedness	6		2	48	
		Inability to repay credit	3		2		2	12	
		Necessity to introduce foreign capital	1		1		2	2	
Unfavourable policy of state authorities towards enterprises		Lack of assistance from public administration	1	Lack of understanding of the situation by government offices. Following specific and rigid procedures	8	Joining a business association	6	48	
	Complicated and time-consuming administrative procedures	2	9		3		54		
Value of exports	Lack of competitiveness in the international arena	8	Difficulty in gaining international customers. Unattractive offer of the company for foreign contractors	7	Finding new markets	7	392		
Business	Low innovativeness of	Lack of government	4	Low attractiveness of the company abroad	6	Starting to work with new suppliers	2	48	

the economy	support for research and production development						
Degree of concentration of production	Increase in competition	3	100% implementation of production in one place	4	Use of outsourcing. Signing a contract with a subcontractor	2	24
Export rate	Low export rate	6	Regress of sales markets	4	---	1	24
Level of execution of strategic transactions	Lack of executed strategic transactions	2	Focusing the production only on one specific type of products and cooperation with only one final customer	2	Winning strategic investment and execution of smaller production orders	3	12
Increase in costs	Low level of production profitability	9	Increase in the prices of energy, raw materials and labour costs	10	---	4	360
Competitiveness policy	Unfair trade practices	4	Development of competition, globalisation	9	Breaking cooperation	4	144
Business relations with clients	Loss of client	4	Disregard for clients, improper customer service, lack of developed and implemented standards of customer service	8	Develop customer service standards. Hiring the right people to contact customers. Employee training	9	288
Quality of communication	Loss of employees	7	Lack of communication between the management and employees at the lowest level	7	Analysing projects with department managers and production workers	2	98
Quality of information flow	Poor quality of information flow	6	Disruptions in the flow of information	7	Improving the information flow process	3	126
Customer insolvency	Non-payment in due time	3	Too much trade credit	5	Confirming the customer's payment and business reliability	3	45
	Bankruptcy of a business partner						
	Too much debt of the organisation						
	Too long payment period						
Quality of purchased goods and services	Breaking off relations with the supplier	3	Poor quality of purchased goods and services	4	Checking the quality of supplied goods. Change of supplier	3	36
	Lack of source of supply						
Quality of goods and services sold	Loss of client	7	Poor quality of goods and services sold	3	Inspection of manufactured products	5	105
Value of international investments	Lack of participation in international investments	6	Impact of globalisation, decrease in the share of international investments, long-term nature of investments, changes	7	---	5	210

			in the international economic environment				
Capacity for fragmentation of production	Lack of opportunities for fragmentation of production	3	Globalisation, imperfect production processes, low quality of manufactured components, different cultural backgrounds influencing the production process, problem with communication and changing time zones, long transport times	4	Cooperation with international contractors who are able to ensure the required quality of goods	4	48
	No possibility for international division of labour	4		2		4	32
Access to international raw material, capital and production resources	Lack of access to the global labour and sales market	6		5		2	60
Degree of raw material storage	Excessive stocks	8	Global steel overproduction	7	---	6	336
Supply of steel	Over-supply of steel	7		6		4	168
	Volatility of energy and transport raw material prices	8		10		2	160
Degree of production profitability	Price discrepancy between steel and raw material	2	High level of raw material prices. Unprofitability of steel production.	6	---	2	24
Low efficiency of mining operations	Inability to meet demand	3	Low level of deposits	3	Searching for new deposits of raw material	4	36
Inaccurate mine life estimates	Exhaustion of resources	1		1		3	3
Drilling failure	Loss of raw material	2	Errors during drilling processes	2	Failure analysis. Implementation of corrective actions	3	12
Errors during production processes	Failure to meet orders	2	Loss of capital. Loss of client	2		2	8
Export capacity	Changes in the commercial policy of steel mills	8	Lack of conviction to export goods. Too much competition. Temporary or permanent ban on export of goods.	4	Verification of foreign counterparties. Obtaining an opinion about the counterparty in the environment	2	64
	Embargo	5		6		2	60
Steel imports	Loss of material	4	Rising costs of raw material extraction. Steel and iron ore prices too low. Persistently low steel and iron ore prices.	7	---	3	84
	Increase in transport costs	3		8		3	72
	Increase in steel prices	4		9		3	108
Decrease in demand for steel	Use of steel substitutes	6	Development of competition from other materials. Price and technological attractiveness of other materials	8	Acquisition of new customers. Flexibility in product range. Speed of transformation of essential production	2	96
	Loss of customers	9		8		2	144
Seasonality of sales	Limited cooperation with a	1	Loss of regular production orders	7		5	35

	Dependence on suppliers	potential supplier		Supplier bankruptcy. Delays in fulfilling supply orders. Lack of a constant flow of raw material. Problem in fulfilling a supply order with a potential new supplier.	3	Securing sources of supply from several suppliers	4	12	
		Production downtime	1						
	Relationship with entities	Loss of production orders	3	Too much trust. Lack of loyalty. Business deception	1	---	6	18	
		Loss of key customer							
		Loss of a subcontractor							
	The impact of globalisation	Relocation of production to Asian markets	6	Global steel overproduction. Inflow of raw material from Asian markets. Low price level. Low quality	10	---	2	120	
		Loss of regular customers	2		2		8		
		Decrease in prices	3		4		3	36	
	Social	Minimum wage level	Increase in labour costs	9	Loss of price attractiveness in the international and domestic arena. Increase in prices of manufactured products	10	---	6	540
	Environmental	Environmental degradation	Adjustment of production facilities to strict environmental restrictions and regulations	2	Increase in steel costs. Need to upgrade the plant to meet environmental standards. High investment costs. Lack of government programmes to support adaptation of workplaces to environmental conditions.	6	Progressive adaptation of the workplace to environmental standards	3	36
High penalties for non-compliance with environmental regulations									
Inability of production plants to adapt to environmental requirements									
Problem of limiting the emission of greenhouse gases									

Source: Own study.

Table 2 shows the key aspects that can affect the heavy industry supply chain. Table 2 analyses the different business areas of the operators involved in the flow of goods and services in the heavy industry industry. The potential type of defect is defined together with its effect. The probability of a defect occurrence is determined on a scale of 1 to 10. A value of 1 is assigned to an improbable situation, while 10 - to a very probable situation. Details of the value assignment are given in Table 3.

Table 3. Determination of the significance of the occurrence of the defect

R	Importance	FMEA service/structure
1	unlikely	Imperceptible impact on service delivery
2–3	small	The defect is minor and has little impact on customer satisfaction
4–6	medium	Medium defect, noticeable customer dissatisfaction
7–8	important	The defect occurs cyclically and has a major impact on customer dissatisfaction
9–10	extremely important	Extremely important defect that affects further operation, safety and is contrary to law

Source: Own study.

The next step was to determine the cause of the defect with its value. Again, the cause of the defect was determined on a scale of 1 to 10. A value of 1 is assigned to an unlikely situation and 10 to a very likely situation. Details of the value assignment are given in Table 4.

Table 4. Determination of probability of defect

W	Probability of defect	FMEA service/structure/process
1	unlikely	No possibility of defect
2	very low	Very low probability of defect occurrence. Defects occur singly and very rarely
3	low	Low probability of individual defects
4–6	average	Defects occur in small quantities on average
7–8	high	Defects are very common
9–10	very high	Very high probability of defect

Source: Own study.

In the next step, preventive measures were specified and detection parameters were estimated, Table 5.

Table 5. Determination of probability of detection

D	Significance of the defect	FMEA service/structure/process
1–2	very large	Reliable detection of a defect
3–4	large	Chances of detecting a defect are high, a test or functional check is used
5–6	medium	Defect inspection may detect an average detection
7–8	small	Difficulty in detecting a defect
9–10	very small	Detection of the defect is difficult or impossible

Source: Own study.

The final stage of the FMEA analysis was to assign the RPN parameter. Assigning the above parameters to the FMEA sheet allowed us to determine the RPN risk priority number, which was calculated according to formula 1.

$$\text{RPN} = \text{Importance (R)} * \text{Occurrence (P)} * \text{Detection (D)} \quad (1)$$

The RPN makes it possible to identify which hazards carry the greatest risk and to prioritise in which order the different determinants are analysed.

The industry supply chain FMEA aimed to demonstrate the relationship between the determinants shaping the areas of industry supply chain materiality for the heavy industry sector. During the analysis a value of RPN = 100 was set, below this value the influence of the factors on the industry supply chain was insignificant, while above this value it had a very significant influence on it.

For the industry studied, social and societal aspects had the greatest impact on industry supply chains, mainly related to the lack of skilled staff, rising labour costs and social benefits, and the need to meet staffing needs with foreign human resources. Other aspects influencing the formation of industry supply chains were rising energy and raw material prices, business relationships with customers, expansion of emerging markets and reduction of spatial barriers.

3. Conclusion

Supply chains are among the structures that are susceptible to the influence of external factors, and thus are conducive to creating conditions for the transformation of supply network structures. As supply chains are directed towards the achievement of specific economic, organisational and quality objectives, they are influenced by the paradigm of reducing costs and increasing benefits for the final customer.

The industry supply chain involves the adaptation, relevant at a given point in time, of its elements to current market conditions. The ability to adapt to market conditions is critical to achieving competitive advantage.

Industry supply chains are primarily target-driven. In the face of increasing change, logistics partnerships, relationships formed, have a significant impact on supply chain management.

The verification of the industry supply chain model was carried out on the basis of an analysis of business entities. The analysis covered the determinants within the distinguished areas that condition effective cooperation according to the studied entities. On the basis of the indicated determinants influencing the industry supply chain, an analysis of the dependence of selected factors on business entities operating within the industry supply chain was conducted. The results obtained after a modified FMEA analysis made it possible to identify the key determinants for the industry supply chain of heavy industry.

The results obtained determine the specificity of the supply chain for the heavy industry industry. For the industry under study, social and societal aspects had the greatest impact on the industry supply chain, mainly related to the lack of qualified staff, the increase in labour costs and social benefits and the need to meet staffing

needs with foreign human resources. Other aspects influencing the formation of industry supply chains were rising energy and raw material prices, business relationships with customers, the expansion of emerging markets and the reduction of spatial barriers.

References:

- Bentyn, Z. 2016. Transformacja łańcuchów dostaw dzięki wirtualizacji procesów logistycznych oraz zmianie zachowań konsumentów (Transformation of supply chains through virtualisation of logistics processes and changing consumer behaviour). *Gospodarka Materiałowa & Logistyka*, 5, p. 4
- Bicocchi, N., Cabri, G., Mandreoli, F., Mecella M. 2019. Dynamic digital factories for agile supply chains: An architectural approach. *Journal of Industrial Information Integration*, 15, 111-121. <https://doi.org/10.1016/j.jii.2019.02.001>.
- Carvalho, H., Govindan, K., Azevedo, S.G., Cruz-Machado, V. 2017. Modelling green and lean supply chains: An eco-efficiency perspective. *Resources, Conservation and Recycling*, 120, 75-87. <https://doi.org/10.1016/j.resconrec.2016.09.025>.
- Chen, H., Liu, S., Oderanti, F. 2020. A Knowledge Network and Mobilisation Framework for Lean Supply Chain Decisions in Agri-Food Industry. In: *Management Association, (Ed.), Supply Chain and Logistics Management: Concepts, Methodologies, Tools, and Applications*, 369-381. IGI Global. <http://doi:10.4018/978-1-7998-0945-6.ch018>.
- Christopher, M., Holweg, M. 2011. Supply Chain 2.0: managing supply chains in the era of turbulence. *International Journal of Physical Distribution & Logistics Management*, 41(1), 63-82. <http://dx.doi.org/10.1108/09600031111101439>.
- Dendera-Gruszka, M., Kulińska, E., Masłowski, D. 2018. Determinanty wymuszające transformację łańcuchów dostaw (Determinants forcing the transformation of supply chains). In: Chodźko, E., Szymczyk, P. (eds), *Wybrane prace z obszaru prawa ekonomii i nauk społecznych*. Wydawnictwo Naukowe TYGIEL, Lublin, 315-332.
- Dendera-Gruszka, M., Kulińska, E., Masłowski, D. 2020. Branżowe łańcuchy dostaw jako szansa dla współczesnych organizacji (Industry supply chains as an opportunity for modern organisations). In: *Zarządzanie strategiczne w dobie cyfrowej gospodarki sieciowej*, red. Sylwester Gregorczyk, Grzegorz Urbanek ISBN: 978-83-8220-335-6; e-ISBN 978-83-8220-336-3. Wydawnictwo Uniwersytetu Łódzkiego, Łódź, 419-430
- Dorn, F., Fuest, C., Potrafke, N. 2018. Globalization and Income Inequality Revisited. IFO Institute, Leibniz Institute for Economic Research at the University of Munich, Munich, 2-5.
- Dubey, R., Gunasekaran, A., Childe, S.J., Papadopoulos, T., Blome, C., Luo, Z. 2019. Antecedents of Resilient Supply Chains: An Empirical Study. *IEEE Transactions on Engineering Management*, 66(1), 8-19. doi: 10.1109/TEM.2017.2723042.
- Frazzon, E., Tortorella, G.L., Dávalos, R., Holtz, T., Coelho, L. 2017. Simulation-based analysis of a supplier-manufacturer relationship in lean supply chains. *International Journal of Lean Six Sigma*, 8(3), 262-274. <https://doi.org/10.1108/IJLSS-03-2016-0009>.
- Gualandris, J., Klassen, R.D. 2018. Emerging Discourse Incubator: Delivering Transformational Change: Aligning Supply Chains and Stakeholders in Non-Governmental Organizations. *Journal Supply Chain Management*, 54, 34-48. <https://doi.org/10.1111/jscm.12164>.

- Kim, Y.H., Henderson, D. 2015. Financial benefits and risks of dependency in triadic supply chain relationships. *Journal of Operations Management*, 36, 115-129, ISSN 0272-6963. <https://doi.org/10.1016/j.jom.2015.04.001>.
- Kurpjuweit, S., Schmidt, C.G., Klöckner, M., Wagner, S.M. 2021. Blockchain in Additive Manufacturing and its Impact on Supply Chains. *Journal of Business Logistics*. <https://doi.org/10.1111/jbl.12231>.
- Leung, G.C.K., Cherp, A., Jewell, J., Wei, Y.M. 2014. Securitization of energy supply chains in China. *Applied Energy*, 123, 316-326. <https://doi.org/10.1016/j.apenergy.2013.12.016>.
- Lin, W.J., Jiang, Z.B., Liu, R., Wang, L. 2014. The bullwhip effect in hybrid supply chain. *International Journal of Production Research*, 52(7), 2062-2084. <https://doi.org/10.1080/00207543.2013.849013>.
- Panchal, G.B., Jain, V., Kumar, S. 2015. Multidimensional utility analysis in a two-tier supply chain. *Journal of Manufacturing Systems*, 37(1), 437-447, ISSN 0278-6125. <https://doi.org/10.1016/j.jmsy.2014.07.001>.
- Parsa, P., Rossetti, M.D., Zhang, S., Pohl, E.A. 2017. Quantifying the benefits of continuous replenishment program for partner evaluation. *International Journal of Production Economics*, 187, 229-245. <https://doi.org/10.1016/j.ijpe.2017.02.017>.
- Pawlewski, P. 2018. Using PFEP For Simulation Modeling of Production Systems. *Procedia Manufacturing*, 17, 811-818. <https://doi.org/10.1016/j.promfg.2018.10.132>.
- Polak, E. 2009. *Globalizacja a zróżnicowanie społeczno-ekonomiczne*. Wydawnictwo Difin, Warszawa, 142.
- Radziwon, A., Bilberg, A., Bogers, M., Madsen, E.S. 2014. The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions. *Procedia Engineering*, 69, 1184-1190. <http://dx.doi.org/10.1016/j.proeng.2014.03.108>.
- Rajesh, R. 2019. Social and environmental risk management in resilient supply chains: A periodical study by the Grey-Verhulst model. *International Journal of Production Research*, 57(11), 3748-3765. DOI: 10.1080/00207543.2019.1566656.
- Sawyer, E., Harrison, C. 2019. Developing resilient supply chains: lessons from high-reliability organisations. *Supply Chain Management*, 25(1), 77-100. <https://doi.org/10.1108/SCM-09-2018-0329>.
- Singh, R.K., Koul, S., Kumar, P. 2017. Analyzing the interaction of factors for flexibility in supply chains. *Journal of Modelling in Management*, 12(4), 671-689. <https://doi.org/10.1108/JM2-04-2016-0039>.
- Stajniak, M., Koliński, A. 2016. *Współczesne technologie transportowe w łańcuchu dostaw (Modern transport technologies in the supply chain)*. Instytut Naukowo-Wydawniczy Spatium, Radom, p. 5.
- Swierczek, A. 2019. Manufacturer structural embeddedness and the network rent: the intervening role of relational embeddedness in the triadic supply chains. *Supply Chain Management*, 24(3), 334-354. <https://doi.org/10.1108/SCM-06-2018-0232>.
- Swierczek, A. 2020. Relational orientation of triadic supply chains with structural holes: an empirical comparison of rents derived from bridging the structural holes. *Supply Chain Management*, 25(5), 565-583. <https://doi.org/10.1108/SCM-10-2019-0382>.
- Tu, H., Mao, X., Wang, X. 2019. Complexity of a dynamic hybrid supply chain game model with a service factor. *Nonlinear Dynamics*, 97(4), 2055-2066. <https://doi.org/10.1007/s11071-019-05096-1>.
- Varsei, M., Soosay, C., Fahimnia, B., Sarkis, J. 2014. Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Management*, 19(3), 242-257. <https://doi.org/10.1108/SCM-12-2013-0436>.

- Wu, C., Barnes, D. 2018. Design of agile supply chains including the trade-off between number of partners and reliability. *The International Journal of Advanced Manufacturing Technology*, 97, 3683–3700. <https://doi.org/10.1007/s00170-018-2205-5>.
- Wyřębek, H. 2012. Znaczenie metody FMEA w zarządzaniu jakością w przedsiębiorstwach (The importance of the FMEA method in quality management in companies). *Zeszyty Naukowe Uniwersytetu Przyrodniczo-Humanistycznego w Siedlcach*, 92, 151-165.
- Yang, J., Xie, H., Yu, G., Liu, M. 2021. Achieving a just-in-time supply chain: The role of supply chain intelligence. *International journal of production economics*, 231, 107878. <https://doi.org/10.1016/j.ijpe.2020.107878>.