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MULTI-CHANNEL SUPPLY CHAIN OPTIMISATION IN CYBER-PHYSICAL ENVIRONMENT UNDER QUANTITY DISCOUNTS

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Abstract: *The procurement, manufacturing, distribution, and recycling processes of circular economy have changed in the last few years. The increased complexity of these processes led to the application of new models, methods, tools and technologies. Multi- and omni-channel purchasing, and distribution solutions opens new challenges for researchers to find new models and algorithms to support the optimal design and operation of these processes. Within the frame of this article the authors describe the mathematical model of a multi-channel supply chain solution in cyber-physical environment, where the processes of purchasing regarding suppliers and customers are integrated in a supply chain cloud. Numerical analysis shows the validation of the described model.*
Keywords: *logistics, multi-channel supply chain, nonlinear regression, purchasing.*

Višekanalna optimizacija lanca snabdevanja u kiber-fizičkom okruženju uz količinske popuste. *Procesi nabavke, proizvodnje, distribucije i recikliranja u ekonomkom okrženju su se promenili u poslednjih nekoliko godina. Povećana složenost ovih procesa dovela je do primene novih modela, metoda, alata i tehnologija. Rešenja za kupovinu i distribuciju sa više kanala otvaraju nove izazove za istraživače u pronalaženju novih modela i algoritama za podršku optimalnog dizajna i rada ovih procesa. U okviru ovog rada autori opisuju matematički model rešenja višekanalnog lanca snabdevanja u kiber-fizičkom okruženju, gde su procesi kupovine dobavljača i kupaca integrisani u oblak lanca snabdevanja. Numerička analiza pokazuje validaciju opisanog modela.*
Ključne reči: *logistika, višekanalni lanac snabdevanja, nelinearna regresija, kupovina.*

1. INTRODUCTION

The transformation of linear economy into circular economy and the increased complexity of product structures led to the evolution of purchasing processes. Single-channel solutions were extended to multi- and omni-channel supply chains and they need more sophisticated methods in design and operation. The lean philosophy, the Toyota production system, the just-in-time, and just-in-sequence supply support the efficiency of complex manufacturing systems regarding logistics. As the FMD Pro Model defines, purchasing processes are quite complex including the following phases: check budget (financial evaluation), prepare purchase requisition, supplier selection (in the case of multi- or omni-channel solution), place orders, delivery, receipt, inspection of received products integrated into the total quality management process, payment [1].

Most of the purchasing processes are based on strategic source agreements, which provide lower pricing through various volume discount, enhanced component quality and higher service level. Due to the regular replanning of purchasing processes, there is a stronger and stronger need to the optimisation of orders. In this paper, we present a concept of such a mathematical model, by which the procurement processes of multi-channel purchasing can be optimised.

2. LITERATURE REVIEW

The emersion of Industry 4.0 technologies, the appearance of new business models, the increase of competition level among retailers and the diversification of customers' demand led to the use of multi-channel supply chains [2]. Various case studies validate the efficiency of multi-channel and omni-channel purchasing and distribution systems in wineries [3], dairy firms [4], fashion industry [5] or global marketing [6]. The design and operation tasks of multi-channel supply chains including forward, and reverse options can be described as complex NP-hard problems, therefore their solutions are usually based on heuristic and metaheuristic solutions. We can find in the literature deterministic and stochastic mixed integer linear programming models [7]. Nonlinear models of multi-channel supply chain can be in special cases linearized by some approximations and the models can solved with local branching-based solution method [8]. Pricing strategies of a virtual trading community are analysed using game theory to compare traditional online sales and e-channels as third-party logistics service [9]. A Lagrangian relaxation-based algorithm is proposed to solve the non-linear integer programming model of a capacitated location model with online demand pooling in a multi-channel supply chain [10]. Since the exact analysis is in most cases of complex multi-channel solutions intractable, researcher propose new decomposition schemes to find near-optimal solutions of optimisation problems in supply chain problems [11]. EOQ and MRP models can be used in many cases of inventory and production related decisions, as a research shows in the case of joint pricing and inventory/production problems of incorporating intra-product line price interactions [12].

The complexity of a single manufacturer two retailer supply chain is demonstrated as a Stackelberg dynamic game model, where a wide range of models as tools, like stability domain, bifurcation diagram, the largest Lyapunov exponent, attractor, and time series can be used to analyse the supply chain problem [13]. The solutions of multi-channel supply chain problems are limited with various constraints and there is a wide range aspects to be taken into consideration: KPI performance measurement [14], bullwhip effect and complexity analysis [15], factory encroachment and channel selection in outsourced environment [16], analysis of inventory record inaccuracy dynamics [17], customer-driven investment decisions in downstream supply chains [18], capacity planning and allocation [19], impact of information asymmetry on pricing strategy and firm's performance [20].

Based on the above-mentioned literature background, the article is organized as follows. Chapter 2 presents a short literature review, which summarizes the research background of multi- and omni-channel supply chain-related researches, focusing on design and optimisation approaches. Chapter 3 is the problem description including the mathematical model of a multi-channel purchasing system in cyber-physical environment. Chapter 4 describes the numerical analysis of the mathematical model, while conclusions, managerial impacts, and future research directions are discussed in the remaining part of the article.

3. MODELLING OF THE MULTI-CHANNEL SUPPLY CHAIN IN CYBER-PHYSICAL ENVIRONMENT

The transformation of conventional purchasing systems into cyber-physical systems make it possible to transform the conventional direct customer-supplier relation into a customer-supply chain cloud-suppliers relation, which opens new opportunities for the optimisation of the whole purchasing process because the impact of process' parameters can be taken into consideration in an effective way with ERP-integrated simulation and digital twin.

The ERP system includes purchase order processing, inventory management, production management, quality management, sales, human resources, fleet management, finance and costing. The warehouse and the storages of components, parts, tools, and raw material has a direct connection to the production management module of ERP, which includes the add-on tool to optimise the multi-channel purchasing process. The ERP make more data available from the warehouses through the inventory management module. Business intelligence is responsible for data analysis, forecasting and controlling of business processes, while the decision making is supported with a digital twin technology. There are various digital twin solutions, like process twinning, component twinning, asset twinning and system twinning. The digital twin-based support of this multi-channel supply chain design is based on process twinning, but component twin can be useful in product design, which has a great impact on the future purchasing process. Supply chain cloud is a common platform for the manufacturer and the suppliers. This chapter describes the mathematical model of this cyber-physical multi-channel supply chain process is described including, cost-based objective function and quantity related constraints.

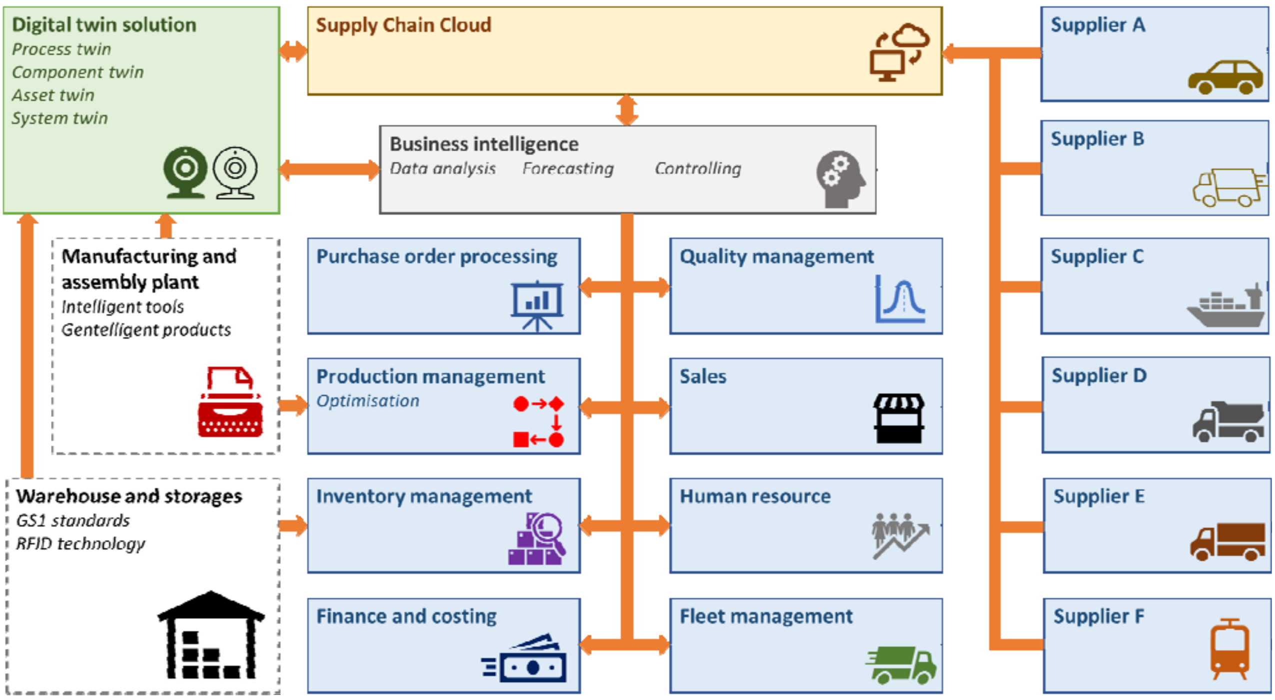

Fig. 1. Model of a cyber-physical multi-channel supply chain

Notations and their explanations used in the article are shown in Table 1.

Notation	Explanation
C	total cost, objective function of the optimisation problem
CP	total purchasing cost including the prizes of products and material handling costs
CBT	total cost of batch transportation
DP	total volume discount regarding the products
DS	total volume discount regarding suppliers
$q_{i,j,\tau}$	the purchased amount of product i from supplier j in purchasing cycle τ, as decision variable of the optimisation problem
$p_{i,j,\tau}$	the purchasing price of product i from supplier j in purchasing cycle τ
$\tau_{\max}$	the total number of purchasing cycles
$btc_{i\Theta}$	additional specific batch transportation cost of product i and supplier set Θ
$k \in \Theta_{i\tau}$	object of the set of suppliers assigned to the purchasing of product i in purchasing cycle τ
$vdp_{i,j,\tau}$	specific volume discount for product i purchased from supplier j in cycle τ
$vds_{j,\tau}$	specific volume discount for supplier j in cycle τ
$b \in \Phi_{j,\tau}$	set of products purchased from supplier j in cycle τ
$oq_{i,j,\tau}^{\min}$	lower limit of orderable product i from supplier j in cycle τ
$oq_{i,j,\tau}^{\max}$	upper limit of orderable product i from supplier j in cycle τ
$pd_{i,\tau}$	product demand i in purchasing cycle τ
$pqs_{j,\tau}$	upper limit of the total value of products ordered from supplier j in cycle τ

Table 1. Notations and their explanations

The objective function of the optimisation problem is based on the sum of purchasing cost, additional costs of batch transport from more suppliers, and quantity discount regarding products and suppliers:

$$C = CP + CBT - DP - DS \tag{1}$$

The first part of the objective function is the sum of the purchasing cost, which depends on the purchased amount and the specific purchasing price and can be calculated as follows:

$$CP = \sum_{\tau=1}^{\tau_{\max}} \sum_{i=1}^{m} \sum_{j=1}^{n} q_{i,j,\tau} \cdot p_{i,j,\tau} \tag{2}$$

The second part of the objective function defines the impact of batch supply of a product from more suppliers. This cost depends on the purchased amount of products and the specific additional batch transportation cost:

$$CBT = \sum_{\tau=1}^{\tau_{\max}} \left(\sum_{i=1}^{m} btc_{i\Theta_{i\tau}} \cdot \sum_{k \in \Theta_{i\tau}} q_{i,\mathrm{k},\tau} \right) \tag{3}$$

The third part of the objective function represents a volume discount for each product, which depends on the order amount from the same supplier and the specific volume discount and can be calculated as follows:

$$DP = \sum_{\tau=1}^{\tau_{\max}} \sum_{i=1}^{m} \sum_{j=1}^{n} q_{i,\mathrm{j},\tau} \cdot vdp_{i,j,\tau} \tag{4}$$

The fourth part of the objective function is the volume discount for purchasing products from the same supplier. This volume discount depends on the total amount of different products purchased from the same supplier and the specific volume discount for suppliers and can be described as follows:

$$DS = \sum_{\tau=1}^{\tau_{\max}} \sum_{j=1}^{n} vds_{j,\tau} \cdot \sum_{b \in \Phi_{j,\tau}} q_{b,\mathrm{j},\tau} \tag{5}$$

Within the frame of the optimisation three constraints are taken into consideration. The value of orderable products from each supplier is limited and it is not allowed to exceed the lower and upper limit of this amount:

$$\forall i,j,\tau: \quad oq_{i,j,\tau}^{\min} \le q_{\mathrm{i,j},\tau} \le oq_{i,j,\tau}^{\max} \tag{6}$$

The total sum of purchased products must be equal to the predefined product demand:

$$\forall i,\tau: \quad \sum_{j=1}^{n} q_{\mathrm{i,j},\tau} = pd_{i,\tau} \tag{7}$$

The total value of purchased products from the suppliers can be limited, at it is not allowed to exceed this upper limit:

$$\forall j,\tau: \quad \sum_{i=1}^{m} q_{\mathrm{i,j},\tau} \le pqs_{j,\tau} \tag{8}$$

4. SCENARIO ANALYSIS

Within the frame of this chapter the numerical analysis of the above-mentioned mathematical model will be described. As Table 2. shows, the multi-channel supply chain includes one manufacturer and four suppliers and seven products are taken into consideration and the available number of products is limited. The numerical example is limited to one purchasing cycle. The specific purchasing prices are shown in Table 3. These prices do not include the logistic costs.

Product	Suppliers			
	A	B	C	D
1	41	54	66	67
2	45	64	35	36
3	49	55	34	16
4	28	67	13	69
5	57	14	55	32
6	53	11	44	63
7	200	53	29	50

Table 2. Available products at the suppliers

Product	Suppliers			
	A	B	C	D
1	2.67	1.03	3.00	0.49
2	1.28	2.86	2.54	3.45
3	1.20	1.61	4.13	1.35
4	3.53	3.45	3.13	1.85
5	2.07	3.65	2.95	0.64
6	3.72	0.59	3.92	3.96
7	3.83	2.67	3.18	0.78

Table 3. Specific purchasing prices of products in EUR

Purchasing may enter into framework agreements with one or more suppliers, which prescribe the terms and conditions which would apply to any subsequent contract and make provision for selection and appointment of a contractor by reference directly to the agreed terms and conditions [21]. The framework purchase contracts can define upper and lower limits of lots to be ordered within one purchase cycle (Table 4 and Table 5). The real-time monitoring of the status of the framework purchase agreements is an importan tprocess of procurement because significant differences between plan and reality can lead to additional costs near the deadline of the agreement.

Product	Suppliers			
	A	B	C	D
1	0	12	0	16
2	10	0	0	8
3	0	6	0	3
4	0	5	3	0
5	13	0	0	7
6	12	0	10	15
7	0	0	0	12

Table 4. Lower limit of purchasing amount

Product	Suppliers			
	A	B	C	D
1	41	54	66	67
2	45	64	35	36
3	49	55	34	16
4	28	67	13	69
5	57	14	55	32
6	53	11	44	63
7	200	10	29	50

Table 5. Upper limit of purchasing amount

Volume discounting strategy is beneficial when done optimised. The scenario takes the volume discount regarding the products into consideration, as shown in Table 6. It is possible to choose tiered model, volume model or package model of volume discount models.

Product	Suppliers			
	A	B	C	D
1	0	1.00	0	0
2	0.25	0.29	0.35	0.11
3	0.14	0.07	0.07	0.33
4	0.18	0.31	0.01	0.06
5	0.31	0.22	0.32	0.04
6	0.32	0.39	0.30	0.33
7	0.33	0.01	0.31	0.35

Table 6. Volume discont regarding the products

In multi-channel supply chains the batch orders and the split of orders has a great impact on the transportation and material handling cost. These additional costs are taken into consideration as shown in Table 7, where TB is for transportation batches. The specific additional cost for batch transportation is caused by the increased transportation routes, additional material handling operations, like loading, unloading, building of loading units or packaging.

TB	Products						
	1	2	3	4	5	6	7
AB	37	31	29	32	35	26	8
AC	12	20	17	20	1	14	40
AD	26	22	35	25	21	2	19
BC	9	31	8	26	38	29	16
BD	19	25	20	2	36	36	25
CD	13	3	8	10	16	31	39
BCD	127	191	181	182	175	189	118
ACD	197	76	152	163	192	167	117
ABD	161	178	145	171	161	161	88
ABC	141	150	170	105	200	150	115
ABCD	342	316	465	353	497	362	378

Table 7. Additional cost of purchasing caused by batch transportation of a product from different suppliers within the same cycle (•10^{-2} EUR)

Using the nonlinear regression and evolutive algorithm of the Excel Solver, we can find the optimal assignment of demands and suppliers. As Table 8 shows, one demand can be divided into two or more suborders.

Product	Suppliers			
	A	B	C	D
1	0	54	0	28
2	41	0	0	8
3	14	6	0	3
4	0	5	13	22
5	13	0	25	32
6	12	11	24	15
7	0	0	21	50

Table 8. Optimal purchasing portfolio

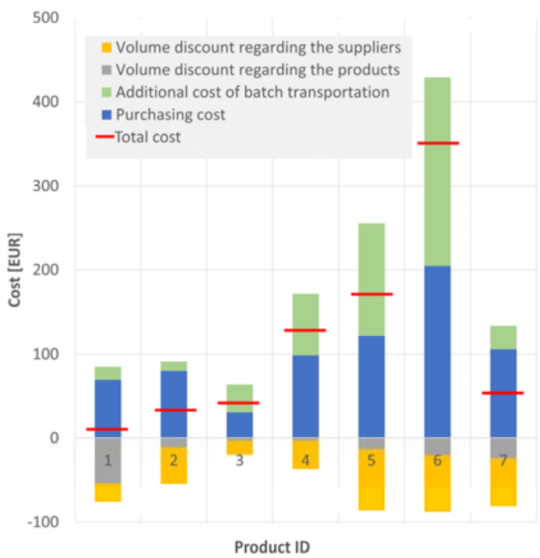

Fig. 2. Cost structure of the products including price, batch transportation costs and volume discounts

The costs regarding the products and the incomes regarding the suppliers are shown in Figure 2 and Figure 3. The figures demonstrate the structure of costs including purchaseing cost, addititonal cost of batch transportation and volume discounts.

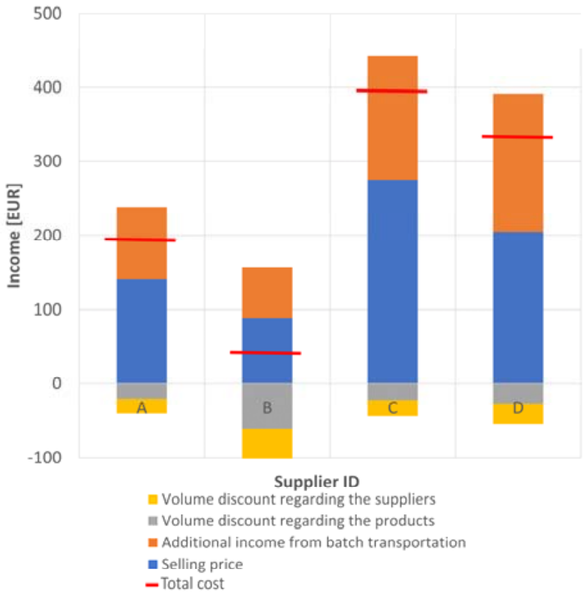

Fig. 3. Income structure of the suppliers including price, batch transportation costs and volume discount.

5. SUMMARY AND CONCLUSIONS

Multi- and omni-channel supply chains have more and more importance in the field of both production and services. The complexity of these supply chain solutions in the field of purchasing and distribution has a great impact on the required models, methods, and tools to defines strategies, make decisions and optimise the processes and operations [22]. With the spread of digitalization, the application of Industry 4.0 technologies, like digital twin, cloud, fog, and edge computing, virtual and augmented reality will be prioritized in the field of both production and related logistics processes [23].

This paper highlights the fact that with the appropriate establishment of purchasing processes in a multi-channel supply chain, we can make significant steps towards the efficiency, availability, and cost efficiency, while environmental impacts can be decreased. As a result of application of Industry 4.0 technologies hallmarked by the transformation of conventional manufacturing and logistics systems into cyber-physical systems, more and more data become available through sensor networks, thus the application of state-of-the art data processing and computation technologies is becoming more and more e□ective.

The added value of the paper is the description of a multi-channel supply chain in cyber-physical environment, where Industry 4.0 technologies, like digital twin support decision making of procurement processes in ERP. The scientific contribution of this paper for researchers in this field is the mathematical model, which includes a cost-based objective functions and various constraints regarding capacity, volume discount and additional costs of batch transportation caused by additional material handling operations, like loading, unloading, building of loading units and packaging. The results can be generalized because the model can be applied for various types of production environment, like conventional or cyber-physical systems. Managerial decisions can be influenced by the results of this research because the decision making of strategy makers of procurement and purchasing can be supported by the results of analysis based on this research. As a future research direction, we can extend our model converting the crisp input values to a fuzzy value using various types of curves, like Gaussian, triangular, and trapezoidal membership functions.

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