TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 65, Issue Special IV, December, 2022

NEW MODELS AND METHODS OF DISRUPTED SUPPLY CHAINS IN THE INDUSTRY 4.0 ERA

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Abstract: *The Fourth Industrial Revolution led to significant changes in the production and service processes. New technologies, tools and solutions make it possible to transform conventional systems into cyber-physical systems, where the problems of disrupted supply chain solutions can be solved. Within the frame of this article, the author focuses on the new supply chain solutions based on consignment storages and cross-docking facilities. The author demonstrates the optimization potentials of consignment storage-based supply chain solutions and describes the impact of multi-level cross-docking facility-based supply chain solutions on the efficiency of logistics processes. The described models and methods validate the importance of consignment storages and cross-docking facilities in supply chains, especially in the case of just-in-time and just-in-sequence supply.*

Key words: *logistics, supply chain, consignment storage, cross-docking, optimization.*

1. INTRODUCTION

The fourth industrial revolution makes it possible to improve conventional solutions of production and services. These technologies can be used to improve the performance of supply chain solutions. The most important fields of supply chain management include consignment contracts, vendor managed inventories and cross-docking facility-based supply. These solutions are especially important in the automotive industry, where just-in-time and just-in-sequence supply is used.

This paper is organized as follows. Section 2 presents a short literature review, section 3 describes the model framework of vendor managed inventory problems with consignment contract and the just-in-sequence supply based on crossdocking. Section 4 demonstrates the scenario analysis. Conclusions and future research directions are discussed in Section 5.

2. LITERATURE REVIEW

The consignment stock policy can be analyzed in the case of different supply chain solutions from single-echelon production supply to integrated closed-loop supply chain. In an integrated closed-loop supply chain a wide range of optimization aspects (objective functions) can be taken into consideration, including the sequencing problems of production processes, scheduling of shipments, batch size optimization and cost reduction [1].

There are different solutions to improve the efficiency of purchasing and inventory management processes. One interesting approach focuses on the coordinated inventory sharing. This solution can lead to reduced amount of return to the dealer. The numerical analysis of a common dealer and two independent retailers’ framework shows, that a coordinated methodology to manage the retailers' sharing and return action can significantly increase the profit on both sides. In a coordinated inventory sharing problem, the retailers' sharing decisions have great impact on the performance of the inventory and purchasing processes under consignment contracts [2].

Researches validate that the vendor managed inventories with consignment contract can be optimized using a two-phase methodology. The first phase is the computation of the consignment price and the economic order quantity using a suitable inventory optimization algorithm to maximize the expected profit of the vendor, while in the second phase the retail price is defined with the objective to maximize the profit of the retailer. Research results show, that it is possible to find an optimal solution of this vendor managed inventory problem constrained by a consignment contract [3]. In this two-phase methodology, the retailer managed consignment inventory and the vendor managed consignment inventory are defined. In this optimization methodology, the vendor chooses the consignment inventory, which defines the expected service level and the supplier is responsible for the fulfillment of this service level. The optimization of vendor managed inventory with consignment contract can be influenced by a wide range of constraints, which are generally based on the production master plan and the production distribution cycle. The consignment inventory problems can be used in the case of both conventional supply chain solutions and in the case of just-in-time and just-in-sequence supply, where both centralized and decentralized methods are available for the optimization [4]. The centralized methods are usually based on centralized consignment stock agreement [5]. Not only technological, but also logistics-related constraints are also important influencing factors of vendor managed inventory problems, including time-windows and capacities [6]. The complexity of vendor managed inventory problems with consignment contract represent NP-hard optimization problems, where the solutions are generally based on simulation and heuristic algorithms [7]. The research of cross-docking facility-based supply problems covers the following topics: vehicle routing, inventory control, scheduling, warehousing, and distribution [8].

Based on this short literature review, the main contribution of this article is the description of the IoT supported model framework of vendor managed inventory problems with consignment contract and the just-in-sequence supply based on crossdocking.

3. MODELS AND METHODS

Within the frame of this chapter, two main streams of supply models of disrupted supply chain solutions are described. The first model focuses on the vendor managed inventories with

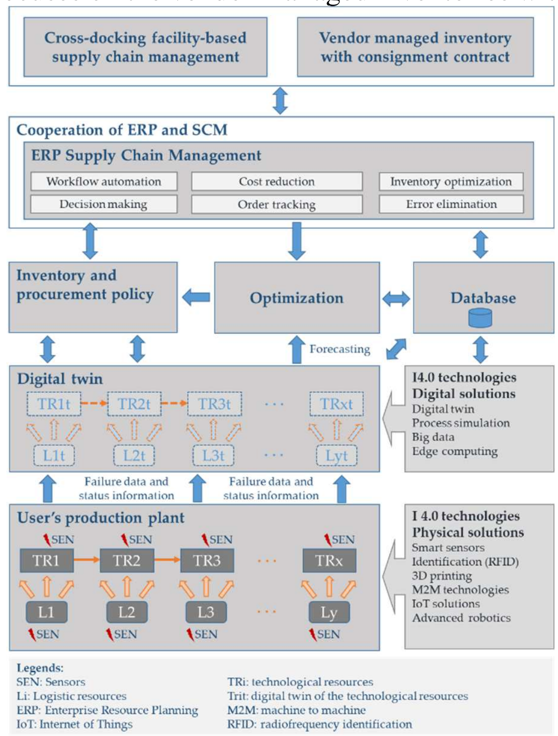

Fig. 1. Cyber-physical supply chain management model in the case of vendor-managed inventory with consignment contract and in the case of cross-docking facility-based just-in-sequence supply.

consignment contract, where the focus is on the analysis of profitability of the supply solution for all players of the supply chain including users and suppliers. The second model discusses the potential of cross-docking facilities, which can improve the flexibility of both conventional and just-in-time supply solutions. Figure 1 shows the framework of the mentioned two supply chain solutions, where the conventional processes of supply chain solutions are transformed into a cyber-physical system using Internet of Things technologies.

3.1 Inventory model with consignment

Within the frame of this chapter, the mathematical model of the vendor managed inventory problems with consignment contract is defined. The explanation of variables is shown in table 3. The model is a single-user single supplier model. The supplier's cost can be defined as follows:

$$C^S = C_m^S + C_t^S + C_w^S + Z^S + Z^U. \quad (1)$$

The manufacturing cost is lower in the case of consignment contract-based supply, because the supplier has less strict time- and capacity-related constraints, as in the case of conventional supply, and it can be defined as follows:

$$C_m^S = \frac{Q}{q} k_{ms} + Q \frac{k_m}{\delta^{\alpha\left(\frac{q}{Q}\right)}}. \quad (2)$$

The transportation cost depends on the average order quantity, demand for the predefined time-window, specific transportation cost, and the specific start-up cost of one transportation:

$$C_t^S = \frac{Q}{q} k_{tsu} + Q k_t. \quad (3)$$

The cost of capital based on the stored inventory at the supplier's warehouse as a conventional inventory can be defined depending on the average warehousing time and specific cost of capital as follows:

$$Z^S = \frac{365q}{2} \vartheta^S, \quad (4)$$

The cost of capital based on the stored inventory at the user's warehouse as a consignment inventory can be defined in the same way:

$$Z^U = \frac{365q}{2} \vartheta^U. \quad (5)$$

The warehousing cost of the supplier can be defined as follows:

$$C_w^S = \frac{365q}{2} k_w + k_w^*. \quad (6)$$

The user's cost is defined by the purchasing cost, because transportation and inventory costs are paid by the supplier:

$$C^U = Q\left(p^* + p^{\beta\left(\frac{q}{Q}\right)}\right). \quad (7)$$

3.2 Cross-docking-based supply

The application of cross-docking facility-based supply solution makes it possible to perform cost-efficient just-in-sequence supply, because the cross-docking facilities can integrate a wide range of logistics operations including packaging, quality control and sequencing. In this chapter, a model framework of a multi-level cross-docking facility-based supply solution is described. The objective function of the design and optimization is the minimization of the total cost:

$$C = C^M + C^T + C^W + C^{SEQ}. \quad (8)$$

Within the frame of this article, the focus of the optimization is on the transportation cost, which can be defined in three phases. The first phase is the transportation between suppliers and cross-docking facilities:

$$C^{T1} = \sum_{j=1}^{n} \sum_{i=1}^{m} C_{S_j \to CD_i}^T (\Phi_\mathrm{i}, \mathrm{CAP}). \quad (9)$$

The second phase is the transportation between different levels of cross-docking facilities:

$$C^{T2} = \sum_{i=1}^{m} \sum_{p=1}^{m} C_{CD_i \to CD_p}^T \left(\Phi_\mathrm{ip}, \mathrm{CAP}\right). \quad (10)$$

The third phase is the transportation between cross-docking facilities ad users:

$$C^{T3} = \sum_{i=1}^{m} C_{CD_i \to C}^T (\Phi_\mathrm{i}, \mathrm{CAP}). \quad (11)$$

The material handling cost can be determined in the same way. In the case of a cyber-physical cross-docking facility-based just-in-sequence supply, all real time information is available to make real-time decision, by the aid of which it is possible to optimize the operational cost, while the service level is also increased.

4. RESULTS

Within the frame of this chapter, the computational results of the above mentioned mathematical models of consignment contract-based vendor managed inventory and cross-docking facility-based supply are discussed.

4.1 Inventory model with consignment

In the case of conventional vendor-managed supply models, the consignment contracts represent a non-flexible environment for both the suppliers and the users, where the dynamically changing conditions of the production, purchasing and distribution are not easy to be taken into consideration. The application of Internet of Things makes it possible to transform conventional vendor managed supply chain solutions into cyber-physical supply solutions, where digital twin, cloud computing, RFID and other Industry 4.0 technologies can lead to a more flexible supply chain. In this new solutions, through a flexible consignment frame contract a flexible and for both party profitable supply can be performed. Figure 2 shows this profitability problem in the case of conventional supply, where depending on the average order quantity, different profits are available for both the supplier and the user. It is important to find the optimal average order quantity, where the supply is profitable for both party.

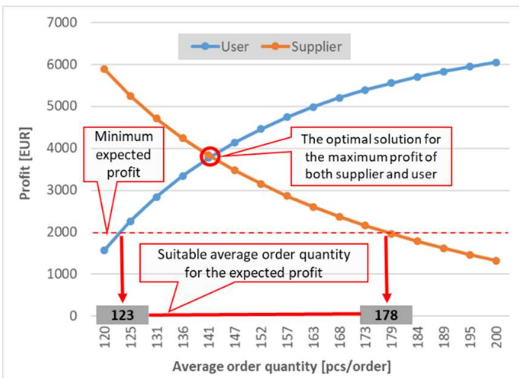

Fig. 2. Impact of the average order quantity on the profit of both the user and the supplier without consignment store.

In the case of consignment contract-based vendor managed inventory, the specific purchasing cost has a great impact on the profit of supplier and user. It is possible to find a lower and upper limit, and between these two limits the supply chain is profitable for both party. It is also possible to optimize the supply chain to reach a maximum profit. The impact of the specific purchasing cost on the profit of suppliers and users is shown in figure 3.

One of the most important influencing factor of vendor managed inventory problems is the lowest contracted consignment inventory. Figure 4 shows the impact of the lowest contracted consignment inventory on the profit of both parties.

It is possible to find the optimal solution, which has the maximum profit for both the supplier and the user. We can also define the lower and upper limit of the profitable lowest consignment inventory for both the supplier and the user.

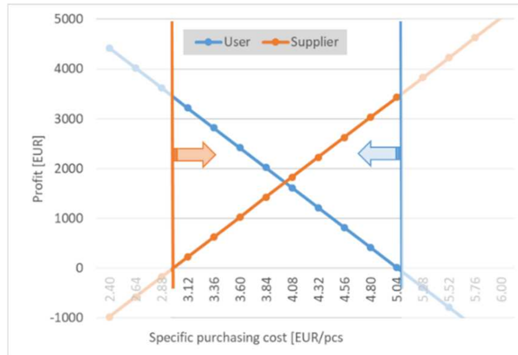

Fig. 3. Impact of the specific purchasing cost on the profit of both the user and the supplier.

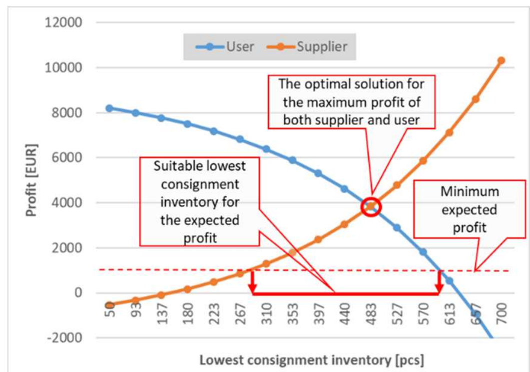

Fig. 4. Impact of the contracted lowest consignment inventory on the profit of both the user and the supplier with consignment store.

There are different cost sharing models, which can be analyzed. In the case of vendor managed inventory with consignment contract, the investment and operation cost of the warehouse for consignment inventory represents one of the most important costs. The different cost sharing models significantly influence the expected profit of both suppliers and users, and the suitable window for each decision variables can be defined depending on the cost sharing model. Figure 5 shows an example, where the lowest contracted consignment inventory is the decision variable, and the window for this parameter is different in the case of two cost sharing models, while in the case of the third cost sharing model (where all costs are paid by the user) no optimal solution can be found for both parties.

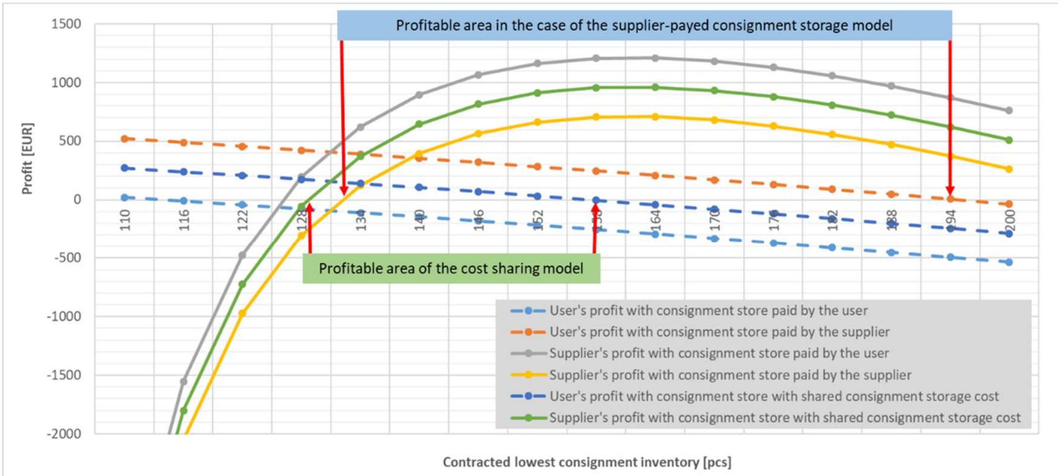

Fig. 5. Comparison of the different cost models of consignment storage-based supply solutions depending on the order quantity.

Based on the results demonstrated in figure 5, figure 6 shows the profit of both the supplier and the user depending on the specific initial purchasing cost and the yearly cost of investment and operation of the warehouse for consignment inventory. The analysis validated, that the investment and operation cost has a great impact on the flexibility of the operational strategy. It means, that lower investment and operation cost of warehouse for consignment store lead to a more flexible operation strategy, which is very important in the case of cyber-physical vendor managed inventory management, where the applied IoT solutions make it possible to optimize the consignment contract real-time.

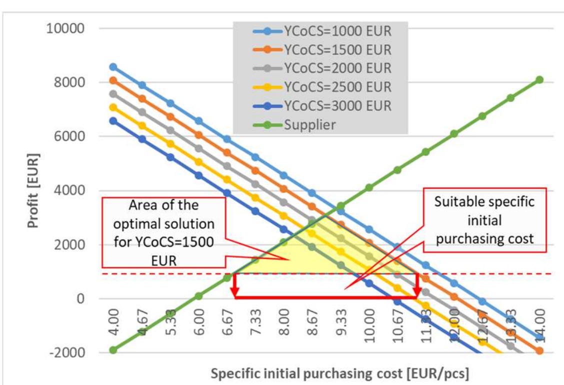

Fig. 6. Impact of the specific purchasing cost and the yearly cost of consignment store (YCoCS) on the profit of both the user and the supplier (the cost of the consignment store is paid by the user).

As the above-mentioned scenario analysis shows, the application of IoT solutions can be integrated into a flexible consignment contract-based vendor managed inventory supply, which can significantly increase the cost-efficiency and flexibility of the whole supply chain.

4.2 Cross-docking-based supply

In the case of conventional direct supply, the users' demands are transported from the supplier to the user. Just-in-sequence supply makes it necessary to organize multi-level supply chain solutions, where the sequenced demands can be transported cost-efficient from the suppliers through cross-docking facilities to the users. The below described scenario analysis demonstrates, that a cross-docking facility-based multi-level supply can lead to decreased transportation cost, because the sequencing operations are allocated to the cross-docking facility, therefore the utilization of trucks can be significantly increased. In the analyzed scenario, the required sequenced components are defined for a 12 weeks long time-window.

In the first case of the scenario we can calculate the performance of the direct supply solutions. This calculation shows, that in the case of direct supply, the trucks performed 10772 km.

In the case of indirect supply, the suppliers transport the required components to the cross-docking facility, where sequencing operations are performed, and the sequenced demands are transported from the cross-docking facility to the user. This centralized transportation from the cross-docking facility to the user can significantly increase the utilization of transportation resources (trucks). Table 1 demonstrates the performed kilometers of trucks from cross-docking facility to the user.

Table 1

Length of transportation routes in the cross-docking facility–user relation in the case of a multi-level cross-docking-based supply.

Time-window	Total quantity	Number of trucks	km
1	488	3	603
2	361	2	402
3	351	2	402
4	382	2	402
5	298	2	402
6	377	2	402
7	397	2	402
8	175	1	201
9	284	2	402
10	388	2	402
11	398	2	402
12	387	2	402
		Total	**4824**

Table 2 shows the length of transportation routes among suppliers and cross-docking facility.

Table 2

Length of transportation routes in the supplier–cross-docking facility relation in the case of a multi-level cross-docking-based supply.

Time-window	ID_01	ID_02	ID_03	ID_04	ID_05	ID_06
1	0	0	30	12	7	26
2	25	40	30	12	7	26
3	25	40	30	12	7	26
4	25	40	30	12	0	0
5	0	40	30	12	7	26
6	25	40	30	12	0	0
7	0	40	30	12	7	0
8	0	40	0	12	7	26
9	0	40	0	12	7	26
10	0	40	30	12	7	0
11	0	40	30	12	7	0
12	25	0	30	12	7	26
					Total	**1221**

As the numerical results show, the cross-docking facility-based just-in-sequence supply can lead to a transportation cost reduction of about 44%. The analysis of the position of cross-docking facility shows, that cross-docking facilities must be located near the suppliers, especially in the case of just-in-sequence supply, because in this case more savings can be realized than in the case of cross-docking facilities near the users.

The system parameters and the parameters of the used resources significantly influence the impact of the resources and operation strategies

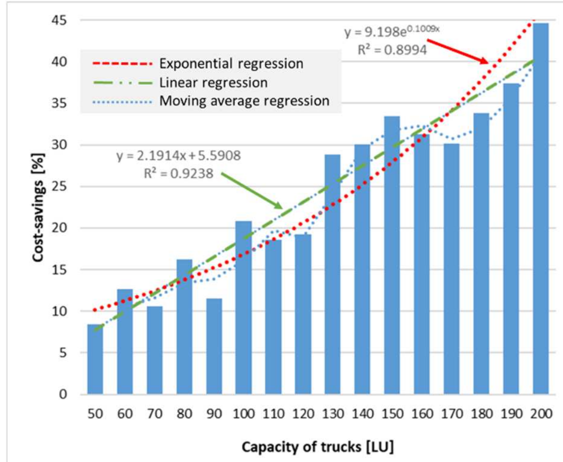

Fig. 7. Impact of the capacity of trucks on the savings in the case of cross-docking facility-based just-in-sequence supply.

on the cost savings and performance. As figure 7 shows, the capacity of the trucks influences the expected cost savings. It means, that depending on the expected scheduling and quantity of just-in-sequence demands, the required transportation resources can be optimized in order to improve the performance and reduce transportation costs, while the utilization of the trucks can be significantly increased.

The analysis of the impact of the capacity of trucks on the utilization of trucks shows, that however the capacity of trucks influences the utilization, but there is no clear relationship between the two parameters. In figure 8 the red columns show examples for local optimum solutions, where the utilization of the trucks is

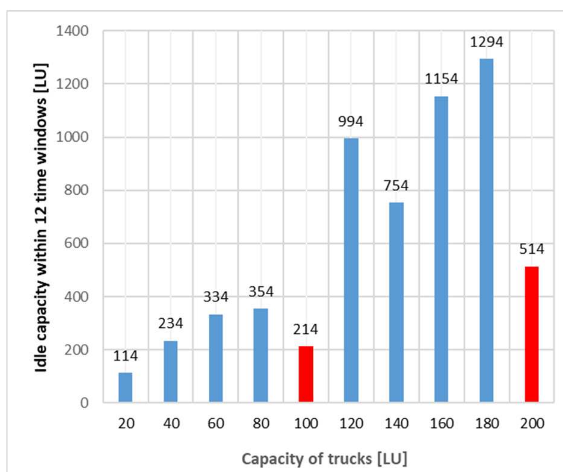

Fig. 8. Impact of the capacity of trucks on the idle capacity in the case of cross-docking facility-based just-in-sequence supply.

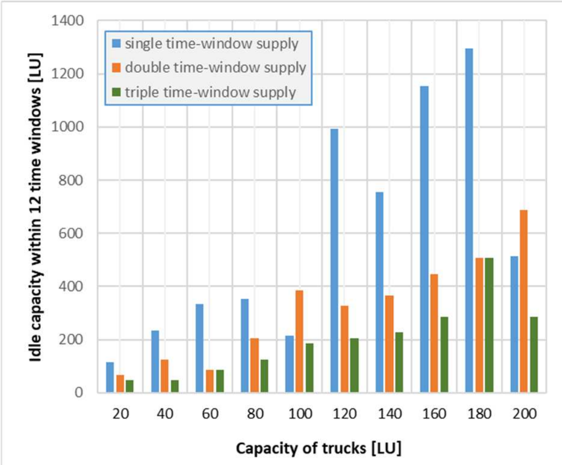

Fig. 9. Impact of the intensity of transportation of just-in-sequence demand from the cross-docking facility to the user on the utilization of transportation resources.

than in the case of both neighbor solutions.

As figure 9 shows, the intensity of the transportation of sequenced just-in-sequence supply demands also influence the utilization of transportation resources.

This analysis shows, that the parameters of the just-in-sequence supply system significantly increases the utilization and the performance of the system, therefore the transformation of the conventional supply chain into a cyber-physical supply chain can improve utilization and performance, because using IoT technologies real-time decision making can be performed.

5. CONCLUSION

Industry 4.0 technologies make it possible to transform conventional production and service processes into a cyber-physical system, where using Internet of Things technologies it is possible to make real-time analysis of the status of the processes. Based on the results of the analysis, the real-time decision making can lead to increased performance and decreased operational cost. In this paper two models of transformed supply chain solutions were discussed. The analysis of the vendor managed inventory with consignment contract and the cross-docking facility-based just-in-sequence supply shows, that Internet of Thing technologies can improve the performance of these supply solutions.

6. VARIABLES OF THE MODELS

The used variables of the models are summarized in table 3.

Table 3

Description of variables.

Variable	Description	Unit
C^S	cost of the supplier	[USD]
C_m^S	manufacturing cost of the supplier	[USD]
C_t^S	transportation cost of the supplier	[USD]
C_w^S	warehousing cost of the supplier	[USD]
Z^S	cost of capital based on the stored inventory at the supplier's warehouse as a conventional inventory	[USD]
Z^U	cost of capital based on the stored inventory at the user warehouse as a consignment inventory	[USD]
Q	demand within the predefined time-window	[pcs]
q	optimal order quantity of the user	[pcs]
k_{ms}	specific start-up cost of manufacturing, which depends on the lot size of production	[USD]
k_m	initial specific manufacturing cost	[USD]
δ	production quantity dependent factor, which describes the impact of the manufacturing lot sizes on the manufacturing cost	[-]
α	factor, influencing the impact of manufacturing lot size and number of start-ups on the specific manufacturing cost	[-]
k_{tsu}	specific start-up cost of transportation	[USD]
k_t	specific transportation cost of one unit	[USD]
ϑ^S	rate of interest at the supplier	[%]
ϑ^U	rate of interest at the user	[%]
k_w^*	initial specific warehousing cost, which is not influenced by the inventory	[USD]
k_w	specific warehousing cost	[USD]
p^*	initial purchasing cost of the products	[USD]
p	specific purchasing cost, which influences the real purchasing price depending on the order quantity	[USD]
β	factor influencing the purchasing cost depending on the order quantity and demand	[-]
C^M	cost of material handling	[USD]
C^T	cost of transportation between suppliers, cross-docking facilities and users	[USD]
C^W	warehousing cost	[USD]
C^{SEQ}	sequencing cost of components required by the user	[USD]
C^{T1}	transportation cost between suppliers and cross-docking facilities	[USD]

$C^T_{S_j \to CD_i}$	transportation cost between supplier *j* and cross-docking facility at level *i*	[USD]
Φ_i	set of products required by the users transported to cross-docking facility at level *i*	[-]
CAP	capacity of the transportation vehicles	[pcs]
C^{T2}	transportation cost between the levels of cross-docking facilities	[USD]
$C^T_{CD_i \to CD_p}$	transportation cost between cross-docking facility at level *i* and *p*	[USD]
Φ_{ip}	set of products transported between cross-docking levels	[-]
C^{T3}	transportation cost between cross-docking levels and users	[USD]
$C^T_{CD_i \to C}$	transportation cost between cross-docking facilities at level *i* and users	[USD]

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NOI MODELE ȘI METODE PENTRU LANȚURILE DE APROVIZIONARE PERTURBATE ÎN ERA INDUSTRIEI 4.0

Cea de-a patra revoluție industrială a condus la schimbări semnificative în procesele de producție și de servicii. Noile tehnologii, instrumente și soluții fac posibilă transformarea sistemelor convenționale în sisteme ciber-fizice, în care pot fi rezolvate problemele legate de întreruperea lanțurilor de aprovizionare. În cadrul acestui articol, autorul se concentrează asupra unor noi soluții pentru lanțurile de aprovizionare bazate pe depozite de tip consignație și pe facilitățile distribuției directe – tip cross - docking. Autorul demonstrează potențialul de optimizare a modelului de lanț de aprovizionare bazat pe depozite de tip consignație și descrie impactul modelului de lanț de aprovizionare bazat pe facilități de distribuție directă pe mai multe niveluri asupra eficienței proceselor logistice. Modelele și metodele descrise validează importanța depozitelor de tip consignație și a facilităților de distribuție directă în lanțurile de aprovizionare, în special în cazul aprovizionării just-in-time și just-in-sequence.

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