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ORIGINAL PAPER

A RANDOM SEARCH ALGORITHM FOR CYCLIC DELIVERY SYNCHRONIZATION PROBLEM

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ABSTRACT. **Background:** The paper is devoted to the cyclic delivery synchronization problem with vehicles serving fixed routes. Each vehicle is assigned to a fixed route: the series of supplier's and logistic centers to be visited one after another. For each route the service frequency is fixed and known in advance. A vehicle loads at a supplier's, then it delivers goods to a logistic center and either loads other goods there and delivers them to the next logistic center along the route or goes to another logistic center. Each logistic center can belong to several routes, so goods are delivered there with one vehicle and then they departure for the further journey with another truck. The objective of this cyclic delivery synchronization problem is to maximize the total number of synchronizations of vehicles arrivals in logistic centers and their load times, so that it is possible to organize their arrivals in repeatable blocks.

Methods: Basing on the previously developed mathematical model for the cyclic delivery synchronization problem we built a random search algorithm for cyclic delivery synchronization problem. The random heuristic search utilizes objective-oriented randomizing. In the paper the newly-developed random search algorithm for cyclic delivery synchronization problem is presented.

Results: A computational experiment consisted of employing the newly-developed random search algorithm for solving a series of cyclic delivery synchronization problems. Results obtained with the algorithm were compared with solutions computed with the exact method.

Conclusions: The newly-developed random search algorithm for cyclic delivery synchronization problem gives results which are considerably close to the ones obtained with mixed-integer programming. The main advantage of the algorithm is reduction of computing time; it is relevant for utilization of this method in practice, especially for large-sized problems.

Key words: cyclic delivery synchronization n problem, mixed-integer programming, optimization, heuristic algorithms, random search.

INTRODUCTION

Internal logistics management system controls processes of handling, loading and discharging goods as well as document circulation. Logistic centers are interested in making warehousing and inventory management as efficient as possible, so that utilization rate of storage areas can increase, inventory costs can decrease, and level of customer service quality can significantly raise. The ways to obtain these goals are: shortening time of receipting and dispatching operations, speeding-up handling operations, eliminating or reducing bottlenecks in handling and warehousing processes [Gudehus and Kotzab 2009, Raa 2014, Mirzapour Al-e-hashem and Rekik 2014, Raa 2015] as well as route and fleet designing and re-designing [Raa and Dullaert 2017].

In general, the objective of the cyclic inventory routing problem is to compose multiple trips which serve all customers and minimize the combination of transportation, inventory and vehicle costs, in a cyclic distribution pattern [Chitsaz et al. 2016]. In a system with cyclic distribution patterns, where deliveries are performed repeatedly

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along fixed routes with fixed frequencies, synchronization of vehicles at logistic centers becomes even more important. Such deliveries are common in food industry, where perishable goods are delivered to customers along fixed routes on regular basis [Akkerman et al. 2010, Azadeh et al. 2017]. The problem is getting more and more important also in the health care sector [Ait Haddadene et al. 2016] as well as in manufacturing with automotive assembly lines where in-house transport of parts is needed [Emde and Gendreau 2017]. It is also to be observed is manufacturing and services where one supplier provides numerous customers with some products or services and the customers' demand is not high and it changes on the seasonal basis [Ching-Ter and Hsiao-Ching 2013, Ekici et al. 2014, Lee and Fu 2014]. Scheduling periodic services – e.g. waste collecting – is also an important problem in municipal services management [Kazan et al. 2012, Mes et al., 2014, Korcyl et al. 2016]. Cyclic deliveries play a significant role also in close-loop supply systems, where the provider needs to deliver new or refurbished products to a group of clients under a fixed cyclic schedule, and also collects back a random portion of the used products in the subsequent delivery cycle for refurbishment [De Giovanni et al. 2016, Huynh et al. 2016].

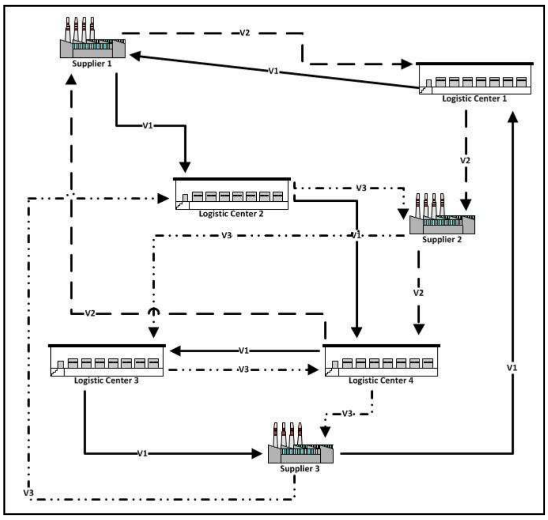
Synchronization of cyclic deliveries is crucial for supply chain management, where cargo needs to be trans-shipped and the problem becomes even more complicated when there are time windows for arrivals [Ulrich 2013] or some deliveries' departure times or arrival times are established in advance and cannot be changed [Leunga and Chen 2013, Zheng et al. 2015] or there is a need to minimize the number of vehicles serving the system [Campbell and Hardin 2005] or to minimize the total costs [Qin et al. 2014, Rad et al. 2014, Vansteenwegen and Mateo 2014, Lefever et al 2016, Laporte et al. 2017] or when a planner has to organize deliveries so that numerous different objectives are achieved in a system with time windows, synchronization and precedence conditions [Ait Haddadene et al. 2016, Laporte et al. 2017]. When some cargo needs to be trans-shipped or handled in a logistic center before the next part of its journey, it becomes crucial to synchronize arrivals of vehicles used for consecutive parts of the cargo's journey. Synchronization can result in reducing the amount of time needed for handling operations as well as in reducing the cargo's waiting time, so cargo can be temporarily stored in the storing area next to the loading ramp. The efficiency of the given loading ramp increases, because the loading ramp handling devices are calibrated once and they can be utilized both for unloading one vehicle and loading another [Groenevelt et al.1992, Kazan et al. 2012, Gdowska and Książek 2013, Gdowska and Książek 2015].

This paper is devoted to the cyclic delivery synchronization problem in a network of manufacturers' plants and logistic centers with vehicles serving fixed routes. The objective of the formulation of cyclic delivery synchronization problem, to which this paper refers, is to obtain such synchronization of vehicles arrivals in logistic centers and load time, so that it is possible to organize their arrivals in repeatable modules. The authors consider synchronization as a situation when the amount of time between arrivals of two vehicles serving different routes is in a predefined range. A mixed-integer programming (MIP) model was developed for the cyclic delivery synchronization problem with vehicles serving fixed routes [Gdowska and Książek 2015]. Cyclic delivery scheduling problem belongs to NP-hard problems [Groenevelt et al.1992, Raa and Dullaert 2007], so it is not possible to obtain optimal solution for medium-sized and large-sized problems with exact methods. Therefore, there was a need to develop a heuristic algorithm for the cyclic delivery scheduling problem, so that we can obtain feasible solutions for a problem of any size.

The objective of research to which this paper refers was to develop a heuristics for solving the cyclic delivery synchronization problem with medium and large data sets in considerably short time. Real cyclic delivery synchronization problems usually require medium and large data sets. Newly developed random algorithm for this problem makes it possible to find feasible solution quickly, so that a decision-maker is able to compare solutions obtained for different configurations. In this paper a newly-developed random search algorithm for the cyclic delivery scheduling problem is presented. The algorithm was employed for solving a selection of problems – in the paper computational experiments are presented and obtained results are reported. A series of random data sets was generated and used in computational experiments. The quality of solutions obtained for them with heuristics algorithm was compared with the ones found with exact method.

CYCLIC DELIVERY SYNCHRONIZATION PROBLEM – A BRIEF DESCRIPTION AND A MIXED INTEGER PROGRAMMING MODEL

Detailed description of the cyclic delivery synchronization problem was presented in the previous works of the authors [Gdowska and Książek 2013, Gdowska and Książek 2015]. Here we provide essential assumptions adopted in this approach to the cyclic delivery synchronization problem. Each vehicle is assigned to one route to which suppliers and logistic centers belong; logistic center can be a trans-shipment node for one route as well as a final customer for another. A vehicle is loaded at a supplier's, then delivers cargo to a series of logistic centers and finally goes back to the supplier's. Routes are fixed and known in advance as well as delivery size. For every route the interval between departures of consecutive vehicles from the supplier's is fixed and known. the scheme of the problem is presented in the Figure 1.



Source: Gdowska and Książek 2015

Fig. 1. Scheme of a network where synchronization of cyclic deliveries to logistic centers is needed
Rys. 1. Schemat sieci w której występuje potrzeba harmonogramowania dostaw cyklicznych do centrów przeładunkowych

In the MIP model the objective is to maximize the number of synchronizations in the system. Synchronization of two vehicles serving different routes is achieved in node b when the interval between arrivals of these vehicles in node b are in the range (w_b; W^b). Two types of decision variables were utilized: continuous non-negative variable X_{ip} – the departure time of the p-th delivery of i-th route, and binary variable Y_{ijbpq} – it stands for the existence or nonexistence of synchronization between every pair of arrivals of vehicles serving different routes at the node b. Notation used in the MIP model for the cyclic delivery synchronization problem is presented in Table 1 and the model is presented in Table 2.

Due to the fixed routes and desirable synchronization of arrivals at nodes shared by different routes this approach to the cyclic delivery synchronization problem is similar to an approache to the bus timetabling synchronization problem [Ceder et al. 2001, Eranki 2004, Ibarra-Rojas and Rios-Solis 2012,] the MIP model for cyclic delivery synchronization problem [Gdowska and Książek 2015] was based on the BTP model [Ibarra-Rojas i Rios-Solis 2012].

Table 1. Notation used in MIP model for the cyclic delivery synchronization problem
Tabela 1. Oznaczenia zastosowane w modelu programowania całkowitoliczbowego mieszanego dla problemu synchronizowania cyklicznych dostaw

Sets:	
I	– set of routes
B	– set of nodes (logistic centers)
J^{ij}	– set of pairs <i, j>, where i-th and j-th routes share a node
S^{ijb}	– set of triples <i, j, b> where i-th and j-th routes share b-th node
Parameters:	
T	– planning horizon, that is the period during which all the deliveries must departure from the first nodes of their routes
fr_i	– the number of the deliveries to be scheduled for the i-th route
H_i	– fixed headway of the i-th route
t_{ib}	– travel time between the first node of the i-th route and the b-th node
w_b	– lower limit of the synchronization range in the b-th node
W_b	– upper limit of the synchronization range in the b-th node
M	– big number
Decision variables:	
X_{ip}	– the departure time of the p-th delivery of i-th route; time variable (non-negative, continuous)
Y_{ijbpq}	Y_{ijbpq} = 1, if the p-th vehicle of i-th route arrives at b-th node before the q-th vehicle of j-th route and the interval between arrivals is in the range <w_b; W_b>; otherwise Y_{ijbpq} = 0

Source: Gdowska and Książek 2015

Table 2. Mixed-integer programming model for the cyclic delivery synchronization problem
Tabela 2. Model programowania całkowitoliczbowego mieszanego dla problemu synchronizowania cyklicznych dostaw

Objective functions:		
$\max \rightarrow \sum_{i \in I} \sum_{j \in I} \sum_{b \in B} \sum_{p \in F_i} \sum_{q \in F_j} Y_{ijbpq}$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j$	(1)
Constraints:		
$X_{i,1} \le H_i$	$i \in I$	(2)
$X_{i,fr_i} \le T$	$i \in I$	(3)
$X_{i,p+1} - X_{ip} = H_i$	$i \in I, 1 \le p \le fr_i - 1$	(4)
$(X_{jq} + t_{jbq}) - (X_{ip} + t_{ibp}) \le W_b + M*(1 - Y_{jibqp})$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j$	(5)
$(X_{jq} + t_{jbq}) - (X_{ip} + t_{ibp}) \ge w_b - M*(1 - Y_{jibqp})$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j$	(6)
$Y_{ijbpq} \le 1 - Y_{jibqp}$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j, <i, j, b> \in S^{ijb}$	(7)
$Y_{ijbpq} = 0$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j, <i, j, b> \notin S^{ijb}$	(8)
$X_{ip} \in \{0,1,...T\}$	$i \in I, p \le fr_i$	(9)
$Y_{ijbpq} \in \{0,1\}$	$i, j \in I; b \in B; 1 \le p \le fr_i; 1 \le q \le fr_j$	(10)

Source: own work based on the BTP model [Ibarra-Rojas and Rios-Solis 2012, Gdowska and Książek 2015]

RANDOM SEARCH ALGORITHM FOR THE CYCLIC DELIVERY SYNCHRONIZATION PROBLEM

Basing on the MIP model presented in the previous section a random search algorithm was developed as there was a need for a tool applicable for medium-sized and large-sized problems. Random heuristic search is a well-known abstract search method which is instantiated to particular search methods with remarkable success [Vose 1999].

Let M be the set of routes for which departure time of the very first vehicle have been defined. Let P^i denote the set of nodes belonging to the i-th route. Let s_i denote weight used for determining probability of choosing i-th route. The value of the i-th route's weight is computed as a number of nodes shared by the i-th route with other routes for which departure times of the very first vehicle have not been determined.

$$s_i = \sum_{j \in I, j \notin M, i \neq j} \left| P^i \cap P^j \right|, i \in I \qquad (11)$$

Let d_b be the weight used for determining probability of choosing b-th node. The value of the b-th node's weight is computed as a number of routes sharing the b-th node.

$$d_b = \sum_{j \in I} \left| \{b\} \cap P^j \right|, b \in B \qquad (12)$$

For weights s_j and d_b we determined decision criteria, respectively, Ω_j and β_b, for which we proportionally chose a route or a node, respectively. Decision criteria Ω_j and β_b, were constructed using random parameters, ε' (ε'') and σ' (σ''). When parameter ε' (ε'') equals 0, probability of choosing the worst (lowest) values of weights for routes (nodes) equals 0 as well. When the value of parameter ε' (ε'') increases, probability of choosing route (node) with the lowest weight also raises. When the value of random parameter σ' (σ'') increases, it becomes more likely to choose a route (a node) of higher weight.

$$\Omega_j = \left(s_j - \min(s_j) + \varepsilon'\right)^{\sigma'}, j \in I \qquad (13)$$

$$\beta_b = \left(d_b - \min(d_b) + \varepsilon''\right)^{\sigma''}, b \in B \qquad (14)$$

Randomize search algorithm works until the departure time of the very first vehicle for every route is set. With respect to determined decision criteria Ω_j and β_b, respectively, route i and node b are randomly chosen. If chosen node b belongs to the certain number of routes (node b belongs at least to one route) for which the departure time of the very first vehicle has been determined already, the departure time of the very first vehicle of the chosen route i is determined, so that it is involved in as many synchronizations as possible. Otherwise, the departure time of the very first vehicle of the chosen route i equals the frequency of i-th route (H_i). The newly-developed random search algorithm is presented in the Figure 2.

```
N = Null
Xj = Null for j∈I
random ε', ε'', σ', σ''
while |N| ≠ |I|:
        i = proportional random route for Ωj for j∈I
        b = proportional random node for βb for b∈P^i
        if b in {set of nodes for routes in set N}:
                select time R with highest number of synchronization in node b
                append item I to set N
                Xj= min(max(0, R - t_i,b), Hi)
        else:
                append item i to set N
                Xj= Hi
calculate objective function FC
```

Source: own work

Fig. 2. Scheme of the random search algorithm for cyclic delivery synchronization problem
Rys. 2. Schemat algorytmu losowego przeszukiwania dla problemu synchronizowania dostaw cyklicznych

COMPUTATIONAL EXPERIMENTS

Computations were conducted with a computer equipped with a processor Intel® Core™ i3 2.20 GHz and 4 GB RAM. Random search algorithm was implemented in programming language Python 2.7. Computations were conducted using compiler belonging to PyPy package.

All the data sets were solved with the random search algorithm for the same ranges of random parameters ε' (ε'') and σ' (σ''); the random parameters were generated with the uniform distribution. The ranges of parameters are presented in Table 3.

Table 3. Ranges of parameters used in computational experiments
Tabela 3. Zakresy parametrów użytych w eksperymentach obliczeniowych

Parameter	Range
ε'; ε''	[0; 1]
σ'; σ''	[0; 10]

Source: own work

For each data set the certain number of searches was performed with PyPy compiler using the newly-developed algorithm. Computation time was limited to 3 sec. (search was performed approximately 104 times). From the set of obtained solution the one with the highest number of synchronizations was selected. Detailed results for selected data sets are presented in Table 4. Solutions obtained with the newly-developed random search algorithm were compared with the optimal solutions obtained with the MIP model. Optimal solutions were found with solver GUROBI 6.0.4 with standard settings.

In Table 4 we present the selection of 15 data sets – the sets have different number of routes and nodes. It was possible to obtain optimal solutions for problems with 3 routes and 5 nodes. For problems with 20 routes were not solvable with solver GUROBI.

Table 4. Results of computational experiments
Tabela 4. Wyniki eksperymentów obliczeniowych

Data set	Number of nodes	Number of routes	Objective function – optimal	Objective function – heuristics	Optimization gap
1	7	3	45	34	0.32
2	7	3	62	59	0.05
3	7	3	51	40	0.28
4	7	3	73	64	0.14
5	7	3	87	73	0.19
1	10	5	112	101	0.11
2	10	5	194	186	0.04
3	10	5	257	218	0.18
4	10	5	270	259	0.04
5	10	5	203	184	0.10
1	30	20	----	2670	----
2	30	20	----	2748	----
3	30	20	----	2762	----
4	30	20	----	2407	----
5	30	20	----	2251	----

Source: own work

The newly-developed random search algorithm for the cyclic delivery synchronization problem is considerably simple, e.g. it does not "learn" anything. This is why we cannot expect the algorithm to find optimal solutions for every data set. Solutions found by the algorithm differ significantly from the optimal ones. Average optimization gap for problems with three and seven routes equals to 15 percent. We can assume that for problems with 20 routes we obtain results which are worse than the optimal ones by more than 15 percent. Nevertheless, the advantage of the introduced random search algorithm is short computing time which always ends with finding a feasible solution. Computing time does not get considerably longer as the problem size arises, so we are able to find solutions for problems which are too big for MIP methods.

CONCLUSIVE REMARKS

In this paper results obtained with the newly-developed randomize search algorithm for the cyclic delivery synchronization problem for selected data sets were presented. The heuristic was constructed with the aim of being as close as possible to the MIP model. Therefore obtained results can be considered as satisfactory despite considerably big optimization gap. A huge advantage of the algorithm is very short time of searching for solutions, even for medium-sized problems, for which it is impossible to obtain optimal solution with the MIP model. The random search algorithm presented in this paper can be used for finding quickly the initial solution for other more advanced heuristic algorithms which will generate solutions with the smaller optimization gap.

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WYKORZYSTANIE ALGORYTMU HEURYSTYCZNEGO DO ROZWIĄZANIA PROBLEMU SYNCHRONIZACJI DOSTAW CYKLICZNYCH DO CENTRÓW PRZEŁADUNKOWYCH

STRESZCZENIE. **Wstęp:** W pracy przedstawiono problem synchronizowania dostaw cyklicznych do centrów przeładunkowych. Dostawy realizowane są na stałych trasach: pojazd, obsługujący daną trasę ma dostarczyć towar do centrum przeładunkowego, załadować tam inny towar i przewieźć go do kolejnego punktu trasy lub wykonać pusty przejazd do punktu załadunku. Punktami synchronizacji obsługi tras są centra logistyczne, w których niejednokrotnie towar przywieziony przez jeden pojazd, wyrusza w dalszą drogę innym. Dostawy na każdej trasie realizowane są ze stałą częstotliwością. Trasy dostaw oraz ilości przewożonego towaru są znane. Celem w zadaniu synchronizacji dostaw cyklicznych jest maksymalizacja liczby synchronizacji przyjazdów i pobytu pojazdów w centrach logistycznych tak, aby możliwe było grupowanie ich obsługi w bloki rozładunkowo-załadunkowe.

Metody: Na podstawie opracowanego wcześniej modelu matematycznego dla problemu synchronizowania dostaw cyklicznych do centrów przeładunkowych został zbudowany algorytm heurystyczny poszukujący rozwiązań poprzez ukierunkowane losowanie. W artykule przedstawiono opracowany algorytm losowego przeszukiwania.

Wyniki: Eksperyment obliczeniowy polegał na rozwiązaniu zestawu zadań synchronizowania dostaw cyklicznych przy pomocy opracowanego algorytmu i porównaniu uzyskanych wyników ze znanymi rozwiązaniami dokładnymi.

Wnioski: Przedstawiony algorytm heurystyczny dla zadania synchronizowania dostaw cyklicznych pozwala na uzyskanie rozwiązań zbliżonych do wyników otrzymanych przy zastosowaniu modelu programowania matematycznego. Zaletą zastosowanego algorytmu jest znaczne skrócenie czasu poszukiwania rozwiązania, co może mieć znaczenie dla praktycznego wykorzystania zaproponowanej metody.

Słowa kluczowe: harmonogramowanie dostaw cyklicznych, programowanie całkowitoliczbowe mieszane, optymalizacja, synchronizacja, algorytmy heurystyczne

DIE INANSPRUCHNAHME DES HEURISTISCHEN ALGORITHMUS FÜR DIE LÖSUNG DES PROBLEMS DER SYNCHRONISATION VON ZYKLISCHEN LIEFERUNGEN ZU UMSCHLAGZENTREN

ZUSAMMENFASSUNG. **Einleitung:** In der Arbeit wurde das Problem der Synchronisation von zyklischen Lieferungen zu Umschlagzentren dargestellt. Die Lieferungen werden an festen Routen durchgeführt: ein Transportfahrzeug, das eine Route bedient, soll die Ware zum Umschlagzentrum liefern, dort eine andere Ware aufnehmen und zum nächsten Punkt an der Lieferstrecke transportieren oder eine Leerfahrt zum Verladungspunkt machen. Die Synchronisationspunkte werden von Güterverkehrszentren gebildet, in denen die mit einem Fahrzeug angelieferte Ware dann mehrfach mit einem anderen Fahrzeug weiter transportiert wird. Die Lieferungen werden bei jeder Durchfahrt mit fester Frequenz realisiert. Die Lieferungswege und Mengen von transportierten Waren sind bekannt.

Das Ziel der Synchronisation von zyklischen Lieferungen ist eine solche Maximierung der Synchronisation von Fahrzeugankünften und -aufenthalten in Güterverkehrszentren, dass eine Gruppierung deren Bedienung in Ver- und Entladungsblöcken möglich ist.
Methoden: Aufgrund eines früher vorbereiteten mathematischen Modells zur Synchronisation der zyklischen Lieferungen zu Umschlagzentren wurde der heuristische Algorithmus aufgebaut, der nach Lösungen mithilfe von gezielten Verlosungen sucht. In diesem Artikel wurde ein ausgearbeiteter Algorithmus zum gezielten Verlosen dargestellt.
Ergebnisse: Das Berechnungsexperiment beruhte auf der Lösung von Aufgaben der Synchronisation der zyklischen Lieferungen anhand des erstellten Algorithmus und auf dem Vergleich von gewonnenen Ergebnissen mit den bereits bekannten Lösungen.
Fazit: Der dargestellte heuristische Algorithmus zur Synchronisation von zyklischen Lieferungen erlaubt es, die dem mathematischen Modell ähnlichen Lösungen zu erzielen. Die Zeitverkürzung bei der Lösungssuche mit Hilfe dieses Algorithmus ist ein Vorteil, der eine große Bedeutung bei der Anwendung der vorgeschlagenen Methode haben kann.

Codewörter: Zeitplanung von zyklischen Lieferungen, die gemischt-ganzzahlige Programmierung, Optimierung, Synchronisation, heuristische Algorithmen

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