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ORIGINAL ARTICLE

A mathematical model and a heuristic approach for periodic material delivery in lean production environment

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Abstract One of the important design elements for a good production system is material handling. In cases where it is not well-designed, it can be the bottleneck in the system. Moreover, it can cause a lot of wastes such as waiting time, idle time, and excessive transportation and cost. In this study, material handling in lean-based production environments is taken into account. Depending on the lean structure of the production systems such as being pull-based, smooth, and repetitive, delivering the materials to the stations periodically becomes important. At this point, milk-run trains are highly used in real applications since they enable the handling of required amount of materials on a planned basis. With this study, it is aimed to develop a specific model for milk-run trains which travel periodically in the production environment on a predefined route in equal cycle times with the aim of minimizing work-in-process and transportation costs. Since the milk-run trains having equal cycle times start their tours at the same time intervals, it becomes simple to manage them. For this reason, they are used in lean production systems where level scheduling is performed. The developed model is based on mixed-integer linear programming, and since it is difficult to find the optimum solution due to the combinatorial structure of the problem, a novel heuristic approach is developed. A numerical example is provided so as to show the applicability of the mathematical model and the heuristic approach.

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1 Introduction

Choosing the most proper material handling equipment (MHE) and using it effectively are very important for eliminating material handling waste which is regarded as one of the seven wastes in the lean production system whose objectives are to improve quality, reduce time and cost, and increase organizational effectiveness [1, 2]. Hiregoudar and Reddy [3] state that material handling constitutes 25 % of the workers, 55 % of the factory area, and 87 % of the production time. In case a good material handling system design is accomplished, it is indicated that the cost will decrease by between 10 % and 30 % [4].

There is not a specific material handling system which is valid for all the production systems. According to the properties of the production environment, the most proper equipment can change. The approaches used for choosing the most proper equipment are mainly deterministic, probabilistic, and knowledge-based approaches [5]. There are a lot of studies dealing with choosing the most proper equipment using various decision making techniques [6–9]. The selection is made among the main material handling equipment types such as conveyors, cranes, industrial trucks, automated guided vehicles (AGVs), storage/retrieval systems, and industrial robots [10]. Moreover, specific studies can also be seen about routing and scheduling of these material handling systems such as AGVs and automatic storage and retrieval systems [11–14].

This study is not dealing with selecting the most proper MHE but deals with using a specific material handling equipment effectively in special conditions. A lean production environment is taken into consideration, and depending on the properties of such a production environment, such as smooth and repetitive production, it is seen that milk-run trains which are shown in Fig. 1 have started to get important in the real applications. Although milk-run approach is widely used for inbound and outbound logistics, there are few applications for production environment [15].

Milk-run trains can be regarded within periodically moving manual systems, and as Chase et al. [16] state, such systems provide a just in time working environment for the production systems. By using the milk-run trains in the lean production areas, as seen in the studies of Akillioglu et al. [17] and Domingo et al. [18], an important improvement in the material handling system is provided with respect to work in process (WIP) quantity, transportation cost, and utilization rate.

Besides other sectors, milk-run train applications especially take place in the sector of automotive industries [19–21]. Most of the observed cases in real production environments specifically in the automotive industries show that the milk-run trains have equal cycle times. That is, all of the milk-run trains in the production environment make their tours at the same time periods which provide an easier management. In this study, for the design of such a specific milk-run train system, a mixed-integer linear programming model is developed aiming to minimize mainly the WIP and transportation costs. Proper routes and time period are investigated. Because of the combinatorial structure of the problem, a novel heuristic approach is proposed as well. For showing the applicability of the mathematical model and the heuristic approach, a numerical example already in literature [15] is used.

The remainder of the article is organized as follows. Literature review is provided in "Section 2." "Section 3" includes the mixed integer linear programming model for milk-run trains having equal cycle times. In Section 4, the heuristic approach is provided. Numerical example is presented in Section 5, and finally, the conclusion part is included in Section 6 with the references following.

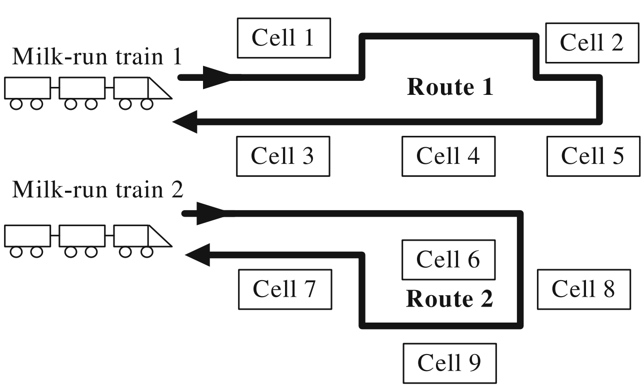


Fig. 1 Milk-run trains in the plant

2 Literature review

Since material handling is regarded as an integral part of the facility layout [22, 23], they are mostly considered together. Moreover, the design of milk-run distribution systems in the plants is also related with vehicle routing problems (VRP). There are so many studies about VRP, but few of them include routing problems in the production environment.

Regarding the VRP literature, it seems that there is a similarity between the milk-run problem in the production environment and the classical VRPs outside the plant in some ways. For instance, since both deliveries and pickups occur and the milk-run train is capacitated, this problem can be regarded as capacitated vehicle routing problem with pickups and deliveries. However, since it includes determining the quantities to be delivered, there seems a similarity with inventory routing problems. Despite some common points with other problems, Vaidyanathan et al. [24] state that it is different from the classical VRPs by having some distinctive properties such as the amounts required by the demand points are the functions of the vehicle feeding them. That is, the cycle time of the vehicles determines the quantity to be delivered. Moreover, the inventory related with cycle time, the relationship between the stations, limited stock areas, and multiple stock areas are the other factors that make the differences. Due to the explained differences, it is hard to model the milk-run problem in production environment with the existing methods used for inbound and outbound logistics [15].

Since the scope of this article is limited with in-plant logistics, the studies about the logistics including the VRPs outside the plant are not regarded. The selected studies which are especially related with in-plant logistics are as follows:

Rajagopalan and Heragu [25] presented a research framework in the areas of facility layout and discrete material handling system design for the aim of observing the trend in the literature. In their study, they tried to merge the fields of facility layout and material flow network designs. Sinriech and Samakh [26] developed a genetic approach for the pickup/delivery station location problem in segmented flow-based material handling systems. Vaidyanathan et al. [24] studied the VRP in just in time systems. Aiming to minimize the total trip time of the vehicles, they developed a nonlinear programming model. Due to the nonlinearity of the problem, they improved a heuristic solution procedure and a lower bound algorithm for comparing the results of the heuristic. Another heuristic procedure was developed by Hwang [27] to find the minimum number of transporters in a fixed facility layout with predetermined material flow paths. Similar to Vadiyanathan et al. [24], Akillioglu et al. [17] developed a model for lean production environment. With the mixed-integer linear programming model they developed, improvements in some of the lean metrics such as transportation and WIP costs are provided. In addition to the model, they also made a simulation study for the production environment. Domingo et al. [18] constructed a milk-run distribution system in a real lean manufacturing environment. Their application results showed that dock-to-dock time and cycle times were decreased, and moreover, unnecessary inventories, excessive transportation, and idle times were reduced. Costa et al. [28] presented a material delivery system simulation using a logistics train in an electronic company. According to the experimental results, it was shown that periodically moving train had financial advantages. Kilic et al. [15] classified the milk-run problems in plants and developed models for one specific category in their classification scheme. Within the category, they developed models for one routed and multiple routed vehicles traveling in determined time periods. They provided a numerical example to show the applicability of the models. Satoglu and Sahin [20] proposed a non-linear mathematical model for a just-in-time periodical material supply system and developed a heuristic algorithm for the related model. Golz et al. [19] proposed a heuristic solution approach to minimize the required number of shuttle drivers at high variant mixed model assembly lines. The proposed heuristic approach consists of two stages. Within the first stage, transportation orders are obtained from the given assembly sequence and in the second stage, the assignment of these orders to the tours of shuttle system is performed by considering constraints such as transportation capacity, due dates, and tour scheduling.

Regarding the literature, it is concluded that the studies are limited about the modeling of periodically moving vehicles in lean production systems. With this study, differently from the existing studies, a mathematical model is developed for a specific type of milk-run problem. The developed model consists of milk-run trains having equal cycle times. Moreover, a novel heuristic approach is developed for the first time for the related type of problem.

3 A mixed-integer linear programming model for milk-run trains having equal cycle times

The milk-run system in the plants consists of periodically moving trains in the production environment. The train starts its tour from the material depot and visits the assigned stations on its route in specified time intervals. The train not only drops off the materials but can also pick up the materials from the stations and take it to the related station or assembly lines. At the end of its tour, it returns the material depot again and repeats the same movement periodically. The required loading–unloading activities are performed at the depots and stations. It is aimed to minimize the cost including WIP and transportation which are the two main resources of waste. By reducing the WIP, the capital spared for it will be free and less floor space will be used. At the same time, the problems hiding with high WIP can begin surfacing. These are the opportunities to improve the systems. On the other hand, delivering the materials less frequently will decrease the transportation costs. The optimum values minimizing the total cost are searched via the proposed model. However, a tradeoff occurs between these two cost variables as shown in Fig. 2, that is, if the number of tours decreases, quantity of WIP increases and vice versa.

To apply milk-run distribution system, the production environment must be smooth and repetitive. That is, it must be lean. To construct a milk-run distribution system, two main design parameters are needed. These are the routes of the vehicles and time periods of the vehicles' tours. In this study, a mathematical model is developed for the milk-run trains having equal tour periods. As seen in some of the lean production applications, milk-run trains having the same tour cycle time enable an easier management. While developing the mathematical model, it is benefited from the studies of Kilic et al. [15] and Akillioglu et al. [17]. Similar indices and abbreviations indicated in the study of Kilic et al. [15] are used in the proposed mathematical model which is originally developed according to the specific conditions mentioned in this study. Mixed-integer linear programming model which is widely used also in different fields [29] is used for choosing the routes and their time periods. For this aim, first of all, probable routes are determined mainly regarding the physical conditions and product flow. The steps for determining the routes are explained in detail in the further parts within the procedure for route construction. Among these probable routes, the most proper ones optimizing the objective function and satisfying the constraints are chosen. Assumptions and the model are as follows:

Assumptions

- A pull-based lean production environment is considered.
- Production is repetitive and smooth.
- No change is made to the layout. The system design is made according to the existing layout.

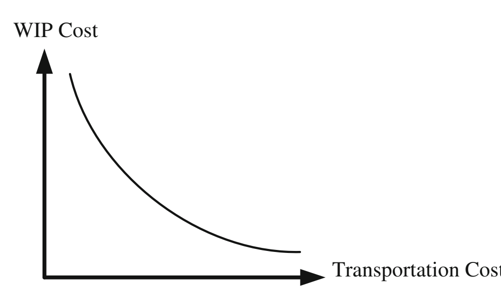


Fig. 2 Relationship between WIP and transportation cost

- Each stock point corresponds to a material; the demand/supply rate of each stock point is constant.
- The material handling within the cells is not considered. The material handling in the input and output stock areas of the cells is regarded.
- The speed of the milk-run train is constant.
- There are no traffic problems during the movements of the milk-run trains.
- The cost of each milk-run train tour is constant.
- No vehicle breakdown happens during the tours.
- Identical vehicles are used in the model.

Subscripts

i, j	Stock points
a, b	Stock areas (Stock points in a specific place make up a stock area)
r	Route or vehicle
t	Time period
s_r, ss_r	The assignment order of stock points that can be allocated to route "r"

Decision variables

$route_r$	Route "r" is chosen or not chosen (1 or 0)
X_{ir}	Stock point "i" is assigned or not assigned to the route "r" (1 or 0)
S_{ir}	The quantity of the safety stock of the stock point "i" that is assigned to the route "r"
D_{ir}	One cycle demand quantity of the stock point "i" that is assigned to the route "r"
L_{ir}	One cycle loading-unloading time of the stock point "i" that is assigned to the route "r"
Z_{tr}	The 0 or 1 binary variable determining the time period "t" of the route "r"
Y_{ar}	The 0 or 1 binary variable determining the route of the stock area "a"
$vehcycle_r$	The total cycle time of the route/vehicle "r" (Including fixed trip time of the vehicle, total loading-unloading time and idle time)
$vehidle_r$	The idle time of the vehicle "r"

Sets

A	The set of stock areas in the material depot, assembly station, and product warehouse (a, b)
B	The set of stock points related with each other (pulling or pushing) (i, j)
C	The stock areas in the same cell (a, b)
N_r	The set of stock points that can be assigned to the route "r"
N_a	The set of stock points in the stock area "a"

Parameters

VT_r	The fixed trip time of the route/vehicle "r" (only the trip time not including loading-unloading or other times)
seq_{sri}	The 0 or 1 integer value showing the assignment orders "s" of the possible assignable stock points "i" to the route "r"
C_r	The transportation cost of one cycle of the route/vehicle "r"
TWT	Total working time
TI	Time interval value
tt_t	The number of time intervals in the time period "t"
W_i	The monetary value of the stock point "i"
$sign_i$	The "−1" or "1" values depending on the stock point "i"'s type ("supply" or "demand")
vol_a	The volume of the stock area "a"
P	The ratio of the safety stock depending on one cycle demand
vcost	The daily fixed cost of the vehicle/route "r"
vehnum	Maximum number of vehicles that can be used in the system
$maxvehidle_r$	Maximum idle time of the vehicle/route "r"
f	The daily opportunity cost ratio for calculating the value of WIP
d_i	The output and input ratio (quantity/time) of the stock point "i"
l_i	The loading-unloading time of the stock point "i"
cap	The capacity of the vehicle
v_i	The volume of the stock point "i"
vv_t	Time period "t" is chosen or not chosen (1 or 0)
M	A big number

Objective function

$$\text{Min z} = \begin{array}{l} \sum_r \sum_i D_{ir}.W_i.f/2 + \sum_r \sum_i S_{ir}.W_i.f + \\ \sum_t \sum_r C_r.Z_{tr}.(TWT/(tt_t.TI)) + \\ \sum_r vcost.route_r \end{array} \quad (1)$$

1. In the objective function, it is aimed to minimize mainly two cost resources. The first one is to minimize the WIP cost consisting of the demand of the stock points within the time period and safety stock. The second one is cost-related, with the vehicle cost consisting of the tour numbers of the milk-run trains and the fixed costs.

Constraints

$$\sum_r X_{ir} = 1 \quad \forall i \quad (2)$$

$$\sum_r Y_{ar} = 1 \quad \forall a, a \notin A \quad (3)$$

$$\sum_{i \notin Nr} X_{ir} = 0 \quad \forall r \tag{4}$$

$$X_{ir} = X_{jr} \quad \forall (i,j) \in B, \forall r \tag{5}$$

$$M.X_{ir} \geq D_{ir} \quad \forall i, \forall r \tag{6}$$

$$M.X_{ir} \geq S_{ir} \quad \forall i, \forall r \tag{7}$$

$$M.X_{ir} \geq L_{ir} \quad \forall i, \forall r \tag{8}$$

$$L_{ir} = D_{ir}.l_i \quad \forall i, \forall r \tag{9}$$

$$D_{ir} + M.(1 - X_{ir}) \geq \text{vehcycle}_r.d_i \quad \forall i, \forall r \tag{10}$$

$$S_{ir} = D_{ir}.P \quad \forall i, \forall r \tag{11}$$

$$\sum_i \sum_r (D_{ir} + S_{ir}).v_i \leq vol_a \quad i \in N_a, \forall a \tag{12}$$

$$M.Y_{ar} \geq \sum_i X_{ir} \quad i \in N_a, \forall r, \forall a, a \notin A \tag{13}$$

$$Y_{ar} = Y_{br} \quad \forall (a,b) \in C, \forall r \tag{14}$$

$$[TI.tt_t - M.(1 - Z_{tr})] \leq \text{vehcycle}_r \quad \forall r, \forall t \tag{15}$$

$$[TI.tt_t + M.(1 - Z_{tr})] \geq \text{vehcycle}_r \quad \forall r, \forall t \tag{16}$$

$$\sum_t Z_{tr} \leq 1 \quad \forall r \tag{17}$$

$$\sum_r \text{route}_r = \sum_r \sum_t Z_{tr} \tag{18}$$

$$M.\text{route}_r \geq Z_{tr} \quad \forall r, \forall t \tag{19}$$

$$M.\text{route}_r \geq \sum_i X_{ir} \quad \forall r \tag{20}$$

$$route_r = \sum_t Z_{tr} \quad \forall r \tag{21}$$

$$\sum_r \text{route}_r \leq \text{vehnum} \tag{22}$$

$$M.\text{route}_r \geq \text{vehidle}_r \quad \forall r \tag{23}$$

$$\text{vehidle}_r \leq \text{maxvehidle}_r \quad \forall r \tag{24}$$

$$M.\text{route}_r \geq D_{ir} \quad \forall r, \forall i \tag{25}$$

$$M.\text{route}_r \geq S_{ir} \quad \forall r, \forall i \tag{26}$$

$$M.route_r \geq L_{ir} \quad \forall r, \forall i \tag{27}$$

$$\text{vehcycle}_r = \sum_i L_{ir} + \text{route}_r.VT_r + \text{vehidle}_r \quad \forall r \tag{28}$$

$$\sum_r Z_{tr} \leq M.vv_t \quad \forall t \tag{29}$$

$$\sum_r route_r - \sum_r Z_{tr} \leq M.(1 - vv_t) \quad \forall t \tag{30}$$

$$\sum_{ss_r=1}^{s_r} \sum_i D_{ir}.v_i.\text{seq}_{ss_r i}.\text{sign}_i \leq \text{cap} \quad \forall r, \forall s_r \tag{31}$$

$$X_{ir}, Z_{tr}, Y_{ar}, \text{route}_r, vv_t \in \{0,1\} \quad \forall i, \forall a, \forall r, \forall t \quad \text{others} \geq 0 \tag{32}$$

2. Each stock point is assigned to only one route.
3. Each stock area except the ones in the material depot, assembly station, and product warehouse is assigned to only one route.
4. The stock points which cannot be assigned to the route due to the flow and precedence constraints are not assigned to the related route.

5. The dependent stock points which push or pull each other are assigned to the same route.
6. The demand of the stock points which are not assigned to the route becomes zero.
7. The safety stock of the stock points which are not assigned to the route becomes zero.
8. The total loading–unloading time of the stock points that are not assigned to the route becomes zero.
9. For each stock point, the total loading–unloading time is determined.
10. The demand of a stock point is determined by the multiplication of the demand rate of a stock point and the cycle time of the vehicle.
11. The safety stock is determined as a ratio “P” of the demand at the related stock point.
12. The volume of the total demand and safety stock of the stock points in a stock area cannot be more than the volume of that stock area.
13. All the stock points in a stock area (except the ones in the material depot, assembly station, and product warehouse) are assigned to only one route.
14. All the stock areas in the same station are assigned to the same route.

15, 16. The time period of the chosen route is determined.

17. Each route is assigned to, at most, one time period.
18. The number of chosen routes and time periods are equal.
19. Time period is not assigned to an unselected route.
20. Any stock point is not assigned to an unselected route.
21. Maximum one time period is assigned to a selected route.
22. The maximum number of vehicles in the system is limited.
23. No idle time is assigned to an unselected route.
24. Each vehicle’s maximum idle time is restricted.
25. No demand is assigned to an unselected route.
26. No safety stock is assigned to an unselected route.
27. No loading–unloading time is assigned to an unselected route.
28. One tour cycle time of the route “r.” The cycle time of the vehicle consists of the total loading–unloading time, the fixed tour time, and the idle time of the vehicle.

29, 30. For each time period, the total number of selected routes is made to be either equal to zero or equal to the total number of selected routes assigned to the related time period for providing the equally timed periods.

31. At each assignment of stock point “i,” the capacity of the vehicle is controlled.
32. The decision variables are either 0–1 integer variables or positive real numbers.

4 A heuristic approach for the model

Depending on the combinatorial structure of the mathematical model proposed, it is difficult to find the optimal solution for large-sized problems having a huge number of variables. So as to overcome this drawback, a heuristic approach is proposed.

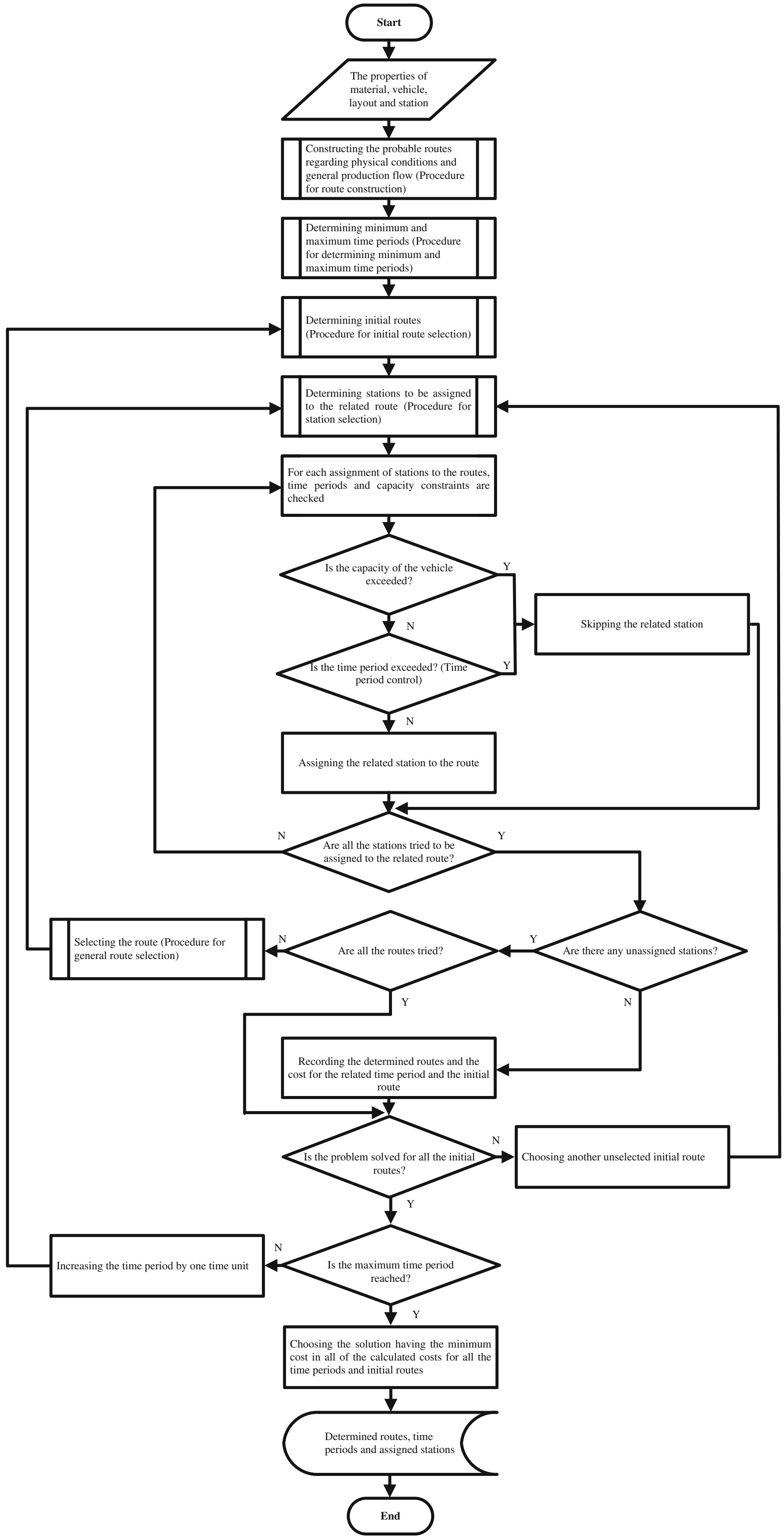
It is mainly aimed to find the routes and time period of the routes in the proposed mathematical model. Since the time period of the milk-run trains is equal, there is only one time period to be found. The time period can be defined as the total time that all the related activities of the milk-run train must be completed in. Within the related activities, there are mainly the fixed cycle time of the train and total loading–unloading time of the materials carried. The time period also determines the quantity to be delivered to the stock areas. For instance, if the time period of the trains is 1 h, this means that the trains will carry 1 h demand of all stock areas. This also affects the loading–unloading time of the materials carried. So, depending on the importance of the time period in the model, it is mainly focused in the heuristic approach. For each time period between minimum and maximum values, the best routes are searched and the most suitable stations are assigned to the routes regarding some procedures. The cost is calculated for each time period, and finally, the time period having the least cost is selected. The proposed heuristic algorithm is shown in Fig. 3. Some of the steps of the algorithm including procedures need further explanations. The procedures included in the algorithm are procedure for route construction, procedure for determining minimum and maximum time periods, procedure for initial route selection, procedure for general route selection, and lastly, procedure for station selection. Moreover, further explanation is also provided for time period control step.

As shown in Fig. 3, within the first step of the proposed heuristic algorithm, the data about the properties of material, vehicle, layout, and station are collected. Some of the such data are the demand rate of the materials, the monetary values of the materials, the capacity of the milk-run train, the velocity of the milk-run train, the distances on the layout, the position of the stations, the physical area of stations, and so on. All of the parameters are given in detail within the numerical example.

After obtaining the related parameters of the system, the probable routes are constructed with respect to the procedure for route construction. The parameters such as the fixed cycle time of the probable routes are then computed by dividing the distance of the route to the velocity of the milk-run train.

After the procedure for route construction, for minimizing the solution time and unnecessary operations, minimum and maximum time period values are obtained with respect

Fig. 3 Steps of the heuristic algorithm



to the procedure for determining minimum and maximum time periods. The obtained minimum time value is taken as the first time value. Then, the initial routes are found by applying the initial route selection procedure, and assignments are made to the chosen route starting from the stations being passed by the least number of routes (station selection procedure).

While assigning stations (stock areas) to the routes, the capacity of the vehicle and time period is checked. If any of them is violated, that station is skipped. If there is no problem about the capacity and the time period, the related station is assigned to the route. Assignment to the related route continues until there is no problem about the capacity and the time period.

If there are unassigned stations and it is impossible to assign any station to the related route, then by applying the procedure for general route selection, a new route is chosen, and similar steps are applied until there are no unassigned stations. If there are still unassigned stations after trying all the routes, the related initial route is skipped and remaining initial routes are tried. When it is provided that there are no unassigned stations, the cost is calculated for the related initial route and the time period. After trying all the initial routes for the same time period, the time period value is increased by one unit for the next iteration. Cost is calculated for each time period until it is reached to the maximum time period. After the last iteration, the solution having the minimum cost is chosen. The time period of the best solution gives the cycle time of the system. The related procedures used within the algorithm are as follows:

Procedure for route construction

A big number of probable routes can be defined regarding the layout of the factory. However, taking into consideration all the probable routes can cause unnecessary workload and long solution times. For this reason, the following points should be considered while constructing the probable routes.

- The route combinations are formed having the start and end at the same point (material depot).
- The routes having a physical constraint regarding the layout and being opposite to the work flow are eliminated.
- The routes not passing by at least one of the related (dependent) workstations are eliminated.
- The routes passing by a workstation more than twice are eliminated.

Procedure for determining minimum and maximum time periods

In the presented mathematical model, the most suitable time periods are searched and assigned to the routes. With the proposed procedure, the lower and upper bounds for time periods are obtained and the number of time periods that will be regarded is decreased. For the minimum time period, the route having the least fixed cycle time is determined. The minimum time period is the minimum value that is greater than that value. Then, the minimum time period value ($t$min) can be indicated as in the Eq. 33.

$$\text{Minimum time period} > \text{The route having the least fixed cycle time} \tag{33}$$

For obtaining the maximum time period, it is benefited from the vehicle capacity and stock areas at the stations.

Since the number of maximum vehicles that can be used in the layout is known, maximum time value can be obtained. When the time period of the vehicle increases, proportionally, the quantity that will be carried also increases, and this affects the capacity usage rate of the vehicle. In that case, the time value satisfying the Eq. 34 gives the probable maximum time period value (t).

$$(\text{maximum number of vehicles*the capacity of vehicle}) = (t\text{*demand of all materials to be carried per time}) \tag{34}$$

On the other hand, when the stock areas at the workstations are taken into consideration, the space that is occupied by the materials must not be more than the workstation area. Regarding also the safety stock quantities, the time value satisfying the following Eq. 35 for each of the stock areas is determined, and the smallest of them becomes the other probable maximum time period value (t).

$$(1 + \text{safety stock ratio})*(\text{demand of materials at the stock area per time*}t) = \text{stock area} \tag{35}$$

The smallest of the probable maximum time period values (t) obtained from the vehicle capacity constraint and the stock area constraint is regarded as the maximum time period ($t$max).

Procedure for initial route selection

While choosing the initial route or routes, the following steps are applied and the initial route set is formed.

- The stations are ranked from smallest to largest with respect to the number of routes passed by them.
- Regarding the station/stations being passed by the smallest number of routes, the related routes are selected.

- Among the selected routes, first of all the one passing by the highest number of stations is selected. If there is more than one route satisfying the condition, the one or ones having the least fixed cycle time are selected and added to the initial route set.
- Secondly, within the selected routes, the route having the least fixed cycle time is selected, and if there is more than one route satisfying the condition, the one or ones passing by the highest number of stations is selected and added to the initial route set.

Procedure for general route selection

After selecting the initial route, general route selection procedure is applied for selecting the other routes. Similar to initial route selection, the following steps are applied.

- The number of routes passing by the unassigned stations is determined.
- Regarding the unassigned station/stations being passed by the smallest number of routes, the related routes are selected.
- Among the selected routes, the one passing by the highest number of unassigned stations is selected. If there is more than one route satisfying the condition, the one or ones having the least fixed cycle time is selected.

Station selection procedure

While assigning a station to a route, it is started from the stations being passed by the least number of routes. Precedence relations are also considered while selecting a station. That is, if one station is related with other station, both of them are chosen at the same time.

Time period control

For each assignment of a station to a route, time period should be checked. Since loading–unloading take place whenever a station is assigned to a route, the total time required for the travelling of the vehicle should be controlled. For checking the suitability of the time period, the inequality (Eq. 36) must be satisfied for each selected route:

$$\begin{aligned}&(\text{The fixed traveling time of the related route} + \text{total}\\&\ \text{loading-unloading times of the related stations}\\&\ \text{assigned to the route} \leq \text{The considered time period}(t)\end{aligned} \tag{36}$$

For making the heuristic approach clearer, pseudocode is provided in Fig. 4. The notations used are as follows:

S	Station (s=1, …,ss)
r	Route (r=1, …,rr)
t	Time period
t_{min}	Minimum time period
t_{max}	Maximum time period
$r_{initial}$	Initial routes ($r_{initial}$=1, …, k)
r_{new}	Route obtained after the execution of the procedure for general route selection
load(r)	Total load of the route r
cycle(r)	Total cycle time of the route r
cap	Total capacity of the milk-run train
cost ($r_{initial}$, t)	Cost computed for the solution including the initial route $r_{initial}$ and the time period t

```
1   Begin Milk-run heuristic
2   Set the parameters (The properties of material, vehicle, layout and station)
3   Run procedure for route construction (Obtain r=1 to rr)
4   Run procedure for determining minimum and maximum time periods (Obtain t_min and
    t_max)
5   Run procedure for initial route selection (r_initial = 1,...,k)
6   For t=t_min to t_max
7       For r_initial = 1 to k
8           r = r_initial
9           Run procedure for station selection (Obtain the assignment order of
            unassigned stations for route r)
10          For each station s with respect to the assignment order
11              If load(r) ≤ cap and cycle(r) ≤ t (when station s is assigned) Then
12              Assign station s to route r
13              Else
14              Skip station s
15              End if
16          Next station s
17          If there are unassigned stations and all routes are not tried Then
18          Run procedure for general route selection (Obtain r_new)
19          r = r_new
20          Go to 9
21          Else if there are unassigned stations and all routes are tried Then
22          Go to 27
23          Else
24          Compute the cost for the related r_initial and t; [cost(r_initial,t)]
25          Record cost (r_initial, t) to the solution set
26          End if
27      Next r_initial
28  Next t
29  Select the least cost(r_initial, t) from the solution set
30  End Milk-run heuristic
```

Fig. 4 Pseudocode for the heuristic algorithm

The pseudocode for the heuristic algorithm is shown as in Fig. 4.

5 A numerical example

For proving the applicability of the mathematical model and the heuristic approach, the numerical example in the study of Kilic et al. [15] is used with some modifications such as considering the monetary values of WIP. There are material depot, 16 cells, assembly station, and a product warehouse as seen in Fig. 5. Totally, there are 98 stock points and 36 stock areas consisting of stock points (sp) in the system. Each cell has two stock areas: input and output. The arrows between the cells indicate that there is a material flow between the cells.

As mentioned before, the first step is to determine the probable routes regarding the layout, flow of the products,

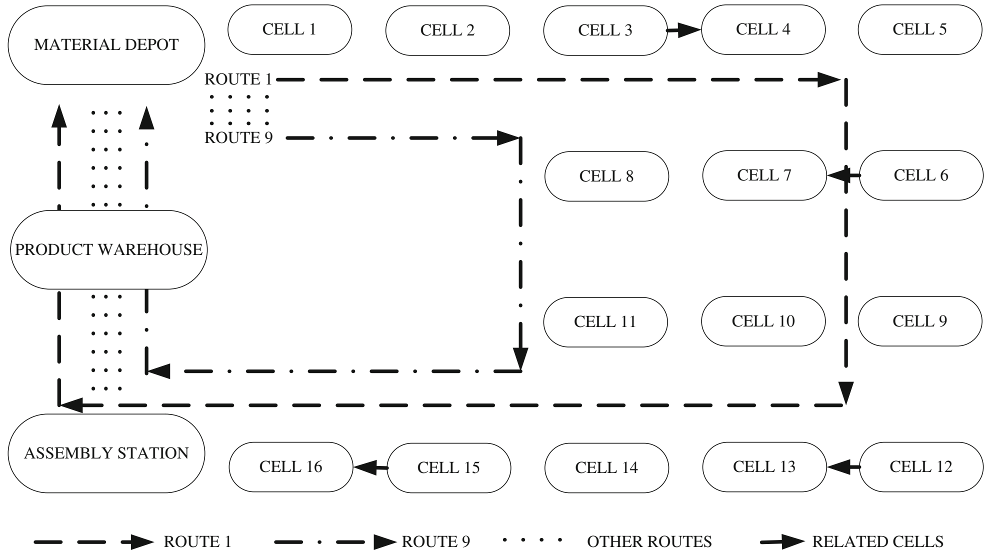


Fig. 5 The layout and the probable routes in the numerical example

and physical conditions. Although more routes could be defined, for the easiness of the problem, the number is limited with nine routes. The probable routes and the cells that can be assigned to the routes are shown as in Table 1.

The parameters can have different values depending on the conditions of the application area. In this numerical example, values of some parameters are determined small for the easiness of operations. The demand rates of each stock point are defined as cases per minute, and the capacity of the vehicles and stock areas are also defined as cases.

5.1 Parameters

The parameters and their values are as follows:

The related cells: There is a material flow between some of the cells. These cells are called related cells; Cell 3-Cell 4, Cell 6-Cell 7, Cell 12–Cell 13, and Cell 15–Cell 16 are related cells.

The time for the vehicles to traverse the routes: The average velocity of the vehicles is 60 m/min. So the time to traverse each route is: route 1, 4.7 min; route 2, 4.7 min; route 3, 4.7 min; route 4, 4.7 min; route 5, 4.2 min; route 6, 4.2 min; route 7, 4.7 min; route 8, 4.2 min; route 9, 3.7 min.

The average cost of one-cycle tour of each route: The transportation cost mainly depends on the energy type used by the material handling equipment and the material to be carried. So there is a wide range of price. Cost per kilometer is regarded as $0.25/km for all the vehicles, and the cost of 1 cycle of each route is: route 1, $0.0705; route 2, $0.0705; route 3, $0.0705; route 4, $0.0705; route 5, $0.063; route 6, $0.063; route 7, $0.0705; route 8, $0.063; and route 9, $0.055.

Total working time: Total working time is determined as 8 h (480 min).

Time interval value: The time interval is determined as 2 min.

The number of time intervals: The total number of time intervals is 120.

The monetary value of the WIP: The monetary value of one case of each stock point “i” is shown in Table 2.

The quantity of safety stock: One cycle demand is the safety stock for each stock point.

The costs related with the milk-run train: Regarding the depreciation and the driver cost of the vehicle, the daily cost is assumed to be $60 for one milk-run train.

The loading-unloading time of the material cases: It is assumed to be 0.3 min for one case. But for the materials in the material depot, taking into account of the searching time, it is assumed to be 0.45 min for one case.

The capacity of the train: The train has four wagons, and each wagon can carry 16 unit cases.

The volume of the stock areas: Each stock area has the capacity of ten unit cases.

Table 1 The routes and the cells that can be assigned to them

Route	Assignable cells
1	C1, C2, C3, C4, C5, C6, C7, C9, C10, C11, C12, C13, C14, C15, C16
2	C1, C2, C3, C4, C5, C6, C7, C10, C11, C14, C15, C16
3	C1, C2, C3, C4, C5, C6, C7, C8, C10, C11, C15, C16
4	C1, C2, C3, C4, C8, C9, C10, C11, C12, C13, C14, C15, C16
5	C1, C2, C3, C4, C8, C10, C11, C14, C15, C16
6	C1, C2, C3, C4, C8, C11, C15, C16
7	C1, C2, C8, C9, C10, C11, C12, C13, C14, C15, C16
8	C1, C2, C8, C10, C11, C14, C15, C16
9	C1, C2, C8, C11, C15, C16

Table 2 The monetary values of the stock points

Stock point	Monetary value ($)	Stock point	Monetary value ($)	Stock point	Monetary value ($)	Stock point	Monetary value ($)	Stock point	Monetary value($)
1	100	21	150	41	200	61	300	81	240
2	100	22	200	42	240	62	150	82	240
3	100	23	200	43	240	63	150	83	900
4	150	24	200	44	250	64	330	84	330
5	150	25	250	45	250	65	330	85	330
6	150	26	100	46	550	66	375	86	450
7	200	27	100	47	550	67	200	87	110
8	200	28	100	48	250	68	200	88	300
9	200	29	165	49	900	69	450	89	375
10	250	30	165	50	300	70	200	90	450
11	250	31	150	51	300	71	125	91	125
12	250	32	150	52	330	72	125	92	420
13	300	33	180	53	330	73	125	93	1,500
14	300	34	180	54	300	74	250	94	2,000
15	300	35	150	55	100	75	420	95	2,500
16	100	36	165	56	450	76	165	96	1,500
17	100	37	165	57	100	77	165	97	2,000
18	100	38	200	58	110	78	180	98	2,500
19	150	39	420	59	100	79	180		
20	150	40	200	60	150	80	420		

The demand or supply quantity of stock points per time: According to the stock point type (demand or supply), the quantity per time and the sign showing the type of the stock point (supply=1 or demand=−1) are shown in Table 3.

5.2 Application of the mathematical model

The mixed-integer linear programming model is coded and run in GAMS optimization program with CPLEX solver. Depending on the structure of the problem type, it is difficult to find the optimum solution in such kinds of problems. However, the model was run for approximately 3 days in a computer having a 4 GB RAM and a 2.93 GHz processor to get a good feasible solution and the cost is found as $226.54. The cycle time of the system is obtained as 18 min. That is, in every 18 min, three milk-run trains will travel in the system for material delivery by using the routes 1, 4, and 9. The summary of the results indicating the routes chosen, cycle times of the routes, and the cells assigned to the routes are shown in Table 4.

5.3 Application of the heuristic approach

The developed heuristic approach is applied in the numerical example. The feasible solutions between minimum ($t$min) and maximum ($t$max) time values are provided.

Within the first steps of the heuristic algorithm, the related parameters about material, vehicle, layout, and station are gathered, and nine routes are constructed with respect to the procedure for route construction. With respect to the minimum and maximum time periods procedure, the minimum time value ($t$min) is regarded as 4 min which is the smallest value greater than the least fixed cycle time of all the routes. Since one time interval is regarded as 2 min. All the increase in time units will be the multiples of 2 min. The maximum time value ($t$max) is obtained by regarding the stock areas and found as 20 min due to the limited area of the cell 1. For the selection of initial routes, the related procedure is applied, and firstly, the cells being passed by least number of routes are obtained as cell 5, cell 6, cell 7, cell 9, cell 12, and cell 13 as shown in Table 5.

Three routes pass by each of these cells. The related routes are route 1, route 2, route 3, route 4, and route 7. With respect to the steps of the procedure, among these routes firstly the one passing by the largest number of cells are selected and considered as initial route, and this is the route 1 passing by 15 cells. Secondly, among these five routes, the one having the smallest fixed cycle time is selected. But since the fixed cycle times of all the routes are equal, the one or ones passing by the highest number of routes is selected and that is again route 1. So there is only one initial route and that is the route 1. After determining the initial route, cells are assigned to the initial route with

Table 3 The supply/demand quantity of each stock point per time [15]

Stock point (sign)	Case/min	Stock point (sign)	Case/min	Stock point (sign)	Case/min	Stock point (sign)	Case/min	Stock point (sign)	Case/min
1 (1)	0.1	21 (1)	0.05	41 (−1)	0.05	61 (1)	0.05	81 (−1)	0.05
2 (1)	0.1	22 (1)	0.05	42 (1)	0.05	62 (−1)	0.05	82 (−1)	0.05
3 (1)	0.05	23 (1)	0.05	43 (1)	0.05	63 (−1)	0.05	83 (−1)	0.10
4 (1)	0.05	24 (1)	0.05	44 (−1)	0.10	64 (1)	0.05	84 (−1)	0.10
5 (1)	0.05	25 (1)	0.10	45 (−1)	0.10	65 (−1)	0.05	85 (−1)	0.10
6 (1)	0.05	26 (−1)	0.1	46 (1)	0.10	66 (1)	0.05	86 (−1)	0.10
7 (1)	0.05	27 (−1)	0.1	47 (−1)	0.10	67 (−1)	0.05	87 (−1)	0.05
8 (1)	0.05	28 (−1)	0.05	48 (−1)	0.10	68 (−1)	0.05	88 (−1)	0.05
9 (1)	0.05	29 (1)	0.05	49 (1)	0.10	69 (1)	0.05	89 (−1)	0.05
10 (1)	0.10	30 (1)	0.05	50 (−1)	0.10	70 (−1)	0.05	90 (−1)	0.05
11 (1)	0.10	31 (−1)	0.05	51 (−1)	0.10	71 (1)	0.05	91 (−1)	0.05
12 (1)	0.10	32 (−1)	0.05	52 (1)	0.10	72 (1)	0.05	92 (−1)	0.05
13 (1)	0.10	33 (1)	0.05	53 (1)	0.10	73 (−1)	0.05	93 (1)	0.10
14 (1)	0.10	34 (1)	0.05	54 (−1)	0.10	74 (−1)	0.10	94 (1)	0.10
15 (1)	0.10	35 (−1)	0.05	55 (−1)	0.05	75 (1)	0.05	95 (1)	0.10
16 (1)	0.05	36 (1)	0.05	56 (1)	0.10	76 (−1)	0.05	96 (−1)	0.10
17 (1)	0.05	37 (−1)	0.05	57 (−1)	0.05	77 (−1)	0.05	97 (−1)	0.10
18 (1)	0.05	38 (−1)	0.05	58 (1)	0.05	78 (−1)	0.05	98 (−1)	0.10
19 (1)	0.05	39 (1)	0.05	59 (−1)	0.05	79 (−1)	0.05		
20 (1)	0.05	40 (−1)	0.05	60 (−1)	0.05	80 (−1)	0.05		

respect to the station selection procedure. The assignments are made starting from the selected cells 5, 6, 7, 9, 12, and 13. But feasible assignments could not be made for the time periods 2 (4 min) and 3 (6 min). For the time period 4 (8 min), a feasible assignment is made which does not violate the constraints. For all the other time periods between minimum and maximum time values, the assignments are performed regarding the steps of the heuristic approach, and finally, the solutions for each feasible assignment are provided. The solution for the time period 10 (20 min) which is also the best solution obtained is shown in Table 6.

Solutions for other time periods are provided in the Appendix. In the tables, there are the routes in the rows and the cells (C1 to C16) in the columns. When an assignment of a cell is made to a route, it is indicated as "1," since each cell is assigned to one route. There is only one "1" in each column except for the assembly column abbreviated by "As." It can be served by more than one route each of which can carry one of the related parts from assembly station to product warehouse. In the last row, the total cost is given, and in the last column, the total time of each route including fixed tour time of the route and total loading–unloading times are provided. This total time can be regarded as the cycle time of each route without the idle times. As can be noticed, the total time value of each route is not greater than the related time period (the cycle time of the system). The difference between the related time period and the total time gives the idle time of the vehicle on that route. Consequently, the results indicate that, in every 20 min, three milk-run trains using the routes 1, 4, and 9 will deliver the required parts with the lowest cost which is $230.60.

Since there are no alternative heuristic approaches in the literature for the related type of problem, it is not possible to compare the results. But when the results gathered from the solution of the heuristic approach and the mathematical model are compared, it is seen that the deviation of the heuristic approach value from the mathematical model value is approximately 1.79 %.

Table 4 The results of the mathematical model

Chosen routes	Cycle time (min)	Cells
r1	18	C5, C6, C7, C12, C13, C14
r4	18	C1, C3, C4, C9, C10, C11
r9	18	C2, C8, C15, C16

Table 5 The initial table showing the routes and the cells

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	Total
1*	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	15
2	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	12
3	1	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	12
4	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	13
5	1	1	1	1	0	0	0	1	0	1	1	0	0	1	1	1	10
6	1	1	1	1	0	0	0	1	0	0	1	0	0	0	1	1	8
7	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	11
8	1	1	0	0	0	0	0	1	0	1	1	0	0	1	1	1	8
9	1	1	0	0	0	0	0	1	0	0	1	0	0	0	1	1	6
Total	9	9	6	6	3	3	3	7	3	7	9	3	3	6	9	9	

Ro. route

6 Conclusion

Milk-run trains travelling periodically on predefined paths provide a standard parts feeding system for the lean production systems which are repetitive and smooth. A special case of milk-run trains in lean production environment is taken into consideration in this study. Within this special case, the cycle times of all the milk-run trains are equal. As observed in real life applications, since it provides simplification of milk-run train management, it has been chosen by the firms. Although milk-run trains having equal cycle times are only mentioned conceptually in the study of Kilic et al. [15], this study differs from the existing studies by presenting a mathematical model and a novel heuristic approach.

Since it is difficult to find the optimum solution with the mathematical model when the number of variables increases, a novel heuristic approach is developed to overcome this drawback. To prove the applicability of the proposed model and the heuristic algorithm, a numerical example already in literature is used with few modifications. The mathematical model and the heuristic approach are applied, and solutions are obtained.

This study also shows that there is need for heuristic approaches depending on the difficulty for finding the optimum solution in such kinds of in-plant logistics problems. Meta-heuristic algorithms such as genetic algorithm, ant-colony optimization algorithm and simulated annealing algorithm can be applied, and the solutions can be compared. Moreover, a lower-bound algorithm can be developed to provide a comparison basis for the developed heuristic approaches. Finally, the proposed model and the heuristic approach can be applied in real production environment, and new models and solution approaches can be developed for in-plant logistics design regarding various situations of production. Furthermore, multiple item situations in the real environment may be incorporated within the context of this study by modifying the parameters of the papers by [30–33].

Table 6 The solution table for the time period "t=20 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1		1					1				19.85
2																		
3																		
4		1	1	1				1		1		1	1					19.55
5																		
6																		
7																		
8																		
9	1										1				1	1	1	18.40
Total cost=$230.60																		

Appendix

The heuristic approach solution tables for the time periods from t=8 min to t=18 min.

Table 7 The solution table for the time period "t=8 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1				1					1				8
2																		
3						1	1			1								8
4		1	1	1								1	1					7.94
5											1				1	1	1	7.62
6																	1	4.68
7																		
8																		
9	1							1										7.84
Total cost=$401.93																		

Table 8 The solution table for the time period "t=10 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1											9.5
2																		
3																		
4			1	1					1	1		1	1					9.8
5		1						1						1			1	9.9
6																	1	4.8
7																		
8																		
9	1										1				1	1	1	9.85
Total cost=$338.42																		

Table 9 The solution table for the time period "t=12 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1			1							1	11.99
2																		
3																		
4			1	1					1			1	1	1			1	11.99
5											1				1	1	1	8.61
6																		
7																		
8																		
9	1	1						1										11.53
Total cost=$277.91																		

Table 10 The solution table for the time period "*t*=14 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1		1									13.83
2																		
3																		
4			1	1				1				1	1	1				13.73
5	1	1								1	1						1	13.65
6																		
7																		
8																		
9															1	1	1	7.38
Total cost=$281.02																		

Table 11 The solution table for the time period "*t*=16 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1		1									15.14
2																		
3																		
4			1	1				1				1	1	1			1	15.98
5	1	1								1	1						1	15
6																		
7																		
8																		
9															1	1		6.94
Total cost=$284.49																		

Table 12 The solution table for the time period "*t*=18 min"

Ro.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	As.	Total time
1					1	1	1		1	1								17.66
2																		
3																		
4			1	1				1				1	1	1			1	17.39
5																	1	5.28
6																		
7																		
8																		
9	1	1									1				1	1	1	17.20
Total cost=$288.22																		

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