Computers and Electronics in Agriculture 121 (2016) 245–259

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Differential evolution algorithms for scheduling raw milk transportation

Kanchana Sethanan [a,*], Rapeepan Pitakaso [b]

[a] Research Unit on System Modeling for Industry, Industrial Engineering Department, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
[b] Research Unit on System Modeling for Industry, Industrial Engineering Department, Faculty of Engineering, Ubonratchathani University, Ubonratchathani 34190, Thailand

ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form 30 December 2015
Accepted 31 December 2015
Available online 11 January 2016

Keywords:
Dairy industry
VRP
Heuristic algorithm
Differential evolution
Total cost
Vehicle utilization

ABSTRACT

This paper focuses on determining routes for raw milk collection from collection centers to dairy factories with the objective of minimizing the total costs, considering fuel costs and costs of cleaning and sanitizing raw milk tanks on vehicles. This problem is considered to be a special case of the vehicle routing problem (VRP) but it is complex compared to the general VRP, especially since each vehicle contains more than one tank with heterogeneous capacity to collect raw milk and raw milk from different collection centers cannot be transferred into the same compartment. In this paper, a DE metaheuristic was used to solve the problem. In order to improve the solution quality, five modified DE algorithms with two additional steps, reincarnation and survival processes, were proposed. In addition, the skipped customer and multi-route attributes are also developed in the decoding process in order to obtain a shorter traveling distance and lower truck usage in the system, especially if they are used together with the reincarnation and survival processes. The computational results reveal that the modified DE algorithms yield higher relative improvement (*RI*) on the total costs and also the *RI* on the number of vehicles used.

1. Introduction

This paper considers a special vehicle routing problem (VRP) with pickup and delivery services (PDP). It is found in various practical operations of real-world industries, especially in the agricultural food industry, such as the poultry and dairy factories. This research focuses on designing the routes for raw milk collection in the dairy factory as a case study application. In the process of milk production, raw milk management is one of the crucial activities in the supply chain of milk production, since raw milk is perishable product. The most commonly used method to retard the deterioration of milk on its way from farms to a dairy factory is cooling (Lambert, 2001). Raw milk is delivered to the dairy using temperature-controlled vehicles. These vehicles have standard cold storage equipment and are usually more expensive, have many compartments, and consume more fuel than regular vehicles. In addition, raw milk usually has a short shelf life; thus its timely delivery not only significantly affects the delivery dairy factory's costs, but also the continuous production of the dairy factory. Furthermore, the requirement to serve the dairy factory within the allowable maximum duration of delivery time can increase the complexity of vehicle routing and the scheduling problem for planners. Due to the high energy price for retardation of milk deterioration on its way from farm to dairy factory, the collection center, which is the place that farmers transport their milk to before transporting it to the dairy factory, plays an important role in cooling raw milk, since farms at which raw milk is collected are quite small and are often inaccessible by temperature-controlled vehicles. The raw milk collection problem is considered to be a special case of the vehicle routing problem (VRP).

In this problem, a fleet of heterogeneous temperature-controlled vehicles located at a depot must be routed to pick up raw milk from the collection centers scattered geographically. The amount of raw milk at each collection center may be different, depending on the amount supplied from the farmers in that area. Once the temperature-controlled vehicles finish picking up raw milk from the collection center of their route, they must deliver the raw milk to the dairy factory within the maximum time specified by the dairy factory planner. Fig. 1 illustrates a tour which represents a solution of the raw milk collection problem (with the constraints mentioned earlier). The vehicle starts from the depot (i.e., the dairy factory) and picks up raw milk from the collection centers at its maximum capacity. Then the vehicle goes back to deliver raw milk to the depot. When the collected raw milk is transported to the dairy factory, it must be inspected to check if it is in good condition. If so, the vehicle is weighed and then cleaned and sanitized in order to prevent deterioration of the incoming raw milk lots, while the raw milk is transferred into the raw milk tank for further processing. However, the raw milk

* Corresponding author. Tel.: +66 815536429 (mobile); fax: +66 43 362299.
E-mail address: skanch@kku.ac.th (K. Sethanan).

http://dx.doi.org/10.1016/j.compag.2015.12.021
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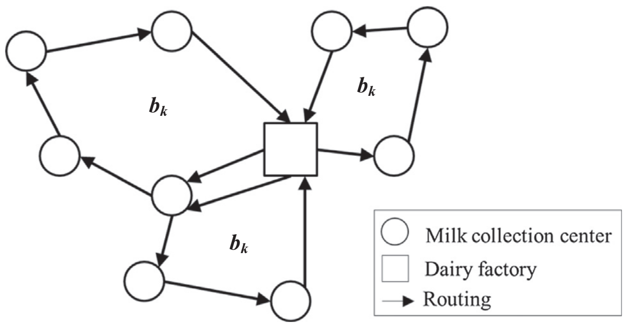

Fig. 1. Illustration of the tour representing a solution of the problem.

collection problem is complex compared to the general VRP in five ways:

1. Unlike the general VRP problem studied in the literature, each vehicle contains more than one tank with heterogeneous capacity to collect raw milk. However, generally, each vehicle usually has three individual compartments (see Fig. 2).
2. In order to maintain traceability of milk product, raw milk from different collection centers cannot be transferred in the same compartment. This means that when raw milk from a particular collection center has been transferred into a compartment, that compartment cannot be used to contain raw milk from other collection centers, until the compartment has been cleaned and sanitized at the dairy factory when the vehicle arrives. Hence, separate milk collection, either independent runs for different milk types, or storage of distinct milk types in the vehicle compartments, may increase the length and number of runs required.
3. Each collection center has a known demand and may be visited more than once by more than one vehicle, and each vehicle may visit more than one collection center depending on the amount of raw milk at that collection center and also the capacity of the vehicle itself.
4. Each vehicle could be used to collect milk on more than one round (route).
5. Both traveling costs and cleaning costs of vehicles are considered as the objective function. That means minimizing not only the travel distance, but also the number of vehicles by fully utilizing the vehicles' capacity.

Due to its complexity, it is therefore difficult to effectively manage cold chain distribution, especially managing vehicle routings and retarding raw milk deterioration. Inefficient transportation may often lead to deterioration of raw milk due to extended travel times and frequent stops during the collection process. Therefore, the dairy factory must cope with (1) high transportation cost especially if the amount of raw milk is much smaller than the compartment capacity, (2) high cleaning cost of tanks on the vehicle (i.e., electricity bill, water supply bill and chemical expenses) due to the temperature-controlled vehicles used in transporting the raw milk not being full-loaded. Therefore, a lot of temperature-controlled vehicles are required to be cleaned before loading the incoming raw milk lots, and (3) raw milk quality concerns due to high travel distance and high frequency of cleanings of temperature-controlled vehicles. Most importantly, due to the sanitization constraint, raw milk from different collection centers cannot be transferred into the same compartment. This restriction causes a significant impact to high production costs of milk production. In order to make higher volumes attractive and possibly produce economies of scale in milk collection, while maintaining the same marginal profit, optimizing transportation and vehicle cleaning costs may allow the dairy factory to pay higher milk prices to farmers with the balancing of a reduction in the milk collection costs (Butler et al., 2005). This paper therefore focuses on determining routes for picking up raw milk from collection centers to the milk factory with the objective to minimize the total costs, with consideration of capacity restriction of heterogeneous fleets, multiple tank compartments in a vehicle, and allowing maximum duration of a route. The total cost consists of two cost components: fuel cost and cost of cleaning and sanitizing tanks on vehicles. The fuel cost can be minimized by reducing the traveling distance while the cleaning cost of temperature-controlled vehicles can be reduced by minimizing the number of vehicles by fully utilizing the vehicles' capacities. To solve the problem, an efficient mixed integer programming model was developed for small-size problems. Since the problem considered is an NP-hard problem, the computational effort, in general, required to find an optimal solution grows exponentially with the size of the problem. In an effort to find a near optimal solution for problems with larger, more practical problems, a meta-heuristic was developed. An efficient algorithm is developed based on Differential Evolution (DE), a well-known metaheuristic. In order to improve the solution quality in terms of traveling cost and cleaning raw milk tank cost, in this paper, the modified DE algorithms were proposed in which two additional steps were included in the traditional DE: (1) reincarnation process and (2) survival process. Additionally, in this paper, the skipped customer and multi-route process were also developed in the decoding process in order to obtain highest utilization of vehicles used. The skipped customer attribute allows the next possible collection center to be a candidate in the route if the current collection center cannot fit in the route if the completion traveling time of the current collection center exceeds the maximum duration of a route. Hence, instead of creating a new route, this attribute allows the new client to be in a route as long as the ending time of a route does not exceed the maximum route duration. For the multi-route attribute, it allows each truck to pick up the raw milk from more than one round (for which each round may be a different route) as long as the maximum route duration is not exceeded.

To illustrate the proposed method effectiveness, numerical experimental results were compared with the mathematical model

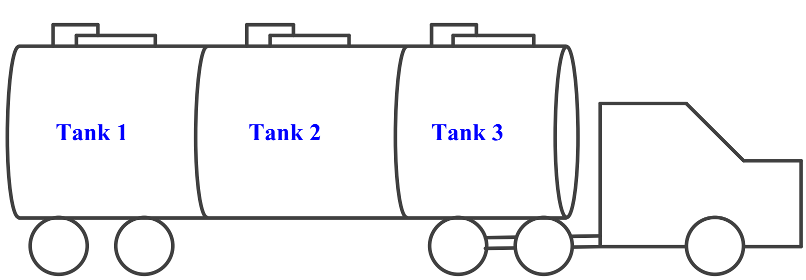

Fig. 2. Milk vehicle with multi-compartments.

and also with the traditional DE. In the next section, related literature is reviewed. Section 3 presents a description of the problem. The methodology used to solve the problem is presented in Section 4. Section 5 presents a comprehensive detail of our solution procedures and an outline of experimental results is presented in Section 6. Finally, a summary of the main findings is given in Section 7.

2. Literature review

Normally, the VRP determines, at minimum total cost, the routing of multiple numbers of vehicles, each of which starts from the depot. Raw milk collection is a specialized case of the vehicle routing problem. Various methods have been used to solve the problem. Generally, a mixed integer programming model has been developed for small-size problems. For example, Basnet et al. (1999) developed a mixed integer program with some non-linear constraints to solve a joint problem of milk-tanker scheduling and sequencing for the New Zealand dairy industry. Since the raw milk collection problem considered is an NP-hard problem, the computational effort required to find an optimal solution grows exponentially with the size of the problem. In an effort to find a near optimal solution for larger more practical problems, a heuristic and meta-heuristic were developed. In addition to presenting the mathematical model to solve the problem, Basnet et al. (1999) also proposed a fast heuristic algorithm to solve the problem for the New Zealand dairy industry. Recently, Worasan et al. (2014) developed a mixed integer programming model to solve the raw milk collection problem. In their problem, the VRP variants considered are: (1) each vehicle contains more than one tank with heterogeneous capacity to collect raw milk, (2) raw milk from different collection centers cannot be transferred in the same compartment, and (3) each collection center be visited more than once by more than one vehicle, and each vehicle may visit more than one collection center. The objective of this research is to minimize the total cost consisting of transportation cost and costs of cleaning raw milk tanks. The problem was solved using the CPLEX-MPL software V.4.2k (4.2.11.79) for Windows. The maximum problem size which was able to be solved was 8 vehicles and 8 collection centers.

In areas with very high volumes of raw milk, a truck with a trailer was used to transfer milk from farmer locations in order to reduce transportation cost. However, some farms are small and inaccessible for a truck with a trailer to transfer raw milk, since the size of the truck and the location of farmers is relevant. In such situations, the trailer must be uncoupled from the complete vehicle (i.e., the truck with trailer) in parking areas before visiting these farmer locations. After visiting locations the trailer must be coupled again to the truck (Caramia and Guerriero, 2010a). This problem is known as the truck and trailer routing problem (TTRP). According to Caramia and Guerriero (2010b), the raw milk collection problem is a generalization of the TTRP which is defined as a generalized assignment problem (GAP) (Fisher and Jaikumar, 1981). Hence, Chao (2002) then assigns vehicle to farmers considered as customers in order to minimize the total distance all vehicles travel. Additionally, an optimal solution is determined using the linear relaxation of the GAP formulation, and also by exploiting some theoretical arguments.

In an effort to find a near optimal solution for problems with larger, more practical problems, Scheuerer (2006) developed two constructive heuristics and a tabu search algorithm to solve the TTRP. In the same year, Tan et al. (2006) developed an evolutionary algorithm to deal with the truck and trailer routing with two objective functions, which are minimizing the number of trucks and minimizing the routing cost. Later, Hoff and Løkketangen (2007) developed a tabu search algorithm to solve the milk collection problem modeled as a TTRP. However, their problem does not consider tank trucks with multiple compartments and a heterogeneous fleet of vehicles. Therefore, Caramia and Guerriero (2010a) proposed two mathematical models and an approach that first solves the farmer routes assigned problem (FRAP). The first mathematical model was developed to minimize the number of vehicles to be routed in the network, while the second minimizes the length of all tours. In their study, in order to solve the larger size problem, a local search embedded within a multi-start mechanism was developed. The experimental results show that their approaches are efficient and can result in a saving of approximately 166,000 Euros per year. In their model, farmers are then assigned to vehicles without considering the sequence in which farmers are visited.

However, to support the use of approaches and algorithms for the users, the decision support system (DSS) on the milk collection problem is necessary and required for the planners. For example, Sankaran and Ubgade (1994) developed and implemented the DSS called CARS that utilizes route construction heuristics for a problem size with about 70 milk collection centers in Etah, India. Later, Sanzogni and Kerr (2001) developed the accuracy of milk production forecasts on dairy farms using a feed forward artificial neural network with polynomial post-processing. Then, Dooley et al. (2005) proposed the Genetic algorithm technique used to search for the order of the farm milk collection pick-ups which gave an optimum. Lately, Claassen and Hendriks (2007) proposed a pilot DSS for collecting goat's milk and proposed an operations research-based approach to support the milk collection.

However, computational experiments indicate that the MIP formulations of most VRP problems, especially in the case that each vehicle contains more than one tank with heterogeneous capacity to collect raw milk and raw milk from different collection centers cannot be transferred into the same compartment, are difficult to solve in a reasonable time for real-size problems. To solve the problem, several solution techniques have been introduced to solve them. In the past decade, metaheuristics such as genetic algorithm (GA), tabu search (TS), and simulated annealing (SA) have been widely used to solve combinatorial problems (El Fallahi et al., 2008). Recently, the evolutionary computation techniques have been applied with significant research effort. Differential Evolution (DE) is one of the most powerful techniques that was effectively applied to continuous optimization. It was first introduced by Storn and Price (1997). DE is a population based search technique consisting of the processes of crossover, mutation, and selection to create new candidate solutions. DE has been successfully applied in several fields such as production scheduling (see Pitakaso, 2015; Pitakaso and Sethanan, 2015), manufacturing problems (see López Cruz et al., 2003), and generalized assignment problem (GAP) (see Sethanan and Pitakaso, 2016). For scheduling vehicle problems, Liao et al. (2012a) propose two hybrid DE algorithms to obtain the truck sequences for cross docking operations aiming to minimize total makespan. Later, Liao et al. (2013) proposed six metaheuristic algorithms for sequencing inbound trucks for multi-door cross docking operations under a fixed schedule of outbound truck departure. The objective of their research is to minimize total weighted tardiness. Erbao and Mingyong (2009) presented the DE algorithm and stochastic simulation for solving the VRP with fuzzy demands (VRPFD). Later, Lai and Cao (2010) developed an improved DE algorithm for the VRP with simultaneous pickups and deliveries and time windows (VRP-SPDTW). In the same year, Hou et al. (2010) proposed discrete DE (DDE) with modifying a mutation operator for the VRP with simultaneous pickups and deliveries (VRPPD). Recently, Dechampai et al. (2015) proposed DE to solve the capacitated VRP with flexibility of mixing pickup and delivery services and maximum duration of a route in the poultry industry. Since the hybrid metaheuristic algorithms outperform traditional metaheuristics for solving various applications in many studies (Sangsawang et al., 2015; Jamrus et al., 2015; Boonmee et al., 2015; Liao, 2010; Liao et al., 2012a, 2012b, 2014; Yi et al., 2013), they have also been applied in the scheduling vehicle problems. For example, Erbao et al. (2008) developed a hybridized algorithm integrating the DE and GA for solving the VRP-SPDTW.

Although there are ample literature that has described the application of the VRP and even on the milk collection problem in the common dairy industry, to our best knowledge, the milk collection problem considered in this research is the first time studied in terms of different objective functions and problem characteristics, especially the methodology to solve the problem efficiently. From the successes of DE in various problems and its attractive features, it is the proposed method for solving the raw milk transportation problem in this paper. Even though DE has been effectively used in many fields, it has been very limited when applying it to solve the VRP, since the encoding and decoding of DE cannot be directly adopted for the VRP (Dechampai et al., 2015). Hence, in this paper, the effective method called differential evolution and the DE with modifications are used to solve the problem, especially for the practical size problems in order to obtain good solutions.

3. Problem description

In the process of raw milk transportation from the collection centers to the dairy factory, vehicles used in transporting the raw milk have three compartments and have limited quantity. Since the collection plants may have different raw milk quantity on each day and the total raw milk of any collection center may exceed the vehicle capacity, vehicles may pick up raw milk from more than one collection center. This means that the collection center may be served by more than one vehicle route. Hence, this problem is complicated by these extensions to the VRP with the maximum duration for a route and the limited number of vehicles.

In general, the VRP problem and the raw milk collection problem objective is to find the routes minimizing the total travel cost or time, corresponding to the related constraints. The collected raw milk transported to the dairy factory must be inspected to check if it is to be accepted. If so, the vehicle is weighed and then cleaned and sanitized. In this paper, the objective is to minimize the travel cost and vehicle cleaning cost while the following constraints are considered:

1. Except for the dairy factory, each node (i.e., collection center) is a loading point that the vehicle picks up raw milk and delivers to the dairy factory.
2. There is more than one compartment on the vehicle, each of which cannot contain a load greater than its capacity.
3. Raw milk from different collection centers cannot be transferred in the same compartment due to raw milk sanitization constraints. That means when raw milk of a particular collection center has been transferred into a compartment, that compartment cannot be used to contain raw milk from other collection centers until the compartment has been cleaned and sanitized at the dairy factory after the vehicle arrives.
4. Each collection center has a known demand and may be visited more than once by more than one vehicle, and each vehicle may visit more than one collection center depending on the amount of raw milk at that collection center and also the capacity of the vehicle itself. However, the collection center with an amount of raw milk to transfer to the dairy factory is available for a vehicle to pick up the milk at any period of time.
5. The time required for a vehicle tour cannot exceed the maximum duration of time specified by the production planner.
6. The vehicles are of heterogeneous capacity. The vehicle capacity should not be exceeded on a full tour.
7. A tour starts and ends at the same depot (i.e., the dairy factory).

4. Mathematical model

In this section, a mathematical model is formulated such that the total costs, transportation cost and cleaning cost of raw milk tanks of a vehicle are minimized. This mathematical model is modified from the study of Worasan et al. (2014). Parameters and decision variables used in formulating the model are defined. The 0–1 mixed integer programming formulation is presented below with a brief explanation of each constraint.

Indices

i, j, p	Collection centers; $i, j, p = 1, 2, \ldots, n$
k	Temperature-controlled vehicles k; $k = 1, 2, \ldots, q$
u	Milk compartment index; $u = 1, 2, \ldots, m$

Input parameters

n	Number of collection centers (centers)
q	Number of temperature-controlled vehicles (vehicles)
m	Number of compartments
a_i	Amount of raw milk at collection center i (tons)
e_k	Start time of vehicle k
l_k	Ending time of vehicle k
s_i	Service time of collection center i
d_{ij}	Traveling distance from collection center i to center j (km)
t_{ij}	Traveling time from collection center i to center j (h)
b_k	Capacity of vehicle k (tons)
o_{uk}	Carrying capacity of compartment u of vehicle k (tons)
δ	Cleaning costs of the compartment (Baht/slot)
γ	Fuel cost (Baht/km)

Decision variables

x_{ijk}	=1; vehicle k travels from collection center i to center j = 0; otherwise
z_{iku}	= 1; vehicle k picks up raw milk from collection center i and uploads the raw milk into compartment u = 0; otherwise
y_{iku}	Amount of raw milk of collection center i uploaded to u_k compartment on vehicle k
r_{ik}	Start time of collection center i for vehicle k
M_{ij}	Subtour elimination variables

Objective function

$$\text{Minimize } Z = \sum_{\forall i}\sum_{\forall j}\sum_{\forall k}\gamma d_{ij}x_{ijk} + \delta\sum_{\forall i}\sum_{\forall k}\sum_{\forall u}z_{iku} \quad (1)$$

Constraints

$$\sum_{\forall j} x_{ojk} = 1; \quad \forall k \quad (2)$$

$$\sum_{\forall i} x_{iok} = 1; \quad \forall k \quad (3)$$

$$\sum_{\forall i} x_{ipk} = \sum_{\forall j} x_{pjk}; \quad \forall p, k \quad (4)$$

$$\sum_{\forall k}\sum_{\forall u} y_{iku} = 1; \quad i > 0 \quad (5)$$

$$\sum_{i>0}\sum_{\forall u} a_i y_{iku} \leqslant b_k; \quad \forall k \tag{6}$$

$$y_{iku} = \sum_{\forall j} x_{jik}; \quad i > 0, \ \forall k, u \tag{7}$$

$$x_{ijk} + x_{jik} \leqslant 1; \quad i > 0, \ j > 0, \ \forall k \tag{8}$$

$$r_{ik} + s_i + t_{ij} - M_{ij}(1 - x_{ijk}) \leqslant r_{jk}; \quad i > 0, \ j > 0, \ \forall k \tag{9}$$

$$x_{ijk} = 0; \quad \forall i, j = i, \ \forall k \tag{10}$$

$$e_k \leqslant r_{ik} \leqslant l_k; \quad i > 0, \forall k \tag{11}$$

$$a_i y_{iku} \leqslant o_{uk}; \quad i > 0, \ \forall k, \ u \tag{12}$$

$$y_{iku} \leqslant z_{iku}; \quad i > 0, \forall k, u \tag{13}$$

$$\sum_{i>0} z_{iku} \leqslant 1; \quad \forall k, u \tag{14}$$

$$x_{ijk} \in \{0, 1\}; \quad \forall i, j, k \tag{15}$$

$$z_{iku} \in \{0, 1\}; \quad \forall i, k, u \tag{16}$$

$$y_{iku} \geqslant 0; \quad i > 0, \forall k, u \tag{17}$$

$$r_{ik} \geqslant 0; \quad \forall i, k \tag{18}$$

The objective function (1) minimizes the total costs: transportation costs and cleaning costs of the raw milk tanks on vehicles. Constraints (2) ensure that vehicle k is the first vehicle that travels from the dairy factory to collection center i. Constraints (3) ensure that vehicle k travels from collection center j back to the dairy factory. Constraints (4) ensure that if a vehicle travels to a collection center, that vehicle must leave from that collection center. Constraints (5) ensure that a vehicle must visit a collection center if that collection plant has an amount of raw milk to be transported to the dairy factory. Constraints (6) ensure that the total amount of raw milk of collection center i uploaded to all compartments of vehicle k must not exceed the capacity of that vehicle. Constraints (7) ensure that if the collection center is visited by vehicle k, there is some amount of raw milk uploaded to any compartment. That means if the value of y_{iku} is more than one then the value of x_{ijk} is also one. Constraints (8–10) ensure to guard subtour conditions. Constraints (11) ensure that each vehicle k that uploaded raw milk at the milk collection center must arrive at the factory on time (as planned) and meet the condition of maximum duration of a route allowed. Constraints (12) ensure that the amount of raw milk of collection plant i uploaded to compartment u of vehicle k must not exceed the capacity of that compartment. Constraints (13) mean that if the value of y_{iku} is more than one then the value of z_{iku} is also one. Constraints (14) ensure that no mixture of raw milk from different collection plants to vehicle k is transferred into the same compartment. Finally, constraints (15)–(18) represent the types of variables.

5. Metaheuristic development

In this section, the differential evolution algorithm (DE) based algorithm is proposed. The original DE algorithm was composed of 4 general steps which are: (1) generate initial solution, (2) perform mutation process, (3) perform recombination process and (4) perform selection process. In order to improve the solution quality in terms of traveling cost and raw milk tank cleaning cost, modified DE algorithms were proposed which included two additional steps from the original DE. The additional steps in the proposed algorithms are: (1) reincarnation process and (2) survival process as shown in Fig. 3.

From Fig. 3, we can see that the number of vectors randomly selected equals 3 for each iteration. After these three vectors are applied in the mutation process, mutant vectors will be formed. Then a trial vector is generated by the recombination process. After the selection, the pre-target vector of the next iteration is generated. After the pre-target vector has been obtained, the reincarnation process will be performed. In this process, 3 re-born vectors will be generated using the k-cyclic moves algorithm. Then the best out of three re-born vectors will apply the survival process to get a new target vector for the next generation. Each process of the proposed algorithm can be explained in the following section.

5.1. Generate initial solution

Table 1 presents an example of target vectors, where NP is the population or the number of vectors generated in each iteration of the DE mechanism. Each vector has dimension of D, where D is the number of customers. Therefore in Table 1, NP is set to 5 and D is set to 6. The value in each D of each NP is randomly generated. We can see that the values are in all positions (positions $1, 2, \ldots, 6$) for each vector. For example, the values of vector 1 in position 1, 2, 3, 4, 5 and 6 are 0.43, 0.31, 0.07, 0.84, 0.97, and 0.53 respectively. This vector is called the "*target vector*". The target vectors will be randomly selected to be processed in the next step of the DE mechanism called the mutation process.

5.2. Mutation process

The mutation process is the second process of DE mechanism. Eq. (19) is used to combine 3 randomly selected vectors into a new vector. The new vector calculated by Eq. (19) is called the mutant vector presented as follows:

$$v_{i,j,G} = x_{r_1,j,G} + F(x_{r_2,j,G} - x_{r3,j,G}) \tag{19}$$

where

r_1, r_2 and r_3	the indices of vectors
F	scaling factor which is set to be 0.8 in the proposed heuristics (Qin et al., 2009)
i	vector number; $i = 1, 2, \ldots, NP$
j	the position within vector; $j = 1, 2, \ldots, D$

5.3. Recombination process

In this process, Eq. (20) is first developed in this paper and used to transform mutant vector ($V_{i,j,G}$) and target vector ($X_{i,j,G}$) to trial vector ($U_{i,j,G}$). After applying the recombination formula, a set of trial vectors ($U_{i,j,G}$) will be produced.

$$U_{i,j,G} = \begin{cases} V_{i,j,G} & \text{when } j \leqslant \vartheta_{i,j,1} \text{ and } j \geqslant \vartheta_{i,j,2} \\ X_{i,j,G} & \text{when } \vartheta_{i,j,1} < j < \vartheta_{i,j,2} \end{cases} \tag{20}$$

From Eq. (20), a series of values in position $\vartheta_{i,j,1}$ to $\vartheta_{i,j,2}$ ($\vartheta_{i,j,1}$ = [0, 1] and $\vartheta_{i,j,2}$ = [0, 1]) of a trial vector will be copied from those of a selected target vector ($V_{i,j,G}$), while remaining positions will be taken from those of a selected mutant vector ($X_{i,j,G}$).

5.4. Selection process

The results of the selection process will be a pre-target vector which will be processed in the reincarnation process. The selection process is applied by using Eq. (21) where $f(U_{i,j,G})$ and $f(X_{i,j,G})$ are the

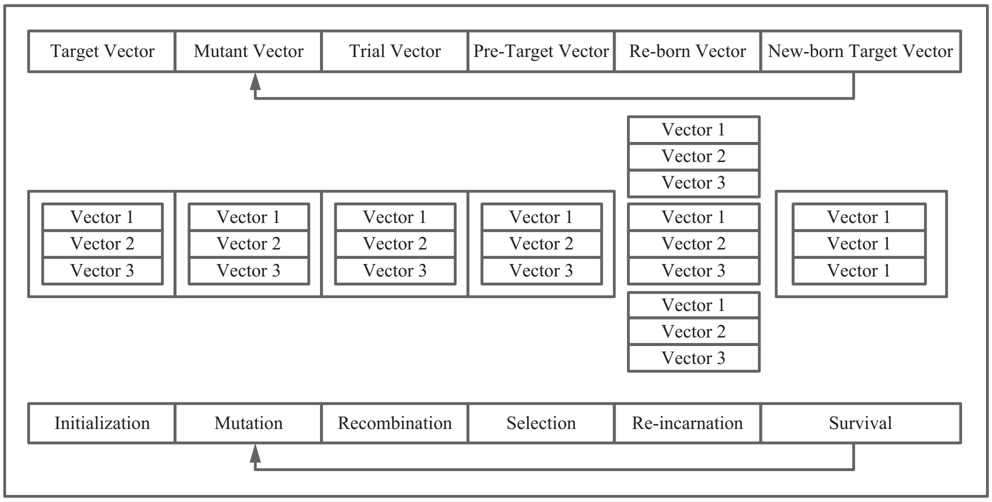

Fig. 3. The framework of modified DE.

Table 1
Example of randomly generated target vectors.

Vector number (*NP*)	1	2	3	4	5	6
1	0.43	0.31	0.07	0.84	0.97	0.53
2	0.54	0.53	0.29	0.13	0.95	0.37
3	0.31	0.73	0.61	0.35	0.50	0.51
4	0.63	0.38	0.08	0.41	0.47	0.89
5	0.36	0.95	0.17	0.40	0.54	0.25

objective functions of the trial vector ($U_{i,j,G}$) and target vector ($X_{i,j,G}$), respectively.

$$X^{pre}_{i,j,G+1} = \begin{cases} U_{i,j,G} & \text{if } f(U_{i,j,G}) \leqslant f(X_{i,j,G}) \\ X_{i,j,G} & \text{otherwise} \end{cases} \tag{21}$$

To obtain the objective function of the trial vector $f(U_{i,j,G})$ and target vector ($X_{i,j,G}$), we can apply the decoding method which can be explained as follows.

5.4.1. The decoding method

The decoding method is used to transform a vector into the problem's solution. The solution of the proposed problem is vehicle routes for transferring raw milk from collection centers to the milk factory with the requirement to serve the dairy factory within an allowable maximum duration of a route, consisting of more than one tank with heterogeneous capacity for each fleet, and no transferring of raw milk from different collection centers into the same compartment. The following example illustrates the decoding method of the problem. Suppose we have 6 milk collection centers (clients or customers), the distance matrix between one depot (label 0) and 6 collection centers (labels 1–6) is shown in Table 2. From this table, the distance matrix can be converted into a traveling time by dividing distance by the speed of the truck which is 60 km/hour. Traveling times can be obtained and are shown in Table 3.

For this example, the amount of milk available at collection centers 1–6 is 20, 10, 2, 11, 5, and 6 tons, respectively. Since, in this example, the rate of service time for loading milk to truck is 0.1 h per ton or 6 min per ton, the service time for loading milk to truck of collection centers 1–6 is 120, 60, 12, 66, 36, and 30 min, respectively. Each truck contains three tanks with the same capacity to collect raw milk (4 tons/compartment). Since the raw milk from different collection centers cannot be transferred into the same compartment, the number of tanks required to serve each collecting center are 5, 3, 1, 3, 2 and 2 respectively.

Table 2
Distance matrix from customer *i* to customer *j* (km).

From/To	0	1	2	3	4	5	6
0	0	20	14	32	17	27	16
1	20	0	35	25	19	20	21
2	14	35	0	21	20	30	40
3	32	25	21	0	30	24	16
4	17	19	20	30	0	27	31
5	27	20	30	24	27	0	28
6	16	21	40	16	31	28	0

Table 3
Traveling times from customer *i* to customer *j* (h).

From/To	0	1	2	3	4	5	6
0	0.00	0.33	0.23	0.53	0.28	0.45	0.27
1	0.33	0.00	0.58	0.42	0.32	0.33	0.35
2	0.23	0.58	0.00	0.35	0.33	0.50	0.67
3	0.53	0.42	0.35	0.00	0.50	0.40	0.27
4	0.28	0.32	0.33	0.50	0.00	0.45	0.52
5	0.45	0.33	0.50	0.40	0.45	0.00	0.47
6	0.27	0.35	0.67	0.27	0.52	0.47	0.00

From Table 1, since the values in positions 1–6 of vector 1 are 0.43, 0.31, 0.07, 0.84, 0.97 and 0.53, respectively, they are then sorted in increasing order as shown in Fig. 4. This order will be used to assign the collection centers to the routes. In this section, two decoding methods of DE are presented: (1) the original decoding method proposed by Worasan et al. (2014) and (2) the decoding method of the proposed modified DE. In the study of Worasan et al. (2014), truck utilization is not considered. Hence, it is considered in this paper in order to minimize the number of trucks used in the system. The details of the original decoding method by Worasan et al. (2014) and the proposed modified decoding method are presented below.

5.4.2. The original decoding method proposed by Worasan et al. (2014)

In the original decoding method, one truck is required to pick up raw milk on only one route. Hence, if there are *r* routes for transporting raw milk, *r* trucks are needed. Details of the decoding method of the original DE can be constructed as in the following procedure:

Customer no.	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining	2	10	20	6	11	5
Number of tanks required	1	3	5	2	3	2

Fig. 4. Result from sorting values of vector 1.

1. **Begin**
2. Set truck number equal 1, $k = 1$, milk farm i is milk factory and $j = 1$ (first collection center in order O_j), $C_k = 0$; // where O_j is the order of milk farm generated by DE mechanism; C_k is used compartment in vehicle k.
3. Truck k goes out from the milk factory at time $e_k = 0$ and arrives at the collection center at $e_k + t_{ij}$
4. **While** $j \leqslant$ Number of collection center **do**
5. **If** $e_k + t_{ij} < l_k$ **do**
6. **If** $N_{jk} \leqslant \eta_k - C_k$ **do** // where N_{jk} is number of compartments in vehicle k that are used by collection center j; η_k is number of compartments that are available in vehicle k
7. Assign collection center j to be served by vehicle k and $C_k = C_k + N_{jk}$
8. update $N_{jk} = 0$; update $e_k = e_k + t_{ij}$
9. update $i = j$; update $j = j + 1$;
10. **else** Assign collection center j to be served by vehicle k
11. Update $N_{jk} = N_{jk} - (\eta_k - C_k)$ update $e_k = 0$;
12. Update $k = k + 1$; $C_k = 0$; *set i = milk factory*
13. **else** $k = k + 1$ set i = milk factory and update $C_k = 0$;;
14. **End**

Start time of the working day is 5:00 a.m. and working day is over at 3:00 p.m. Total working hours are 10 h (or 600 min). Service time and ending time of collection center is also 5:00 a.m. and 3:00 p.m., respectively.

5.4.2.1. Route No. 1: Truck No. 1. First assignment: collection center 3 is firstly assigned to the first route. Currently, the traveling time and service time of this route are 32 and 12 min, respectively. If truck No. 1 goes back to the depot without going further to visit other clients, the traveling time will be 64 min, service time of loading milk into the truck is still 12 min, and time for unloading milk at the depot will be 12 min (0.1 × amount of loading milk out from the truck × 60 min). Then, truck No. 1 will be cleaned for 30 min per tank. Since collection center No. 3 requires 1 tank, the tank cleaning time is 15 min. Therefore, the total time used for truck 1 if it picks up the milk from collection center No. 3 and then goes back to depot will be 103 min (32 + 12 + 32 + 12 + 30). If truck No. 1 leaves the depot at 5.00 a.m., then it is supposed to finish the first route at 6:43 a.m. which is earlier than 15:00 and the number of tanks used is only 1 tank. Therefore, two remaining tanks can be used to serve the next collection center.

Second assignment: Collection center No. 2 will be now assigned in the first truck. Truck No. 1 leaves from depot at 5:00 a.m. and picks up milk from collection center No. 3. Traveling time and loading time of this truck are 32 and 12 min, respectively. Thus, currently, the time used so far in this route is 44 min. If collection center No. 2 is added into this route, the traveling time from collection center No. 3 to collection center No. 2 will be an additional 21 min. Hence, there are two tanks available for Truck No. 1. The tanks capacities are 8 tons (service time is now 48 min). Therefore, collection center No. 2 still has 2 tons to be collected by the next visiting vehicle. Hence, in the first route, truck No. 1 travels from the depot to collection center No. 3, from collection center No. 3 to collection center No. 2, and from collection center No. 2 to the depot. Total traveling time of this route is 67 min (32 + 21 + 14). Loading times of milk into the truck of collection center No. 3 and collection center No. 2 are 12 and 48 min, respectively (2 tanks with capacity of 8 tons), while unloading time is 60 min (12 + 48). Total loading time is 120 min, and total tank cleaning time is 45 min (3 tanks). Hence, total time used if collection centers Nos. 3 and 2 are added into the first route is 232 min (67 + 60 + 60 + 45). The completion time of the first route is 8:52 am. Thus truck No. 1 has completed. Then, the second truck will be operated next with the start time of 5:00 am which is the same as the first truck. After truck No. 1 is assigned, the updated status of amount of milk and number of tanks required for all collection centers is shown in Fig. 5.

5.4.2.2. Route No. 2: Truck No. 2. First assignment: Collection center 2 is firstly assigned to the second route, the route using traveling time 14 min and the service time is 12 min (2 tons). If truck number No. 2 goes back to the depot now, the traveling time will be 24 min and the service time for loading milk into the truck will be 12 min and unloading the milk at the depot will take 12 min. The cleaning time of the truck is 15 min (1 tank). Therefore, the total time which is used for truck 2 (route 2), if truck 1 goes to pick up the milk from collection center 2 and then goes back to the depot will be 67 min (14 + 14 + 12 + 12 + 15) which is less than 600 min, thus collection center No. 2 can be assigned to this route. Truck 2 has 2 tanks (8 tons) remaining to pick up milk from other clients.

The second assignment: Collection center No. 1 will be now put in the second truck (route 2). Currently, travel from depot to collection center No. 2 uses a traveling time of 14 min and loading time of 12 min. Therefore, this route use 26 min. If collection center No. 1 is added into this route, the traveling time from collection center No. 2 to collection center No. 1 is 35 min and loading time of 2 tanks at collection center No. 1 (8 tons) is 48 min. Currently, after 8 tons of milk from collection center No. 1 is loaded in the truck, truck No. 2 has no tank available, thus it has to return to the depot which has traveling time from collection center No. 1 to depot of 20 min. The unloading time is 60 min (12 + 48). This route has traveling time of 69 min (14 + 35 + 20) and loading in and out time of 120 min (12 + 12 + 48 + 48). The cleaning time is 45 min (3 tanks). The total time used in this route is 234 min. This route starts from 5:00 a.m. and finishes at 8:54 a.m. After truck No. 2 is assigned, the updated status of all collection centers is shown in Fig. 6.

This decoding method will be executed until all collection centers are assigned to exactly one route. Suppose the fuel cost is 4 Baht/km, cleaning tanks is 500 Baht/time, the result of the assignment is shown in Table 4. It should be noted here that approximately 30 Baht is one US dollar. From this table, we can see that the total traveling cost is 1376 Baht and total cleaning cost is 8000 Baht resulting in 9376 Baht in total.

5.4.3. The proposed decoding method

The proposed decoding method has two attributes that are different from the one proposed by Worasan et al. (2014). These two attributes are (1) skipped customer attribute and (2) multi-route attribute. Details of each attribute are given below:

```
Begin
Set truck number equal 1, k = 1, milk farm i is milk
factory and j = 1 (first collection center in order O_j),
C_k = 0.
Truck number k goes out from the milk factory at time
e_k = 0 and arrives at the collection center at e_k + t_ij
  While j ≤ Number of collection center do
    If N_jk = 0 then set j = j + 1;
      If e_k + t_ij < l_k do
        If N_jk ≤ η_k − C_k do
        Assign collection center j to be served by vehicle
        k and C_k = C_k + N_jk
        update N_jk = 0; update e_k = e_k + t_ij
        update i = j; update j = j + 1;
        else
          Assign collection center j to be served by
          vehicle k
          Update N_jk = N_jk − (η_k − C_k);
          C_k = 0; set i = milk factory
            While e_k + t_ij < l_k do (multiple route
                  attribute)
              If N_jk ≤ η_k − C_k do
                Assign collection center j to be served
                by vehicle k and C_k = C_k + N_jk
                update N_jk = 0; update e_k = e_k + t_ij
                update i = j; update j = j + 1;
            else
                Assign collection center j to be served
                by vehicle k
                Update N_jk = N_jk − (η_k − C_k);
              C_k = 0; set i = milk factory, update
              e_k = e_k + t_ij
            end
          else
              set s=1;
            while s ≤ Number of collection center
                  (skipped customer attribute)
              if N_sk = 0; set s = s + 1;
                while e_k + t_is < l_k do
                If N_sk ≤ η_k − C_k do
                  Assign collection center s to be served
                  by vehicle k and C_k = C_k + N_sk
                  update N_sk = 0;   update e_k = e_k + t_ij
                  update i = s; update s = s + 1;
                  else
                  Assign collection center s to be served
                  by vehicle k
                  Update N_sk = N_sk − (η_k − C_k);
                C_k = 0; set i = milk factory; k = k + 1;
                Update e_k = 0, C_k = 0;
              endwhile
            endwhile
  endwhile
End
```

(1) For the skipped customer attribute, if the current collection center in position j after sorting cannot be assigned into the current route (k^{th} route), since the completion traveling time of the current collection center exceeds the maximum duration of a route, the remaining collection centers ordered after clients j (i.e., positions $j+1$ to D) are possible to enter to the current route. That means this attribute allows the next possible collection center to be a candidate in the route if the current collection center cannot fit in the route. Hence, instead of creating a new route, the skipped customer attribute allows the new client to be in a route as long as the ending time of a route does not exceed the maximum route duration. However, for the assignment of route No. $k+1$, collection center j will be assigned as the first collection center.

(2) The multi-route attribute allows each truck to pick up the raw milk from more than one route (which each round may be a different route) as long as the maximum route duration is not exceeded.

The new encoding method can be explained as follows.

Truck No. 1: Route No. 1: Start time of the working day is 5:00 a.m. and ending time of working day is 3:00 p.m. Total working hours are 10 h or 600 min. Service time and ending time of collection center is also 5:00 a.m. and 3:00 p.m., respectively.

Collection centers No. 3 and 2 are assigned to the first route yielding total traveling time of 67 min. The loading in and out time is 120 min and the cleaning time is 45 min. Therefore, the total time used in the first route is 232 min. If truck 1 starts to operate at 5:00 a.m., it will complete the first route at 8:52 a.m. The remaining time for truck No. 1 is 368 min. After truck No. 1 is assigned, the updated status is shown in Fig. 7.

Truck No. 1: Route No. 2: Start time of working day is 8:52 a.m. and it is over at 3:00 p.m. Remaining time of this route is 368 min. Service time and ending time of collection center is also 5:00 a.m. and 3:00 p.m., respectively.

Collection center No. 2 (2 tons) and collection center No. 1 (8 tons) are assigned to the second route of truck No. 1. Total traveling time is 69 min. The loading in and out time is 120 min and the cleaning time is 45 min. Therefore, the total time used of the first route is 234 min. If truck No. 1 starts to operate for route No. 2 at 8:52 a.m., it will finish the route at 12.46 a.m. The remaining time to operate for truck No. 1 is 134 min. After truck No. 1 finished serving collection center 2 and partially served collection center 1, the updated status is shown in Fig. 8.

Truck No. 1: Route No. 3: Start time is 12:46 p.m. and working day is over at 3:00 p.m. Time remaining for the route is 134 min. Service time and ending time of collection center is also 5:00 a.m. and 3:00 p.m., respectively.

If collection center No. 1 is assigned to the third route of truck No. 1, its traveling time takes 40 min, loading in and out time (12 tons) is 144 min, and tank cleaning time is 45 min. Therefore, total time used in this route will be 229 min which is greater than 134 min. Therefore, collection center No. 1 cannot be assigned to the third route. The next collection center will be assigned is collection center No. 6. It will take 32 and 72 min for traveling time and loading in and out time (6 tons), respectively. The tank cleaning time is 30 min. Therefore, total time used in this route is 134 min, and there is no time available for this truck. After truck No. 1 finished serving collection center 6, the updated status is shown in Fig. 9.

The process is repeated for truck No. 2 until all collection centers are assigned to any route and the results of the assignments are shown in Table 5.

No. of customers	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining (tons)	0	2	20	6	11	5
Number of tanks required	0	1	5	2	3	2

Fig. 5. Current situation of the sequence of Truck No. 1 using the original decoding method.

No. of customers	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining (tons)	0	0	12	6	11	5
Number of tanks required	0	0	3	2	3	2

Fig. 6. Current situation of the second route of Truck No. 1 using the original decoding method.

Table 4
Results of decoding vector 1 (original DE).

Route No.	Route sequence	Operating time (min)	Distance (km)	Total transportation cost (Baht)	No. of tanks used	Cleaning cost (Baht)	Total cost (Baht)
1	0–3–2–0	232	67	268	3	1500	1768
2	0–2–1–0	234	48	192	3	1500	1692
3	0–1–0	229	40	160	3	1500	1660
4	0–6–4–0	229	64	256	3	1500	1756
5	0–4–5–0	248	71	284	3	1500	1784
6	0–5–0	81	54	216	1	500	716
Total			344	1376	16	8000	9376

Note: Approximately 30 Baht is one US dollar.

No. of customers	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining (tons)	0	2	20	6	11	5
Number of tanks required	0	1	5	2	3	2

Fig. 7. Current situation of the sequence of Truck No. 1 using the new decoding method.

No. of customers	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining (tons)	0	0	12	6	11	5
Number of tanks required	0	0	3	2	3	2

Fig. 8. Current sequence of the second route of Truck No. 1 using the new decoding method.

5.5. Reincarnation process

The reincarnation process allows the new target vector to reincarnate itself to get a better solution. The result of the reincarnation process is the re-born vector. The re-born vector can be represented mathematically as $Y_{i,l,j,G}$ when G is the generation number, i is the vector number ($i = 1, 2, \ldots, NP$), l is the re-born vector number ($l = 1, 2, \ldots, p$ when p is the number of re-born vectors (pre-defined parameters)) and j is the position number ($j = 1, 2, \ldots, J$). Parameter p is also important for the proposed algorithm. In the experiment results we found that the suitable p for our algorithm is five. The method used to generate the re-born process is the k-cyclic move method detailed below.

5.5.1. k-cyclic move technique

If K is the number of moves required and D is the number of collection centers, the procedure of the k-cyclic move method is

(1) Randomly select value of K.
(2) Randomly select K positions out of D positions in a vector.
(3) Cyclic move selected positions.
(4) Re-do steps (1)–(3) until you get enough re-born vectors (p vectors).

In the first step, each vector value of K is randomly selected. The example of the reincarnation process can be explained as follows. If we want to reincarnate vector 2 which is shown in Table 1, firstly,

No. of customers	3	2	1	6	4	5
Real Number	0.07	0.31	0.43	0.53	0.84	0.97
Amount of milk remaining (tons)	0	0	12	0	11	5
Number of tanks required	0	0	3	0	3	2

Fig. 9. Current sequence of the third route of Truck No. 1 using the new decoding method.

Table 5
Results of decoding vector 1 using new decoding method.

Truck No.	Route No.	Route sequence	Operating time	Remaining time of the route	Distance (km)	Total traveling cost (Baht)	No. of tanks	Cleaning of tanks cost (Baht)	Total cost (Baht)
1	1	0–3–2–0	232	368	67	268	3	1500	1768
	2	0–2–1–0	234	134	69	276	3	1500	1776
	3	0–6–0	134	0	32	128	2	1000	1128
2	1	0–1–0	229	371	40	160	3	1500	1660
	2	0–4–0	211	160	34	136	3	1500	1636
	3	0–5–0	144	16	52	208	2	1000	1208
Total					294	1176	16	8000	9176

Note: Approximately 30 Baht is one US dollar.

1	2	3	4	5	6
0.54	0.53	0.29	0.13	0.95	0.37

Fig. 10. Vector 2 which is the original vector to be reincarnated by the reincarnation process.

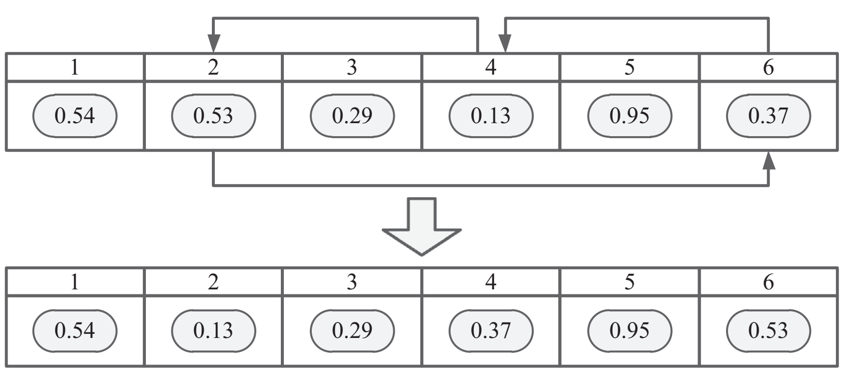

Fig. 11. A re-born vector.

the value of K has to be randomly selected from 2 to D. From Fig. 10, D is 6 and values in position of collection center No. 1 to D are 0.54, 0.53, 0.29, 0.13, 0.95 and 0.37, respectively.

If K is selected as 3, then the second step of the reincarnation process will be performed; 3 out of 6 positions in the vector will be selected. If positions 4, 2 and 6 are selected then these three vectors will have values in these positions cyclically moved, and the result of the move is shown in Fig. 11.

From Fig. 10, values in positions 4, 2, and 6 are 0.13, 0.53, and 0.37. They will be cyclically moved. The original value of position 4 which is 0.13 will be moved to be the value in position 2. The original value of position 2 (0.53) will be the new value of position 6 and the original value of position 6 (0.37) will be the new value of position 4. The new vector is called the *re-born vector*.

Each new target vector will generate p re-born vectors. After p re-born vectors are generated, the decoding method explained in Section 3.4 will be applied for all re-born vectors. One vector with the best objective function out of p re-born target vectors will be selected as the best re-born vector ($Z_{i,j,G}$). Then the survival process will be applied to select the best re-born vector as the new target vector.

5.6. Survival process

The survival process is the selection process of the best re-born vector ($Z_{i,j,G}$) and the pre-target vector ($X^{pre}_{i,j,G+1}$). The better vector between these two vectors will be selected as the new target vector for the next iteration. Eq. (22) is used to find the new target vector for the next iteration of the DE.

$$X_{i,j,G+1}\begin{cases} Z_{i,j,G} & \text{if } f(Z_{i,j,G}) \leqslant f(X^{pre}_{i,j,G+1}) \\ X^{pre}_{i,j,G+1} & \text{otherwise} \end{cases} \tag{22}$$

6. Computational results

In this section, the performance of the modified DE algorithms for the raw milk transportation problem is validated by comparing the optimal solution obtained by the MPL/CPLEX software and the traditional DE and modified DEs. The algorithm is coded with C++ and tested with a PC Intel ® Core ™ i5–2467 M CPU 1.6 GHz for testing and evaluation. In this section, the algorithms are evaluated using two performance measures: (1) amount of total costs consisting of traveling cost and raw milk tank cleaning cost and (2) number of vehicles used. The parameter settings for test instances and the design of test instances are given in Tables 6 and 7, respectively. To compare between the proposed DE algorithms and the original DE, we need to determine the suitable parameter p used in the proposed problem. For the test experiment, 12 large test instances (i.e., instances No. 3–14) are used. The value of p is set to be equal to NP, $NP/2$, $NP/4$ and $NP/6$, where NP is the population or number of clients. The stopping criterion is the time limitation which is set to be 10 min (based on our preliminary experiment that was performed following the research about the stopping criteria for DE of Zielinski et al., 2005, 2006; Zielinski and Laur, 2008). The DE parameters in Table 8 have been defined by the preliminary experiment and some values were set following the results of the existing research).

Table 9 shows the results of the pre-tests. From Table 9, we can conclude that $NP/4$ is the most suitable parameter p for our proposed algorithm. It can find 100% lowest total cost compared with other levels of parameters. $NP/2$ is the second best level of parameter p. From Table 9, we can see that if p is set to be too high, the result is getting worse due to the limitation of computational time. Therefore, too large a neighborhood size cannot find a good solution in a short computational time. However, if p is set to too small a neighborhood size ($NP/6$), the search ability is reduced.

We re-coded the traditional DE (DE-1) proposed by Worasan et al. (2014) and compared it with the modified DE (DE-2 to DE-6) proposed in this paper. The lists of the algorithm characteristics which are re-coded are presented in Table 10. From this table, we can see that the attribute is added to the DE-1 step by step. The skipped customer attribute is added in DE-2 in order to see if it can enhance the traveling costs, while the multi-route attribute is added in DE-3 in order to see if it can reduce the number of vehicles used. We tested our algorithms with 14 randomly generated instances. Each instance was run five times. The stopping criterion used is the run time which was set to 60 min (based on our preliminary experiment that was performed following the research about the stopping criteria for DE of Zielinski et al., 2005, 2006; Zielinski and Laur, 2008).

Table 6
Parameter setting of test instances.

Item	Value	Remarks
No. of compartments of a vehicle	3	
Sizes of vehicles	3	12 tons/vehicle: 4 tons/compartment 9 tons/vehicle: 3 tons/compartment 6 tons/vehicle: 2 tons/compartment
Speed of the truck	60 km/h	
Cleaning raw milk tanks on a vehicle	500 Baht/tank	
Loading time of raw milk to truck	0.1 h per ton	
Fuel cost	4 Baht/km	
Maximum duration of a route	600 min	

Table 7
Design of test instances.

Test instance No.	No. of collection centers	Distance (km)	Amount of raw milk in each collection center (tons)
1	6	15–80	2–15
2	8	15–80	2–15
3	15	15–80	2–20
4			2–20
5	20	15–80	2–15
6			2–20
7	30	15–80	2–15
8			2–20
9	35	15–80	2–15
10			2–15
11	40	15–80	2–20
12			2–15
13		15–80	2–20
14			2–15

Table 8
DE parameters.

Test instance No.	*NP*	*F*	Stopping criterion
1	6	Is set to be 0.8 (Qin et al., 2009)	60 min (based on our preliminary experiment that was performed following the existing research)
2	8		
3	15		
4	15		
5	20		
6	20		
7	30		
8	30		
9	35		
10	35		
11	40		
12	40		
13	40		
14	40		

Table 9
Pre-test results of 10 randomly generated data sets.

No. of test instances	No. of collection centers	Total cost (Baht)			
		NP	NP/2	NP/4	NP/6
1	15	12,100	12,100	12,100	12,100
2	15	11,300	11,300	11,300	11,300
3	20	14,200	14,200	14,200	14,500
4	20	13,500	12,800	12,800	13,100
5	30	19,000	19,000	18,100	19,200
6	30	18,400	18,100	18,000	18,200
7	35	21,800	21,400	21,400	21,500
8	35	20,750	20,230	20,100	20,140
9	40	26,400	26,200	26,200	26,800
10	40	24,500	24,250	23,000	25,420

Note: Approximately 30 Baht is one US dollar.

Table 10
Lists of characteristics of the algorithms.

Attribute No.	Process	DE-1	DE-2	DE-3	DE-4	DE-5	DE-6
1	Initial solution	√	√	√	√	√	√
2	Mutation	√	√	√	√	√	√
3	Recombination	√	√	√	√	√	√
4	Selection	√	√	√	√	√	√
5	Reincarnation			√	√	√	√
6	Survival			√	√	√	√
7	Jumped customer		√		√		√
8	Multi-route		√			√	√

Table 11
Computational results of the total cost and the number of vehicles used for each instance number.

Instance No.	# Of clients	Items	MPL/CPLEX (Optimal solution)	DE-1	DE-2	DE-3	DE-4	DE-5	DE-6
1	6	Traveling cost (Baht)	2084	2084	2084	2084	2084	2084	2084
		Cleaning cost (Baht)	9000	9000	9000	9000	9000	9000	9000
		Total cost (Baht)	11,084	11,084	11,084	11,084	11,084	11,084	11,084
		No. of vehicles used	6	6	6	6	6	6	6
2	8	Traveling cost (Baht)	2392	2392	2392	2392	2392	2392	2392
		Cleaning cost (Baht)	11,500	11,500	11,500	11,500	11,500	11,500	11,500
		Total cost (Baht)	13,892	13,892	13,892	13,892	13,892	13,892	13,892
		No. of vehicles used	8	8	8	8	8	8	8
3	15	Traveling cost (Baht)	[a]	5888	5788	5720	5720	5784	5732
		Cleaning cost (Baht)	[a]	21,000	21,000	21,000	21,000	21,000	21,000
		Total cost (Baht)	[a]	26,888	26,788	26,720	26,720	26,784	26,732
		No. of vehicles used	[a]	14	7	14	14	7	7
4	15	Traveling cost (Baht)	[a]	6432	6396	6316	6316	6364	6320
		Cleaning cost (Baht)	[a]	24,000	24,000	24,000	24,000	24,000	24,000
		Total cost (Baht)	[a]	30,432	30,396	30,316	30,316	30,364	30,320
		No. of vehicles used	[a]	16	9	16	16	9	9
5	20	Traveling cost (Baht)	[a]	6720	6704	6572	6676	6588	6292
		Cleaning cost (Baht)	[a]	24,000	24,000	24,000	24,000	24,000	24,000
		Total cost (Baht)	[a]	30,720	30,704	30,572	30,676	30,588	30,292
		No. of vehicles used	[a]	16	9	16	16	8	8
6	20	Traveling cost (Baht)	[a]	8280	8256	8148	8152	8120	8060
		Cleaning cost (Baht)	[a]	31,000	31,000	31,000	31,000	31,000	31,000
		Total cost (Baht)	[a]	39,280	39,256	39,148	39,152	39,120	39,060
		No. of vehicles used	[a]	21	10	21	21	9	10
7	30	Traveling cost (Baht)	[a]	10,988	10,504	10,576	10,564	10,804	10,504
		Cleaning cost (Baht)	[a]	38,500	38,500	38,500	38,500	38,500	38,500
		Total cost (Baht)	[a]	49,488	49,004	49,076	49,064	49,304	49,004
		No. of vehicles used	[a]	26	13	26	26	12	13
8	30	Traveling cost (Baht)	[a]	14,908	14,676	14,464	14,388	14,476	14,460
		Cleaning cost (Baht)	[a]	49,500	49,500	49,500	49,500	49,500	49,500
		Total cost (Baht)	[a]	64,408	64,176	63,964	63,888	63,976	63,960
		No. of vehicles used	[a]	33	18	33	33	19	16
9	35	Traveling cost (Baht)	[a]	13,380	13,500	12,868	12,832	13,104	12,788
		Cleaning cost (Baht)	[a]	43,000	43,000	43,000	43,000	43,000	43,000
		Total cost (Baht)	[a]	56,380	56,500	55,868	55,832	56,104	55,788
		#of vehicles used	[a]	29	15	29	29	16	16
10	35	Traveling cost (Baht)	[a]	10,964	10,892	10,588	10,328	10,756	9,996
		Cleaning cost (Baht)	[a]	34,500	34,500	34,500	34,500	34,500	34,500
		Total cost (Baht)	[a]	45,464	45,392	45,088	44,828	45,256	44,496
		No. of vehicles used	[a]	23	12	23	23	11	12
11	40	Traveling cost (Baht)	[a]	19,816	19,896	19,548	19,396	19,804	19,804
		Cleaning cost (Baht)	[a]	61,500	61,500	61,500	61,500	61,500	61,500
		Total cost (Baht)	[a]	81,316	81,396	81,048	80,896	81,304	81,304
		No. of vehicles used	[a]	41	22	41	41	18	18
12	40	Traveling cost (Baht)	[a]	15,532	15,664	15,292	15,160	15,288	15,152
		Cleaning cost (Baht)	[a]	48,500	48,500	48,500	48,500	48,500	48,500
		Total cost (Baht)	[a]	64,032	64,164	63,792	63,660	63,788	63,652
		No. of vehicles used	[a]	33	17	33	33	19	17
13	40	Traveling cost (Baht)	[a]	16,772	16,712	15,996	15,748	16,640	15,521
		Cleaning cost (Baht)	[a]	52,500	52,500	52,500	52,500	52,500	52,500
		Total cost (Baht)	[a]	69,272	69,212	68,496	68,248	69,140	68,021
		No. of vehicles used	[a]	35	20	35	35	20	19
14	40	Traveling cost (Baht)	[a]	18,140	18,120	17,384	17,152	17,656	17,050
		Cleaning cost (Baht)	[a]	57,000	57,000	57,000	57,000	57,000	57,000
		Total cost (Baht)	[a]	75,140	75,120	74,384	74,152	74,656	74,050
		No. of vehicles used	[a]	38	23	38	38	23	22

[a] MPL/CPLEX run out of memory, Approximately 30 Baht is one US dollar.

In this paper, two quantities are investigated: (1) the performance (P_{heu}) of the proposed heuristic algorithm (%), obtained by comparing solutions in terms of the total costs to the optimal solutions. It is used to evaluate the solution quality of the proposed heuristic algorithms and (2) the relative improvement (RI) of the solutions in terms of the total costs and number of vehicles obtained by the traditional DE algorithm with respect to those of the modified DE algorithms. The performance (P_{heu}) and the relative improvement (RI) of the solutions obtained from the traditional DE after applying the modified DE algorithms are evaluated and presented below:

Let

$$P_{heu}(Sol_{opt}/Sol_{heu}) \times 100 \tag{23}$$

where

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	DE1 - DE2	59.33333	166.61623	48.09796	-46.52957	165.19624	1.234	11	.243
Pair 2	DE1 - DE3	362.33333	229.44967	66.23641	216.54797	508.11870	5.470	11	.000
Pair 3	DE1 - DE4	449.00000	321.25719	92.73896	244.88292	653.11708	4.842	11	.001
Pair 4	DE1 - DE5	203.00000	139.88177	40.38039	114.12336	291.87664	5.027	11	.000
Pair 5	DE1 - DE6	511.75000	398.39453	115.00660	258.62219	764.87781	4.450	11	.001

Fig. 12. Paired samples test on the total costs.

Sol_{opt}	the optimal solution
Sol_{heu}	the solution obtained from the proposed heuristic algorithm (traditional DE and modified DE algorithms)

Let

$$RI = \{(Sol_{TDE} - Sol_{MDE})/Sol_{TDE}\} \times 100 \quad (24)$$

where

RI	the relative improvement (%) between Sol_{TDE} and Sol_{MDE}
Sol_{TDE}	the solution obtained from the traditional DE algorithm (DE-1)
Sol_{MDE}	the solution obtained from the modified DE algorithms (DE-2, DE-3, ..., DE-6)

Results of the experiments are shown in Table 11. The solution with symbol "*" means the optimal solution cannot be obtained by the CPLEX/MPL since the CPLEX optimizer ran out of memory. To investigate the DE performance, their solutions were compared with those of the mathematical model. In comparing the computational results of DE algorithms with the mathematical model, the DE algorithms (DE-1, DE-3, ..., DE-6) yielded optimal solution (P_{heu} = 100%) for two small sized instances (i.e., instances No. 1 and 2). Based on these results shown in Table 11, *RI* results of the total costs and the number of vehicles used are determined as shown in Tables 12 and 13, respectively. Additionally, based on the results of large instances (i.e., instances No. 3–14), the modified DE algorithms with several attributes added to the traditional DE generate better solutions than those of the classical DE proposed by Worasan et al. (2014). The average relative improvement on the total cost and the number of vehicles used ranges between 0.246–0.968% and 0–48.558%, respectively. For the total costs, DE-6 yields the highest *RI*, while DE-4, DE-3 and DE-5 algorithms are the next three algorithms providing the highest *RI*. Considering the *RI* on the number of vehicles used, the modified DE-6 algorithm provides the highest *RI*, while DE-5 and DE-2 yield the next two highest *RIs*.

From this table, the traveling cost of DE algorithms is different because the algorithms have different characteristics, while the tank cleaning cost of the vehicle does not change. This is because, in this problem, the amount of raw milk from different collection centers cannot be transferred into the same compartment. It results in the same number of vehicles being used to transport the total amount of raw milk from all collection centers to the dairy factory.

To evaluate the performance on the total costs of the proposed DE algorithms and the traditional DE algorithm, the analysis was carried out using SPSS software V14 for windows. Figs. 12 and 13 show the paired samples tests of MPL/CPLEX performed to compare the total cost of the traditional DE and modified DE algorithms, respectively. Results of the tests indicate that there are differences in the *RI* at $\alpha = 0.05$. From Fig. 12, the reincarnation and survival processes included in the modified DE algorithms can significantly enhance the total costs as seen between DE-1 vs. DE-3, because, while using the same computational time, the modified DE can gain advantage from the generation of more

Table 12
Relative improvement of the total costs of the proposed algorithms compared to the traditional DE.

Instance No.	DE-1 vs. DE-2	DE-1 vs. DE-3	DE-1 vs. DE-4	DE-1 vs. DE-5	DE-1 vs. DE-6
3	0.372	0.625	0.625	0.387	0.580
4	0.118	0.381	0.381	0.223	0.368
5	0.052	0.482	0.143	0.430	1.393
6	0.061	0.336	0.326	0.407	0.560
7	0.978	0.833	0.857	0.372	0.978
8	0.360	0.689	0.807	0.671	0.696
9	−0.213	0.908	0.972	0.490	1.050
10	0.158	0.827	1.399	0.458	2.129
11	−0.098	0.330	0.517	0.015	0.015
12	−0.206	0.375	0.581	0.381	0.593
13	0.087	1.120	1.478	0.191	1.806
14	0.027	1.006	1.315	0.644	1.451
Average (%)	0.246[a]	0.659	0.783	0.389	0.968
Maximum (%)	0.978	1.120	1.478	0.671	2.129
Minimum (%)	−0.213	0.330	0.143	0.015	0.015

[a] The average value of the instances with positive relative improvement value.

Table 13
Relative improvement of the vehicles used of the proposed algorithms compared to the traditional DE.

Instance No.	DE-1 vs. DE-2	DE-1 vs. DE-3	DE-1 vs. DE-4	DE-1 vs. DE-5	DE-1 vs. DE-6
3	50.000	0.000	0.000	50.000	50.000
4	43.750	0.000	0.000	43.750	43.750
5	43.750	0.000	0.000	50.000	50.000
6	52.381	0.000	0.000	57.143	52.381
7	50.000	0.000	0.000	53.846	50.000
8	45.455	0.000	0.000	42.424	51.515
9	48.276	0.000	0.000	44.828	44.828
10	47.826	0.000	0.000	52.174	47.826
11	46.341	0.000	0.000	56.098	56.098
12	48.485	0.000	0.000	42.424	48.485
13	42.857	0.000	0.000	42.857	45.714
14	39.474	0.000	0.000	39.474	42.105
Average (%)	46.550	0.000	0.000	47.918	48.558
Maximum (%)	52.381	0.000	0.000	57.143	56.098
Minimum (%)	39.474	0.000	0.000	39.474	42.105

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	DE1 - DE2	12.50000	3.94277	1.13818	9.99488	15.00512	10.982	11	.000
Pair 2	DE1 - DE5	12.83333	4.36585	1.26031	10.05941	15.60726	10.183	11	.000
Pair 3	DE1 - DE6	13.16667	4.74501	1.36977	10.15183	16.18150	9.612	11	.000

Fig. 13. Paired samples test on the number of vehicles used.

solutions at each iteration. The solutions generated from modified DE are generated from the good solutions which are obtained from the original DE (pre-target vector). Therefore, the solutions are continuously improved using the reincarnation and survival processes.

For the skipped customer and multi-route attributes, they are developed for use in the decoding process. From the computational results shown in Table 11, they cannot significantly improve the total costs when they are applied alone (see DE-1 vs. DE-2). However, these two attributes will obtain shorter traveling distance and fewer trucks used in the system if they are used together with the reincarnation and survival processes. The combination of these two attributes works well because whenever the route is formed by the trucks, it always searches for the short distances from the behavior of the skipped customer attribute.

Considering the number of vehicles used, paired samples tests were also performed. Results of the tests show differences in the RI (see Fig. 13). From Fig. 13, the multi-route attribute added in modified DE-3 can reduce the number of trucks used significantly compared to the traditional DE-1, since this attribute allows each truck to be able to travel more than one route as long as the time does not exceed the maximum route duration. Hence, the multi-route attribute provides a lower number of vehicles used.

7. Conclusions

In this paper, modified DE algorithms were developed to determine routes for raw milk collection from a dairy factory, with the objective to minimize the total costs considering traveling costs and costs of cleaning and sanitizing raw milk tanks on the vehicles. This problem is more complex than the general vehicle routing problem (VRP), especially in that each vehicle contains more than one tank with heterogeneous capacity to collect raw milk and raw milk from different collection centers cannot be transferred in the same compartment. The modified DE metaheuristics developed in this study can improve the solution quality obtained over that of the traditional DE, because the modified DE algorithms include two additional steps which are reincarnation and survival processes. In addition, the skipped customer and multi-route attributes are also developed in the decoding process in order to obtain shorter traveling distance and lower truck use in the system, especially if they are used together with the reincarnation and survival processes.

The results also demonstrate that the proposed method is useful not only for reducing the total cost, but also for efficient management of the number of vehicles used. However, our planned future work will be to improve the DE algorithm, since Multi-objective functions need to be studied simultaneously to increase the decision potential, and the method can be hybridized with other powerful metaheuristics to improve the search quality. Another valuable avenue for future research is to consider the mix of the raw milk from different collection centers in the same compartment. We believe that this can add to the ability of our technique to model real world problems and will be a valuable extension. Additionally, although the modified DE algorithm has shown an outstanding ability to solve the problem at hand, there is a possibility to use other metaheuristics or hybrid methods to improve the solutions of the same problem.

Acknowledgment

This work was supported by the Research Unit on System Modeling for Industry (Grant No. SMI.KKU 3/2558), Khon Kaen University, Thailand.

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