Process Capability Indices for Dairy Product's Temperature Control in Dynamic Vehicle Routing

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Abstract. During a delivery process, and in the global transportation network chain, milk and dairy products are considered as sensible and so a higher requirement must be imposed. This paper addresses a vehicle routing problem and propose an optimization model that consider the temperature as a source of uncertainty that has an impact on dairy products. Temperature is maintained and controlled within specified interval and limits, using some sensors introduced inside the vehicles. The process capability indices are introduced to measure the capability of the process, especially thermal characteristics. Dynamic Vehicle Routing (DVR) is presented in this work, optimizing both of the distance traveled and product's temperature. The objective is to deliver products to different BIM stores in El Jadida city, and find the optimal route while maintaining the dairy product Temperature in their optimal values. We propose then a developed algorithm using the meta-heuristic Simulated Annealing (SA) algorithm. Numerical results show the optimized route sequence and also the optimized product's temperature along the route.

Keywords: Dairy product's temperature · Dynamic Vehicle routing (DVR) · Simulated Annealing · Process Capability Indices · Uncertainty

1 Introduction

Please In recent years, there has been a significant increase in the demand for high-quality products. Consumers are more aware of the benefits of consuming fresh and high-quality products. This has led to a growing need to ensure that refrigerated and frozen products are kept at the right temperature to maintain their quality and freshness. Cold chain distribution is a process that involves the transportation of temperature-sensitive products under controlled conditions. This type of distribution is essential for products such as fresh produce, meat, dairy products, and pharmaceuticals. Compared

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to regular distribution, cold chain distribution requires strict temperature control to preserve food quality. Temperature fluctuations can result in spoilage, loss of nutrients, and decreased shelf life, which can impact product quality and safety. Companies responsible for delivering products under cold chain conditions must ensure that their products are delivered to customers in different locations at minimal delivery cost while maintaining the food's quality and reducing product damage. This involves investing in appropriate refrigeration technology, monitoring temperature throughout the transportation process, and training personnel to handle and transport products safely. Maintaining the cold chain can be challenging and costly, but it is necessary to ensure that customers receive high-quality products that meet their expectations. It is also important for companies to adopt sustainable practices that minimize energy consumption and reduce the carbon footprint of their operations. Therefore, the growing demand for high-quality products has made it necessary to prioritize the maintenance of refrigerated and frozen products at the right temperature. Cold chain distribution is essential to ensure that products are delivered to customers in good quality and at minimal cost. Companies must invest in appropriate technology and adopt sustainable practices to maintain the cold chain effectively. In the field of operational research, the Vehicle Routing Problem (VRP) is a well-known problem that deals with the optimal routing of vehicles to visit a set of customers while minimizing the total distance traveled or the total cost incurred. This problem has many practical applications, including in the field of cold chain distribution, where the efficient and effective routing of vehicles is critical to maintaining the quality and freshness of temperature-sensitive products. Using VRP algorithms, companies can optimize their delivery routes and schedules, which can result in significant cost savings while ensuring that products are delivered on time and in good condition. The VRP can also help companies to reduce their carbon footprint by minimizing the number of vehicles needed and the distance traveled, leading to a more sustainable and environmentally friendly cold chain distribution. [1] have presented a model that takes real-time outside temperature into account, serve good quality of food to customers while reducing the distribution cost. Temperature control is critical for the quality and safety of temperature-sensitive products, especially during the distribution stage. When the refrigerator door is opened and closed frequently during distribution, it can lead to temperature fluctuations and damage to the products. Frozen products should be maintained between 4 °C to -1 °C to prevent them from thawing and spoiling. Refrigerated products, such as fresh produce and meat, should be kept between 2 °C to 6 °C to maintain their quality and reduce the risk of bacterial growth. Milk and dairy products are particularly sensitive to temperature, and they should be maintained between 2 °C to 7 °C to prevent spoilage and maintain their freshness. Hence, in cold chain not only minimize the total transportation cost but also keep products in good quality and high safety [2]. To keep product fresh, temperature constraint should be introduced during optimization to consider the temperature variation during the delivery process. The result would impact to reduce products case and increase customer satisfaction. The cold chain is considered as a complex network with cost efficiency, product quality, and carbon emission, environmental impacts, and cost. Hence, one of the most important challenge of the cold chain is to find the balance between cost and product quality. In addition to the cost reduction, dealing with requirements regarding product quality is challenging

[3]. In the same context [4] have developed the Simulated Annealing algorithm to get the optimal distance travelled, respecting the quality level expressed by the Capability Indices (PCI) to distribute perishable food. To keep sensible products fresh, temperature criteria must be introduced in the route optimization of the delivery process in order to control the optimal temperature values, especially during frequent door opening and hot weathers. In addition, short distance delivery, refrigerated and frozen products could be impacted by the high number of doors opening, where there is the heat ingress from outside air ([5] and [6]). There is a growing recognition of the significance of maintaining appropriate temperature conditions in various domains, including transportation, storage, and manufacturing processes. Researchers have emphasized the impact of temperature on crucial parameters such as product integrity, microbial growth, chemical reactions, and sensory attributes. For instance, [7] conducted a comprehensive study on the influence of temperature on microbial growth in food, developing a predictive model for different temperature conditions. Nevertheless, to optimize transportation for temperature-sensitive products, previous studies have primarily focused on minimizing transportation cost without explicitly considering temperature control during the delivery process. For example, [8] proposed an algorithm for fresh meat distribution in Athens, Greece, but did not explicitly analyze temperature variations during the delivery process. The thermal behavior of products was not considered a critical factor in the specific conditions and parameters outlined in their research. Similarly, [9] compared optimization techniques for pharmaceutical distribution in West Jakarta but did not incorporate temperature control as a crucial aspect. In our work, we aim to address the gap in previous studies by explicitly considering temperature variations during the delivery process of dairy products. We recognize the importance of temperature control in preserving the quality and safety of perishable goods, such as dairy products. By incorporating temperature as a critical factor, we intend to provide valuable insights into the optimization of delivery routes that not only minimize transportation time but also ensure appropriate temperature conditions throughout the distribution process. In comparison to previous studies, our work presents a novel approach that considers temperature control during the delivery process of dairy products. By integrating temperature constraints into the vehicle routing problem, we have optimized the route delivery of dairy products while maintaining the temperature within predefined limits.

In this study, we consider a delivery process of multiple products including milk and dairy products that have to be delivered with a minimize cost while keeping products in their optimal temperature value and hence in good quality. To do that, Simulated Annealing algorithm is developed considering the temperature variation during distributing products to some BIM stores in El Jadida city. Sensors have been introduced into the delivery trucks in order to control the temperature values inside the vehicle refrigerator. This paper is recognized as follows: Sect. 2 describes the cold chain transportation, Sect. 3 defines the process capability indices, Sect. 4 presents the mathematical modelling of the Dynamic vehicle Routing and of the Simulated Annealing (SA), Sect. 5 presents the problem description including the context study and computational results, Sect. 6 contains conclusion and perspectives.

2 Literature Review

This section presents an overview of the cold chain management, and the role of refrigerated transports to ensure a good quality of milk and dairy products from the point of temperature to its destination.

2.1 Cold Chain Logistics

The cold chain logistics (CCL) is full of complexity. This complexity is due to the fact that the cold chain involves the transportation of temperature-sensitive products through thermal methods. Cold chain logistics (CCL) can be affected by different factors including temperature variation especially during hot weathers, or during a frequent door opening and a risk to have damaged products is then strongly present. This impact is noticed in general as physical, chemical and biological changes in products. [10] have showed that temperature variation can impact directly the temperature-sensitive product along the cold chain causing quality losses. Hence, temperature can be seen as the most important factor affecting the deterioration rate and postharvest lifetime [11]. Among the different part of cold chain logistics, [12] and [13] have mentioned that transportation and storage are two principles parts of the cold chain. Thus, distribution process should be optimized reducing logistics cost and in the same time avoiding product's waste. [14] considered that quality lost should be included in distribution process of perishable food. In this study, and in order to optimize distribution process while maintaining a good quality of sensitive-product, a temperature control have been introduced, this temperature is related to the time of door opening when servicing a customer. [4] have introduced the temperature criteria during a distribution process of perishable food respecting the quality level, and using the Process Capability Indices (PCI). In general, temperature variation of sensitive products is impacted by the time and the frequency of door opening when servicing the customer, especially in short distances and hot weather. In this context, temperature constraint can be considered as a source of uncertainty that should be added during optimization of the route sequences. Compared with traditional distribution logistics, requirements on product quality in cold chain logistics is a real priority, so ensuring the freshness of temperature-sensitive products is the major problem to be solved in cold chain logistics. To solve this kind of problems, vehicle routing problem (VRP) is used by researchers through literature [15], and [1]. [16] and [17] have studied the normal temperature logistics under stochastic demand. Figure 1 presents the definition of the cold chain logistics.

As shown in Fig. 1, for a good control of the cold chain, and to maintain ambient conditions, temperature variation should be kept in optimal values within the limits of acceptability. In practical terms, the control of an optimal temperature throughout the distribution process is one the most sensible tasks, especially in short distance delivery when temperature-sensitive products can be subjected to many doors opening. As temperature considered as a source of uncertainty, Dynamic Vehicle Routing (DVR) is introduced adding the temperature constraint in the initial objective function. Hence, this work intended to minimize travel cost, and in the same time keeping temperature of products in optimal values.

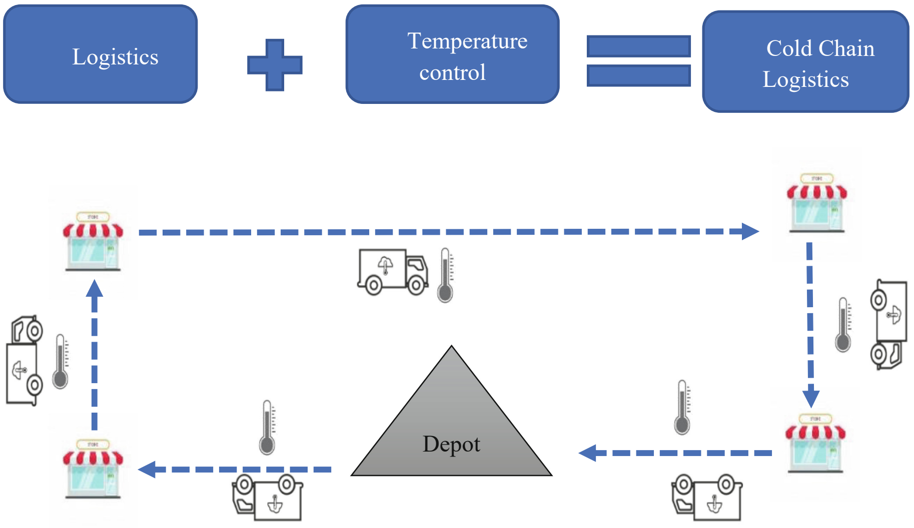

Fig. 1. Cold chain logistics.

2.2 Temperature Performance Analysis

Several models have been introduced temperature aspects in transportation process including ambient conditions, door opening, loading/unloading of products, travel time and others. Some of researchers focused on the effects of transportation temperature on microbial growth and its influence and impact on food safety. [18] and [6] studied the effects of door openings in refrigerated cargo transport. Refrigerated products can be subjected to up to fifty door openings per transportation run [5]. In short distance-transportation of temperature-sensitive products, as in the case of this work, it is important to control the temperature of the product within defined limits. Dynamic nature of the problem is due to the fact, that temperature of sensitive products can be change during distribution process because of the ambient conditions (for example hot weathers), and the frequent door openings where there is heat ingress from outside. These factors converge to produce a complex system, where a good optimization algorithm should be implemented to obtain a balance between optimal cost and optimal product temperature and so to get good quality of products. The classical distribution process starts with a vehicle loaded at the depot and traveling to a series of customers. During the process, product's temperature is assumed to be optimal anywhere in the vehicle along the journey. In this work, to control temperature inside vehicles, sensors have been introduced to measure product's temperature. Sensors indicate input temperature when the driver arrives at the customer, and indicate also the output temperature when the driver leaves the customer. In one hand, when the driver arrives at the customer, temperature is impacted by the "time of door opening" in order to take products from the refrigerator and unload them from the truck. In the other hand, when the driver leaves the customer, temperature is impacted by the travel time: the longer the distance between customers, the more time have products for cooling. Figure 2 explains temperature variation during a delivery process for temperature-sensitive products.

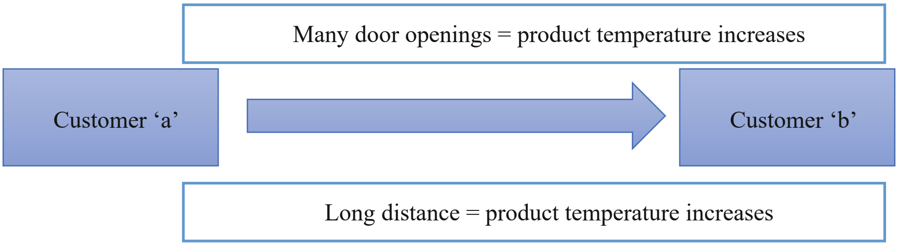

Fig. 2. Temperature variation during delivery process.

As we can see in Fig. 2, temperature variation is affected by both travel time and door opening. These factors have been considering to implement the optimization algorithm. The aim is to minimize the travel cost within maintaining temperature in the optimal values measured by the Process Capability Indices (PCI).

3 Process Capability Indices to Assess Temperature Data

Process Capability indices (CPI) is defined as the ability of the process in achieving whether or not the mean of a measurement. It compares the characteristics of a certain process to its engineering specifications [19]. PCI is highly used as a part of statistical control of quality process and productivity. In this study, we used PCI to measure temperature performance inside the vehicle along the distribution journey for refrigerated products. Hence, temperature is the variable considered in this case. For normal distribution, four capability indices can be used: C_p, C_{pk}, C_{pm}, C_{pmk} [20]. The lesser the standard deviation, the greater the capability indices. We consider μ as the mean, and σ as the standard deviation. That is:

$$C_p = \frac{USL-LSL}{6\sigma} \tag{1}$$

where USL is the upper limit and LSL is the lower limit.

- If $C_p > 1$, then the temperature fits within the specification limits.
- If $C_p < 1$, it means that the process does not meet with the specifications.
- If $1 \leq C_p < 1.33$, it indicates that maybe the process meets with the specifications, but more attention should be taken.
- If $C_p \geq 1.33$, it indicates that the process is fully capable.

In general, the process mean is not assumed to be centered between the specified boundaries. To control these situations the index C_{pk} is defined:

$$C_{pk} = min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right\} \tag{2}$$

In addition, C_{pm} can considers the distance between the mean and the target value:

$$C_{pm} = \frac{USL-LSL}{6\sqrt{\sigma^2+(\mu-T)^2}} \tag{3}$$

where T is the target value.

In our application, we will not define a target value for temperature, it should only respect the specified limits, $USL = 7°C$ and $LSL = 2°C$. Thus, the index C_{pk} is employed.

4 Dynamic Optimization Model

In this section, we present the mathematical modeling of the objective function where the temperature constraint is added. Also, we present the algorithm used in this paper, Simulated Annealing (SA).

4.1 Mathematical Model

We used DVRP in this work to optimize both of cost travel and temperature variation, and a vehicle capacity is respected. Temperature is considered as a source of uncertainty and hence a source of dynamism. We consider "n" customers to be served from "i" to "j", and m vehicles. c_{ij} is the travel cost, x_{ij} is the binary variable that equal 1 if vehicle k goes from customer i to customer j, and x_{ij} equal 0 otherwise. Each vehicle has a maximal capacity Q and each customer is associated with a demand q_i of goods to be delivered. Hence the objective function contains constraint capacity that defines the classical Capacitated Vehicle Routing Problem (CVRP) [21], and contains also the penalty function of the temperature.

The objective function can be presented as follows:

$$Min \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} c_{ij}x_{ij}^{k} + \beta \sum_{i=0}^{n}\left[S\left(T_{(i)in}\right) + S\left(T_{(i)out}\right)\right] \tag{4}$$

where $\left[S\left(T_{(i)in}\right) + S\left(T_{(i)out}\right)\right]$ is the temperature penalty function and β is the penalty coefficient, that is:

$$S(T) = P^{+}(T) + P^{-}(T) \tag{5}$$

where

$$P^{+}(T) = \left(T - T_{upper}\right)^{+} = \begin{cases} 0, & T \le T_{upper} \\ T - T_{upper}, & T > T_{upper} \end{cases} \tag{6}$$

And

$$P^{-}(T) = (T - T_{lower})^{-} = \begin{cases} 0, & T \ge T_{lower} \\ T - T_{lower}, & T < T_{lower} \end{cases} \tag{7}$$

Subject to

$$\sum_{i=0}^{n} \sum_{k=1}^{m} x_{ijk} = 1, \ \ j = 1, \ldots\ldots\ldots n \tag{8}$$

$$\sum\nolimits_{i=0}^{n} x_{ipk} - \sum\nolimits_{j=0}^{n} x_{pjk} = 0,\ k = 1, \ldots\ldots.m;\ p = 1, \ldots\ldots.n \tag{9}$$

$$\sum\nolimits_{i=1}^{n} (q_i \sum\nolimits_{j=0}^{n} x_{ijk}) \le Q,\ k = 1 \ldots\ \ldots\ \ldots m \tag{10}$$

$$\sum\nolimits_{j=1}^{n} x_{0jk} = 1,\ \ k = 1 \ldots\ldots\ldots m \tag{11}$$

Constraint (4) defines the objective function, constraints (5), (6) and (7) define the temperature penalty function, constraint (8) means that every customer should be visited exactly once, constraint (9) shows that every vehicle should depart from the customer visited by this vehicle, constraint (10) means that every vehicle should not exceed the maximal capacity Q, and constraint (11) means that every vehicle must be used exactly once.

4.2 Optimization Algorithm

Simulated Annealing (SA) is a useful meta-heuristic to solve combinatorial optimization problems. It was introduced by [22], it is an approach bases on annealing process of solids. Annealing process is based on heating a material followed by slow cooling procedure to obtain strong crystalline structure. The basic principle of SA is to move from a current solution to a random neighbor in each iteration. If the cost of neighboring solution is less than the one of the current solution, then the neighboring solution is accepted; otherwise, it is accepted or rejected with the probability $p = e^{-\frac{\Delta C}{T}}$. The probability of accepting inferior solutions is a function of the temperature T, and the change in cost between the neighboring solution and the current solution, ΔC. The temperature is decreased during the optimization process and so the probability of accepting a worse solution decreases. First, the temperature T is large and an inferior solution has a high probability of being accepted. During this step, the algorithm acts as a random search to find a promising region in the solution space. The temperature decreases as long as the optimization process progresses, and there is a lower probability of accepting an inferior solution. In general, meta-heuristics algorithms are used to solve large problems called NP-Hard. For example, [23] have used Simulated Annealing to solve large instances for a problem of no-idle open shops scheduling.

5 Case Study of Dairy Products

This section presents the context setting of this paper and numerical results concerning a delivery process of refrigerated products considering the temperature constraint.

5.1 Problem Description and Settings

The case study of this paper concerns delivering refrigerated products from the depot to 10 BIM stores in El Jadida City. The aim is to deliver these temperature-sensitive products in an optimal distance traveled while maintaining product's temperature in optimal values. In this context, we introduce the Dynamic Vehicle Routing to solve this problem using the meta-heuristic Simulated Annealing (SA).

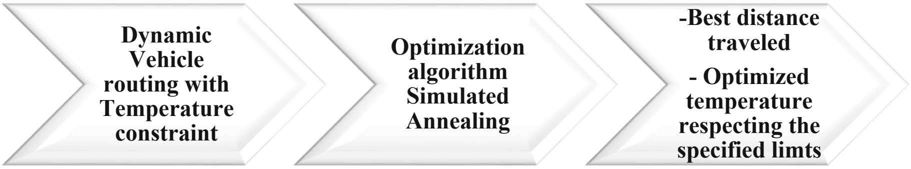

Fig. 3. Optimization process.

Figure 3 explains the optimization process of this study, introducing the Dynamic Vehicle Routing. The objective function is introducing both of minimizing the distance traveled and optimizing product's temperature. The optimized result is given by the developed algorithm Simulated Annealing on MATLAB R2018a.

We apply the following data:

- Customer number: 10 plus one depot
- Truck number: 3
- Store demand: 0, 30, 40, 20, 30, 50, 25, 10, 20, 30, 50
- Truck capacity: 110 (assume that all trucks have the same capacity = 110 box)

The matrix distance is calculated based on the customer's location (longitude and latitude from Google map). Temperature variation is calculated considering the travel time as a random variable, and the time of refrigerator door opening is based on experimental data. Such that the temperature decreases if the travel time is large, and temperature increases if we have frequent door opening, or when the time of refrigerator door opening is higher.

5.2 Computational Results and Discussion

In this work, we present route optimization and in the same time controlling temperature of milk and dairy products that must be maintained in an interval of 2 °C to 7 °C, for a delivery process to 10 BIM stores in El Jadida city. The optimization algorithm used in this work is the Simulated Annealing (SA), and Fig. 4 presents the optimized route sequence designed and (Fig. 5) presents the best cost Iteration:

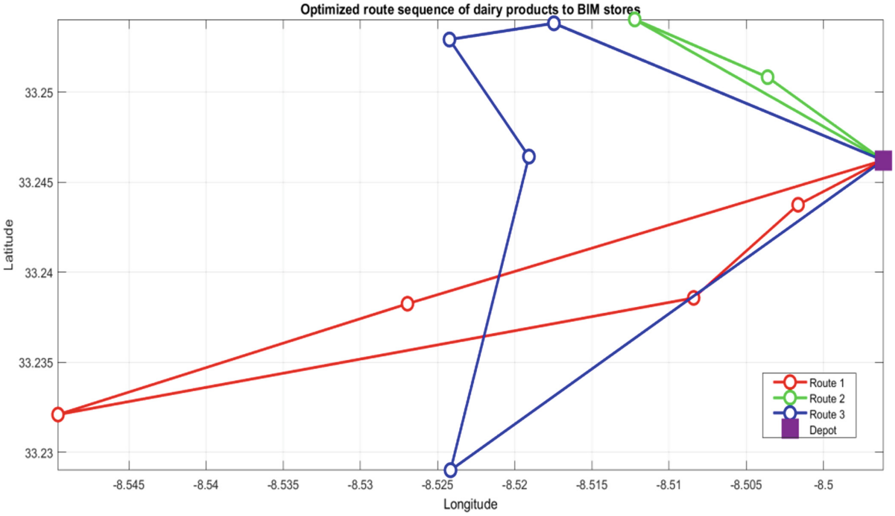

Fig. 4. Optimized route sequence.

In the figure above, optimized route sequence is presented using 100 iteration:

- **Route 1:** El Wahda -- > Touria Chaoui -- > Mwilha -- > Al Moukawama, $\boldsymbol{\mu} = 4.84$,$\boldsymbol{\sigma} = 0.66$, $\boldsymbol{C_{pk}} = 1.09$**:** in this route we can conclude that the process is capable but with tight control.
- **Route 2:** Alaouine -- > Sidi Bouzid -- > Khalil jabrane -- > Ibnou Badis, $\boldsymbol{\mu} = 4.76$, $\boldsymbol{\sigma} = 0.5$, $\boldsymbol{C_{pk}} = 1.49$**:** in this route, we conclude that the process is capable.
- **Route 3:** Mohamed Errafii -- > Lala Zahra, $\boldsymbol{\mu} = 4.35$, $\boldsymbol{\sigma} = 0.58$, $\boldsymbol{C_{pk}} = 1.35$: **in this route, the process is** capable.

C_{pk} is obtained by considering the mean μ and σ of each route, it was computed basing on the Eq. (2).

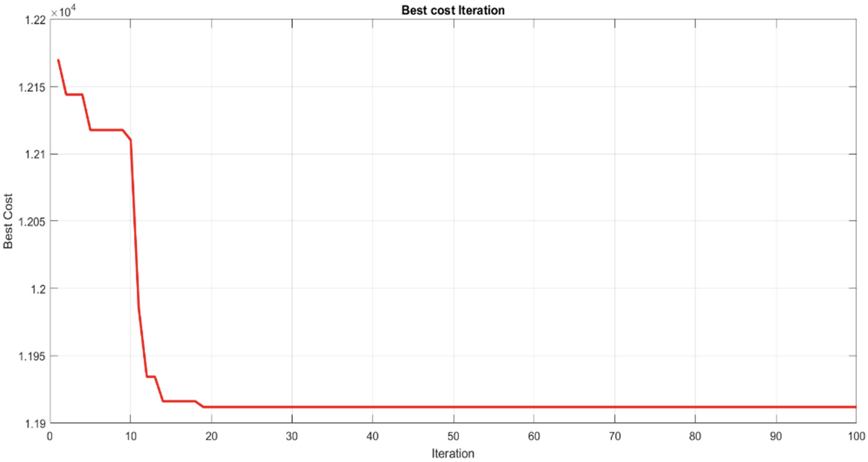

Fig. 5. Best cost Iteration.

The optimization of temperature control in the cold chain distribution system is of paramount importance to maintain the quality of dairy products during transportation. In addition to the optimized route sequence, the temperature values are also considered as an important parameter to be optimized. By using the developed algorithm, the temperature values are kept within the optimal interval, which lies between the specified limits of the milk and the dairy products, where USL = 7 °C and LSL = 2 °C. This ensures that the quality of the products is maintained and that they are following the specified limits. Then the optimized temperature is presented as follows:

For route 1:

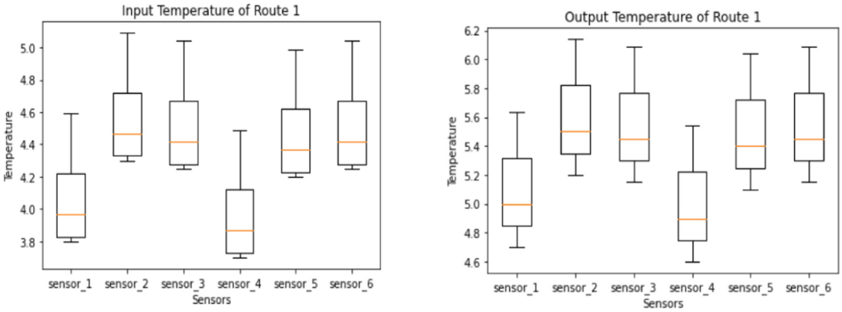

Fig. 6. Boxplot of Input and Output temperature of route 1.

For route 2:

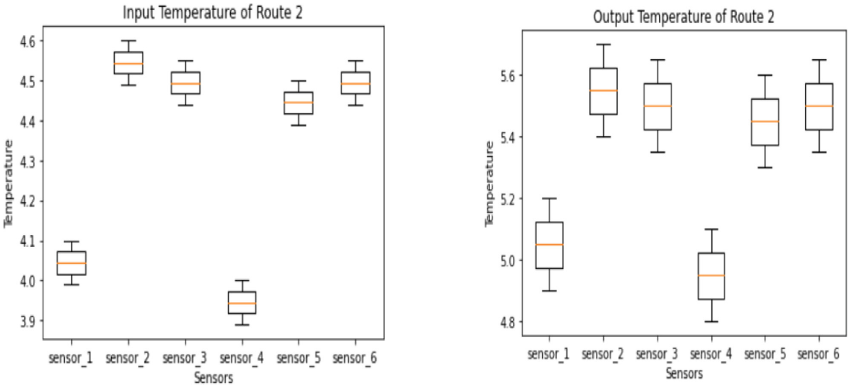

Fig. 7. Boxplot of Input and Output temperature of route 2.

For route 3:

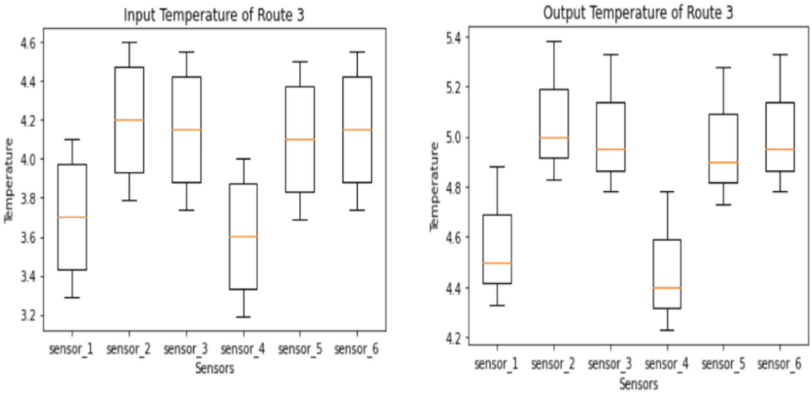

Fig. 8. Boxplot of Input and Output temperature of route 3.

Figures 6, 7, and 8 presents the boxplot of temperature values that were kept within the optimal range during cold chain distribution. The input temperature refers to the temperature of the product when the distributor arrives at the customer's location, while the output temperature represents the temperature of the product when the distributor leaves the customer's location, considering factors such as door opening frequency and discharging time. In addition, results of the developed model indicate that the product characteristics, especially product temperature inside the vehicle is related to travel time and its variation along the delivery route. Hence, specified surveillance and high attention have to be given to the product quality along short distance delivery route, and during hot weather conditions as well.

6 Conclusion and Perspectives

In this work, we propose a novel approach to the Vehicle Routing Problem (VRP) by incorporating temperature constraints as part of the objective function. The goal is to optimize the delivery route to minimize cost while simultaneously maintaining the quality of dairy products by ensuring they are kept at the appropriate temperature. The algorithm developed was applied to a simple case study, but the approach can be extended to more complex delivery processes with a larger number of customers. One of the challenges in incorporating temperature as a constraint is that it introduces an element of uncertainty, as temperature can fluctuate based on external factors such as weather conditions and door opening frequency. Temperature is considered in this work as a source of uncertainty. Hence, in future work, we can apply the simheuristic methods considering stochastic parameters such as travel time, loading/unloading time, etc. Simheuristic algorithms are very closed to a real-life distribution and transportation problems where several variables and parameters are modeled as random.

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