ROUTING EFFECTS ON THE THERMAL PERFORMANCE OF REFRIGERATED VEHICLES IN THE DISTRIBUTION OF PERISHABLE PRODUCTS

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ABSTRACT

The temperature of chilled and frozen products along the distribution process must be maintained within close limits to ensure optimum food safety levels and high quality. The variation of cargo temperature along the vehicle routing sequence is represented by non-linear functions which depend on the process stage (line haul, unloading at customer's premises, local displacements, etc.). The temperature variability is also correlated with the time required for the refrigeration unit to recover after cargo unloading, due to door openings and the cargo discharging process. The vehicle routing optimization strategy employed in traditional cargo distribution applications is generally based on a *TSP* (Travelling Salesman Problem) sequence, with the objective of minimizing travelled distance or time. It is shown in the paper that in order to maintain the temperature variability within adequate restriction limits, other routing strategies, apart from the *TSP* criterion, should be considered.

Keywords: cold chain, perishable cargo distribution, TTI, vehicle routing

1 INTRODUCTION

Lifestyle changes over the past decades led to increasing consumption of refrigerated and frozen foods, which are easier and quicker to prepare than the traditional types of food. In order to ensure product quality and health safety, the control of temperature throughout the cold chain is necessary. Since temperature largely determines the rate of microbial activity, which is the main cause of spoilage of most fresh food products, continuous monitoring of the full time temperature history usually allows for an adequate control of the process along the short and medium distance distribution situations (Giannakourou et al, 2005; Garcia, 2008). In practical terms, the maintenance of an adequate temperature throughout the postproduction handling chain is one of the most difficult tasks, and is far from being universally attained. In short or medium distance delivery runs, the chilled or frozen product can be subjected to many door openings, where there is heat ingress directly from outside air and from personnel entering to select and remove product (James et al, 2006; Pereira et al, 2010). Additionally, the design of the vehicle refrigeration system has to allow for extensive variation in load distribution, which is a function of different delivery rounds, days of the week and the removal of product during a delivery run (Tassou et al, 2009; 2012). As a result, there are substantial difficulties in maintaining the temperature of refrigerated products transported in small and medium-size refrigerated vehicles that perform multi-drop deliveries to retail stores and caterers (James et al, 2006).

This paper reports a Time–Temperature Integrators (TTI) analysis of a distribution case of refrigerated products along a route containing a number of retail customers with different demand levels. TTI are defined as specific devices that can show an easily measurable, time and temperature dependent changes that cumulatively indicate the thermal history of the product from the point of manufacture to its destination (Giannakourou et al, 2005; Estrada-Flores and Eddy, 2006; Sahin et al, 2007). Process Capability Indices (PCI), on the other hand, can additionally be calculated to yield easily computed coefficients measured with dimensionless functions on TTI parameters and specifications (Chang and Bai, 2001; Chang et al, 2002; Estrada-Flores and Eddy, 2006). This kind of TTI application, combined with PCI analysis, helps to reveal undesired thermal conditions that may impair the compliance of product quality requirements along the supply chain.

Problems on the distribution of fresh food are analysed by Tarantilis and Kiranoudis (2002) and Oswald and Stirn (2008). This paper analyses alternative vehicle routing strategies intended to minimize travel cost, but at same time keeping thermal PCI performance indicators within the required levels. It is shown that the standard *TSP (Travelling Salesman Problem)* approach, used to solve classical routing problems where vehicle travel distance or time is minimized, usually leads to temperature restriction violations. Thus, instead of using a heuristic routine to get the optimized *TSP* vehicle routing sequence, such as the largely employed 2-opt and 3-opt improvement methods (Syslo *et al*, 2006), other routing strategies, apart from the *TSP* criterion, are considered.

2 THERMAL PERFORMANCE ANALYSES

Papers investigating the thermal performance of refrigerated vehicles can be classified into four groups: (a) approaches of pure theoretical nature, (b) performance laboratory tests, (c) experimental field tests, and (d) TTI-based simulations. Studies of the first group use pure mathematical CFD (computational fluid dynamics) models based on physical aspects of heat transfer (Cuesta et al, 1990; Zhang et al, 1994, Campañone et al, 2002). In the second group are the papers describing controlled laboratory tests, such as Moureh and Derens (2000), Tso et al (2002), Estrada-Flores and Eddy (2006), and Garcia (2008). In the third group are the papers involving field tests, with information eventually supplemented with laboratory data, such as the CoolVan experiment (Gigiel et al, 1998; James and Scholfield, 1998; James et al, 2006), as well as other similar efforts (Giannakourou et al, 2005; Pereira et al, 2010; Nga, 2010). The fourth group comprises TTI – Time-Temperature Indicator analyses, usually employing computer simulations (CoolVan Manual, 2000, Hoang et al, 2012a,b). Of course, a good part of these papers employ combined methods.

2.1 Theoretical models

Laguerre and Flick (2010) and Flick et al (2012) developed a simplified steady-state heat transfer model for a loaded refrigerated unit. Let T_C be the temperature of the cold wall, T_W the temperature of the warm wall, and T_L the temperature of the load, all of then expressed in Kelvin degrees (K). Assuming the thermal steady state has been reached, one has (Laguerre and Flick, 2010)

$$(T_C - T_L) = \alpha_L \, (T_W - T_L), \quad \text{with} \tag{1}$$

$$\alpha_L = \exp\left[-K_{value} \left(\frac{A_L}{f_m \, C_p}\right)\right], \tag{2}$$

where K_{value} is the heat transfer coefficient $(W \, m^{-2} K^{-1})$, A_L is the load surface, f_m is the mass flow rate of the air in the refrigerated unit $(Kg \;\, s^{-1})$, and C_p is the air heat capacity $(J \; kg^{-1} \; K^{-1})$. In a refrigerated truck, the cooling process is not the same, but a similar relationship among variables still holds. However, during the most part of a cold food distribution process, the heat transfer follows a sequence of transient states, and equations (1) and (2) do not apply.

Hoang et al (2012) presented a mathematical expression to measure the evolution of the temperature of a product placed inside a refrigerated container

$$\theta_i(\tau) = \theta_0 + \left(\theta_i^{(load)} - \theta_0\right) \, \exp\left(-\frac{H_i \, \tau}{m_i \, C_i}\right), \tag{3}$$

where $\theta_i(\tau)$ is the temperature of the product i at time τ, θ_0 is the temperature inside the refrigerated container, $\theta_i^{(load)}$ is the temperature of the product i at loading time, H_i is the heat transfer conductance of product i $(W \; K^{-1})$, m_i is the mass of product i (kg), and C_i is the thermal capacity of the product $(J \; kg^{-1} \; k^{-1})$. It is assumed that $\theta_i^{(load)} > \theta_0$.

The paper by Ge and Tassou (2001) presents a comprehensive model, based on the finite difference technique, to predict and optimise the performance of air curtains. Air curtains are widely used in doorways of retail premises, as well as doors of refrigerated vehicles. The main purpose of the air curtain is to reduce the air exchange and hence heat and moisture transfer between the conditioned environment and the surrounding ambient. The model was validated against results from tests on a vertical refrigerated display cabinet air curtain.

Apart from the research results summarized above, the literature shows a good number of papers dealing with theoretical approaches to problems related to the thermal performance of refrigerated vehicles.

2.2 Thermal performance laboratory tests

Thermal performance laboratory tests serve as benchmarking instruments to compare diverse refrigerated transport systems and to ensure that these systems provide a minimum level of operating effectiveness. Relevant laboratory tests (Moureth et al, 2002; Estrada-Flores and Eddy, 2006; Nga, 2010) normally evaluate the insulation effectiveness (heat leakage) of the insulated body, measured as a K_{value} (overall heat transfer coefficient), by means of creating a temperature differential of no less than 20 ^{0}C between the cargo space and the external environment. Estrada-Flores and Eddy (2006) research included measurement of at least 12 temperatures encompassing the corners, sidewalls, ceiling and floor of the vehicle. Another performance test evaluates the ability of the truck to maintain the set-point temperature within the cargo space during 8 h of uninterrupted operation. The vehicle was tested for a further 4 h with an additional heat load. A third trial was the *in-service,* or *pull-down* test, which measures the time required to cool down the empty truck to the pre-established temperature.

Tso et al (2002) performed an experimental study on the heat and mass transfer characteristics in the body of a refrigerated truck for cases without an air curtain, with a fan air curtain and with a plastic strip curtain. The main purpose of door curtains in refrigerated vehicles is to reduce the air exchange and hence heat and moisture transfer between the conditioned environment and the surrounding ambient. In fact, during delivery runs, the chilled product can be subjected to many door openings, where there is heat ingress directly from outside air and from personnel entering to select and remove the product. In the Tso et al (2002) experiment, the testing focus was the temperature variation and the relative humidity inside the stationary truck during a short period after the door was opened. Comparison between the experiment and numerical results showed reasonable agreement in terms of average temperature inside the body. The test results showed that, in general, when the truck door is opened, the average temperature and relative humidity of the air inside the body increase rapidly. It could be deduced from the tests that both air and plastic strip curtains are useful to prevent hot air from infiltrating into the refrigerated body when the door is opened. It was observed that the air curtain would become less effective when the ambient temperature is too high (> 40 ^{O}C). For the cases without any protective device across the door, the rate of temperature rise is the highest, as expected. From temperature comparisons, it could be deduced that the plastic strip curtain is able to reduce hot air infiltrating into the refrigerated space, but would not be as effective as the air curtain. Other papers also report thermal performance laboratory tests as, for example, Moureh and Derens (2000), Ge and Tassou (2001), and Garcia (2008), among others.

2.3 Time-Temperature Indicators (TTI) associated with simulation models

A number of papers on refrigerated food address the TTI evaluation along the cold chain process (Gigiel et al, 1998; James and Scholfield, 1998; Jacxsens et al, 2002; Giannakourou and Taoukis, 2003; Giannakourou et al, 2005; Estrada-Flores and Eddy, 2006). The main purpose of maintaining good temperature control during refrigerated transport is to decrease the rate of microbial growth and hence maintaining the safety and eating quality of the food. In fact, there are many microbial models that can be applied to represent the growth of microorganisms in food during transport. But since temperature largely determines the rate of microbial activity, which is the main cause of spoilage of most fresh and frozen food products, continuous monitoring of the full time temperature history usually allows for the adequate control of the process along medium distance distribution situations.

One of the most systematic attempts to predict the temperature of refrigerated food during multi-drop deliveries has been the CoolVan research programme. CoolVan is a software developed by the Food Refrigeration and Process Engineering Research Centre at the University of Bristol, UK. The brief description set forth was extracted from Gigiel (1997), Gigiel et al (1998), and the Cool Van Manual (2000).The objective of CoolVan is to aid the design and operation of small and medium delivery vehicles intended to distribute refrigerated food products (Gigiel, 1997; Gigiel et al, 1998; James and Schofield, 1998; James et al, 2006; CoolVan Manual, 2000). The software contains a mathematical model that predicts food temperatures inside a refrigerated delivery vehicle, analysing the temperature changes that take place during a delivery journey as well as the energy used by the refrigeration equipment. The model is solved using an implicit finite difference method. It starts with the given initial conditions and proceeds to the end of the journey with variable time steps. The heart of the CoolVan program is the temperature of air inside the vehicle. The internal air exchanges heat with the outside environment by the movement of air into and out of the truck, while the doors are either opened or closed.

The usual food distribution scheme starts with the vehicle being loaded at the distributor’s premises and travelling next to a series of retail outlets, where the individual lots are discharged in sequence. Often, the vehicle has a large number of servicing stops in a journey, when the doors are opened and food is removed. Sometimes, food which has passed its shelf-life date, together with empty trays, return from the retail shops to the distributor. In another cases the insulation, door protection and refrigeration equipment fitted to the vans prove to be inadequate to maintain food temperature as cold as required. Vehicle data are fed into the CoolVan program: the thermal properties of the insulation system, the year of the van manufacture, the ageing rate which depends on the vehicle maintenance characteristics, etc. Then, the program calculates the reduced thermal properties of the vehicle insulation. The mathematical structure of the program also allows for different external heat transfer coefficients to be entered for each side of the vehicle. Solar radiation onto each surface of the van is modelled separately. The infiltration of outside air into the van is dependent on the van structure, the degree of maintenance and the speed of the vehicle. These effects were measured empirically in several vans, allowing for the fitting of appropriate equations and parameters into the model.

2.4 Thermal performance field tests

To confirm the possible effectiveness of TTI as monitoring tools in the real distribution of refrigerated products, and detect the eventual problematic points of its application, field tests are frequently performed. These tests simulate in reality the temperature conditions recorded in laboratory experiments or predicted through theoretical models.
Simpson et al (2012) report a TTI monitoring field test covering a multimodal fresh salmon transport from Puerto-Montt (Chile) to Gainesville (Florida). Another interesting field test was performed in 2007 by Pereira et al (2010). The tests were carried out in the Campinas region, state of São Paulo, Brazil, where the authors installed sensors in a refrigerated truck operated by a large industry of refrigerated and frozen meat products. These tests were performed in August and September 2007. The delivery tours started from the company's distribution centre and attended retail outlets in towns placed around the town of Campinas. TTI data were gathered from seven daily delivery tours of cold food products. The vehicle rounds covered different days of the week, with a total of 60 delivery stops, representing an average of 8.6 stops per tour. There was a tour with only 2 stops, and another with 28 stops, showing great variability in the number of delivery calls per round.

Field tests, as this one performed by Pereira et al (2010), are important to detect drawbacks in the local cold chain practice. They indicate technical aspects and logistics operating points that require improvements. For instance, the combined distribution of chilled and frozen products in the way it has been performed in several cases in Brazil must be revised, since the performance results are frequently poor.

3 PROCESS CAPABILITY INDICES TO ASSESS THERMAL PERFORMANCE

Process Capability Indices (PCI) are frequently used as an integral part of the statistical control of process quality and productivity. The relationship between the actual process performance and the specification limits or tolerance may be quantified using appropriate variables. We closely follow Chang and Bai (2001), Chang et al (2002) and Estrada-Flores and Eddy (2006) in applying PCI analysis to the distribution of refrigerated food products.

Let *USL* and *LSL*, respectively, be the upper and lower value limits of the specified temperature to carry the refrigerated product in analysis. The two most widely used standard PCIs are *Cp* and *Cpk* defined as (Chang et al, 2002)

$$C_p = \frac{USL - LSL}{6\sigma} \tag{4}$$

$$C_{pk} = min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\}, \tag{5}$$

where μ and σ are, respectively, the mean and the standard deviation of the temperature θ inside the vehicle, and assuming θ is normally distributed. The first coefficient C_p is defined as the ratio of the allowable tolerance spread and the actual spread of the data. If $C_p > 1$ it indicates that the temperature variation fits within the specified temperature limits.

On the other hand, the coefficient C_{pk} accounts for the data that is normally distributed but it is not centred on the targeted mean μ (Pearn and Chen, 1999; Estrada-Flores and Eddy, 2006).

As a rule of thumb, a $C_{pk} = 1.33$ or higher is indicative of a capable process. In this application, a capable process means that a vehicle will be able to maintain a temperature distribution along the journey within the specification limits all the time (Estrada-Flores and Eddy, 2006). When the distribution of ϑ is normal and the mean is at the midpoint of *USL* and *LSL*, then $C_p = C_{pk} = 1$, implying that 99.73% of the observations will fall within the specified values of ϑ. In such a case, the proportion of non-conforming items will be only 0.27%. In many situations, however, the probability distribution of the evaluating variable is not normal, showing a skewed pattern instead. As it will be seen in Section 5, this is the case of this application. Several approaches to the *PCI* problem with skewed populations have been suggested in the literature *(*Chang et al, 2002*)*. Some methods are complicate to apply or require large samples. A simple approximate method for adjusting the values of *PCI* by considering the skewness of the underlying population is due to Chang and Bai (2001).

The method is based on the idea that σ can be divided into upper and lower deviations, σ_U and σ_L , which represent the dispersions of the upper and lower sides around the mean μ, respectively. An asymmetric probability density function $f(x)$ can be approximated with two normal pdfs

$$f_U(x) = \frac{1}{2\sigma_U}\, \emptyset\left[\frac{\theta-\mu}{2\sigma_U}\right] \quad \text{and} \quad f_L(x) = \frac{1}{2\sigma_L}\, \emptyset\left[\frac{\theta-\mu}{2\sigma_L}\right], \tag{6}$$

with the same mean μ but different standard deviations $2\sigma_U$ and $2\sigma_L$, where $\emptyset$ represents the standard normal pdf. The upper and lower sides of $f(\theta)$ are approximated with the upper side of $f_U(x)$ and the lower side of $f_L(x)$, respectively. The values of σ_U and σ_L are computed as (Chang et al, 2002)

$$\sigma_U = P_\theta\, \sigma \quad \text{and} \quad \sigma_L = (1 - P_\theta)\, \sigma, \quad \text{with} \quad P_\theta = Pr\{\theta \le \mu\} \tag{7}$$

The C_p based on the Chang and Bai (2002) method , after some transformations, is

$$C_p = \frac{USL-LSL}{6\sigma}\, \frac{1}{D_\theta}, \tag{8}$$

with $D_\theta = 1 + |1 - 2P_\theta|$ and where $1/D_\theta$ is a corrective coefficient on (8) due to the skewness of the probability distribution of ϑ (Chang et al, 2002). On the other hand, according to the Chang and Bai (2002) method, the value of C_{pk} corrected for skewness can be estimated as

$$C_{pk} = min\left\{C_{pk}^{(U)}, C_{pk}^{(L)}\right\} = min\left\{\frac{USL-\mu}{6\, P_\theta\, \sigma}, \frac{\mu-LSL}{6\,(1-P_\theta)\,\sigma}\right\} \tag{9}$$

4. PROBLEM DESCRIPTION

The objective of the problem is to analyse a regional distribution of ready-to-eat refrigerated meat products (ham, turkey and chicken breasts, salami, sausage). The urban distribution district is located about 84 km from the base depot. The served urban district has an approximated area of 73 sq.km, where are located 12 retail shops to be attended, as shown in Figure 1. Traditionally, the optimal sequence of points to be visited is the one obtained via a TSP (Travelling Salesman Problem) algorithm, which yields the shortest Hamiltonian cycle that includes, in this application, all the retail outlets, plus the depot. Figure 1 depicts the TSP route, obtained with a 3-opt local search heuristic (Syslo et al, 2006), with a total extension of 204.1 km.

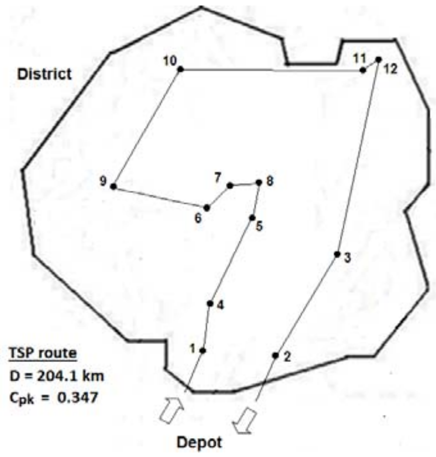

Figure 1 – Vehicle TSP route

The search for an optimal vehicle routing sequence requires quite a number of combinatory evaluations. On the other hand, the process for obtaining accurate TTI data is not a simple task, since it requires special laboratory settings (Section 2.2) and/or elaborate field tests (Section 2.4). One possibility is to apply the simulation approach, such as the CoolVan software (Section 2.3), in order to gather basic data to be used in a computer-aided routing analysis. This is because the CoolVan program does not permit automatic replications of the runs, whereas combinatorial routeing analysis implies automatic changes of the delivering sequences in order to obtain the corresponding TTI evaluating results. In fact, the basic objective of the CoolVan effort was to produce a program that could be used by transport managers to predict food temperature during a given journey (Gigiel, 1997).

After analysing the pro and con of the modelling possibilities, a hybrid approach was devised. It involves a combination of methods divided in three steps. First, the CoolVan software was used to simulate the thermal characteristics of the basic routing scheme represented by the TSP formulation as shown in Figure 1. Next, taking the CoolVan simulation results, the operating stages that compose the temperature evolution along the distribution journey were analysed individually in order to define mathematical functions that relate temperature to the explaining variables. Third, a computer program was developed to estimate temperature levels step by step, considering different delivering sequences and forming TTI sets. PCI coefficients are then computed in order to analyse the thermal performance of the delivery sequences, leading to an optimal solution that minimizes travelled distance, but at same time maintaining temperature levels within satisfactory limits. This methodology will be described in more detail in the next sections.

This line of research has some points in common with the work by Oswald and Stirn (2008). Their approach differs from the present investigation in two aspects. First, the variable that expresses product quality in our research is temperature, whereas in Oswald and Stirn paper (2008) product quality is based on market acceptance. One has 100% quality when the product can be sold entirely at the current market price and the quality drops to 0% when the product loses completely its commercial value (Oswald and Stirn, 2008). Second, the mathematical routing model developed by these authors builds up the routes to be assigned to the vehicles step by step, while in this application there is only one truck and the best route is searched in a combinatorial way.

4.1 CoolVan Simulation

Presently, the CoolVan software is not available commercially, but its developers kindly offered to ran the basic TSP configuration to serve as a data base for this application. The necessary inputs for the simulation are presented in Table 1. Next, the food data are fed into the CoolVan program (CoolVan Manual, 2000). The product is ready-to-eat refrigerated meat products (ham, turkey and chicken breasts, salami, sausage). A total of 12,000 kg of assorted products are distributed in the daily round, with two retailers receiving larger quantities (7,000 and 2,000 kg respectively), while the other ten clients getting 300 kg each (Table 2). The basic delivery sequence shown in Table 2 is the one obtained via the TSP optimization algorithm, with a total travelled distance of 204.1 km. Table 2 also shows the distance travelled along the various segments of the route and the delivering time at the retail premises. As previously mentioned, the time steps in the CoolVan simulation vary along the run. The size of these time steps increase when there are few events during the journey. The time steps decrease, however, in order to represent in detail any special event which occurs, as for example, the opening of the door at a client premise. In the CoolVan run the average time step was 1.47 minutes. The results of the CoolVan simulation are saved in Excel format. The program also plots on the screen the output data graphically allowing the visual inspection of the thermal evolution during the journey. The simulation starts with a line-haul phase, which goes from the depot to the first client in the district, and taking 84.3 minutes (line-haul I in Figure 2). It is followed by a sequence of visits, intercalating cargo discharging tasks with vehicle displacements between successive delivery points. Finally, there is the line-haul II segment, linking the last served client to the depot (Figure 2).

4.2 Operating stages along the routing sequence

Three different stage types were considered in the analysis: (1) line-haul, which corresponds to the vehicle displacement from the depot to the first visiting retail outlet and, inversely, from the last served client back to the depot; (2) product discharge at a retailer premise; (3) vehicle displacement from a served retail outlet to the next.

4.2.1 Line-haul stage

Let $i = 1,2,\dots,n$ be the n retail outlets to be attended in sequence along the journey. The number $n+1$ is assigned to the depot. A square and symmetric matrix *D*, of dimension $n+1$, represents the distances between points. Let v_h be the vehicle average line-haul speed. The outbound line-haul travelling time is then

$$T_{n+1,1} = D(n+1,1)/v_h. \tag{10}$$

Table 1 – CoolVan simulation inputs

- **Vehicle characteristics:**
  - Volkswagen model 8150, diesel-powered, 143 HP
  - Internal dimensions of cargo compartment (m): 5.0 ×2.3 ×2.2 (25.3 m^3)
  - Insulation and Wall thickness: 0.1 m; insulation density: 40 kg/m^3
  - Door protection (none, plastic strip curtain, vertical air curtain): none
  - Insulation ageing: new vehicle
  - Cargo space loading factor: 79%
  - Cargo load: 12,000 kg
- **Refrigeration characteristics:**
  - Equipment: Transfrigor type, RB-TF6, MAXI, refrigerant R404A
  - Compressor Sandem, model SD7H15, 7 pistons, fixed displacement, total of 154.7 mL, max speed of 6,000 rpm
  - Refrigeration type: Vapour Comp of Van Engine
  - Refrigeration capacity (kW): 17530 BTU/h = 5.14 kW
- **Product characteristics:**
  - Meat products (ham, turkey and chicken breasts, salami, sausage)
  - Product temperature when loaded in the vehicle: 5°C
- **Environmental details:**
  - Equivalent UK weather: hot day (summer in July), approximately similar to February in São Paulo, Brazil
  - Relative humidity: 70%
  - Cloud covering: 40% (sunny spells)
  - Mean temperature: 18° C; maximum temperature: 28° C

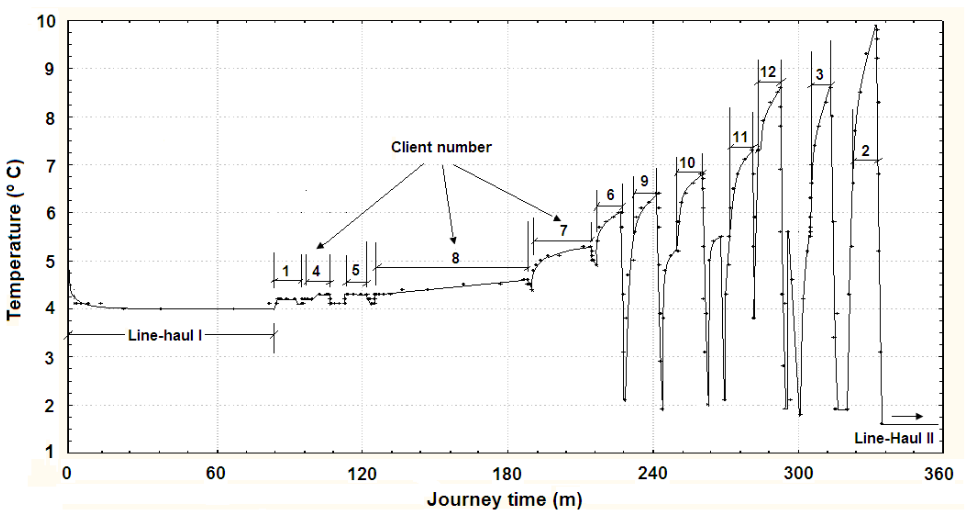

Figure 2 – Plotting of CoolVan simulated temperature during journey

Conversely, the inbound line-haul travelling time, from the last servicing stop to the depot, is

$$T_{n,n+1} = D(n, n+1)/v_h \qquad (11)$$

Let $\theta(\tau)$ be the air temperature (°C) inside the vehicle at time τ, along the outbound line-haul (Hoang et al, 2012)

$$\theta(\tau) = \theta_0 \ \exp(\beta \frac{H_{\theta_{st}} \tau}{m\, C}), \qquad (12)$$

where θ_0 is the product initial temperature at departure time (assumed uniform), *m* is the total product mass contained in the vehicle, $H_{\theta_{st}}$ is the heat transfer conductance ($W\ K^{-1}$), *C* is the thermal capacity ($J\ kg^{-1}K^{-1}$), and β is a coefficient to be fitted on the CoolVan simulation data. In the application, *m* is expressed as a fraction of the total load carried by the vehicle. Since the vehicle is assumed to be fully loaded when leaving the depot, $m = 1$ in the outbound line-haul, with τ expressed in minutes.

Table 2 – Input data for the TSP sequence of delivery points

Segment Type	Point of origin	Point of destination	Distance travelled (km)	Attended client	Cargo discharged (kg)	Delivering time (m)
Line-haul	Depot	1	84.3	-	-	-
Delivery	-	-	-	1	300	10
Travel	1	4	1.6	-	-	-
Delivery	-	-	-	4	300	10
Travel	4	5	2.9	-	-	-
Delivery	-	-	-	5	300	10
Travel	5	8	1.2	-	-	-
Delivery	-	-	-	8	7,000	64
Travel	8	7	0.9	-	-	-
Delivery	-	-	-	7	2,000	24
Travel	7	6	1.3	-	-	-
Delivery	-	-	-	6	300	10
Travel	6	9	2.5	-	-	-
Delivery	-	-	-	9	300	10
Travel	9	10	4.2	-	-	-
Delivery	-	-	-	10	300	10
Travel	10	11	5.7	-	-	-
Delivery	-	-	-	11	300	10
Travel	11	12	0.6	-	-	-
Delivery	–	–	–	12	300	10
Travel	12	3	6.2	–	–	–
Delivery	–	–	–	3	300	10
Travel	3	2	3.8	–	–	–
Delivery	–	–	–	2	300	10
Line – haul	2	Depot	86.4	–	–	–

When calibrating expression (12) on CoolVan simulation results, the values of $H_{\theta_{st}}$ and *C* are embedded in the resulting value of β. Furthermore, considering time steps $dt_{j-1,j}$ along the simulation, expression (12) can be represented as

$$\theta_j = \theta_{j-1} \ \exp(\beta \frac{dt_{j-1,j}}{m}), \quad j=1,2.... \qquad (13)$$

Applying logarithms to (13), one gets

$$\beta = \frac{\ln\left\{\frac{\theta_j}{\theta_{j-1}}\right\}}{\frac{dt_{j-1,j}}{m}}. \qquad (14)$$

Three events along the outbound line-haul were considered, as shown in Table 3, starting with the vehicle departure from the depot when the temperature was assumed to be 5°C in the simulation. Putting $m = 1$ in (13) and applying equation (14), one gets two values for β. For the time interval 0 – 20 seg, one uses $\beta = -0.7670$. For the time interval 20 seg – 22 min, one uses $\beta = -0.0044$. From $T \geq 22$ min to the end of the outbound line-haul the temperature remains constant and equal to 4°C.

Table 3 – Output data concerning the outbound line-haul stage

Event	T - Time elapsed (minute)	dT - time interval (minute)	Temperature (°C)	β
1	0	-	5.0	-
2	0.17	0.17	4.4	-0.7670
3	21.99	21.75	4.4	-0.0044

The expression to compute the temperature variation for the inbound line-haul is similar. Now, the initial temperature is equal to the vehicle air temperature at the moment the last cargo delivery is accomplished, $\theta_0 = 10$°C. The temperature drops to $\theta_1 = 4$°C after an elapsed time $d_\tau = 2$ min. It is also assumed that no chilled product is sent back to the depot, only working elements such as racks, fittings, empty trays, etc. remain in the truck. An equivalent mass equal to 2.5% of the total load was assumed for such elements, and therefore $m = 0.025$. Applying equation (14) for this time interval one gets $\beta = -0.0112$. For $T \geq 2\,min$, to up the end of the journey, the temperature remains constant and equal to 4°C.

4.2.2 Cargo unloading stage

During the unloading stage the door remains opened, with the truck engine and the refrigerating equipment turned down. Temperature variation during the unloading stage follows a thermal process similar to the one represented in equation (12), with β assuming a positive value instead. However, during the fitting analysis of a representative mathematical expression it was noticed that the external ambient temperature has an important influence in the thermal process. In fact, the truck departing time from the depot, in the CoolVan simulation, was 6 a.m., with an external temperature of 9.3°C, reflecting a typical UK situation in the month of July. Assuming an approximate 7 ½ h daily round trip, the journey would end up about 1:30 p.m., indicating that it could reach 25° C or more, and showing a expressive variation along the day. Because of this fact we adopted a modified expression of (12), as follows

$$\frac{\theta(\tau)}{\theta_0} = \alpha_1\ (\theta_{ext})^{\alpha_2}\ \exp(\beta_{unl} \frac{H_{\theta_{sr}} \tau}{m\, c}), \qquad (15)$$

where θ_{ext} is the external ambient temperature, and α_1, α_2 and β_{unl} are coefficients to be adjusted via regression fitting. Since the external temperature does not change appreciably during a specific cargo unloading operation, it was taken, in the calculations, the average temperature between the values observed at the beginning and at the end of the unloading process.

Let $i = 1,2,\ldots,n$ be the sequence of delivery stops, and let $K(i)$ be the retailer outlet served at the i^{th} discharge point. Let m_K be the quantity of cargo to be delivered to client K, represented by a fraction of the full truck load. On the other hand, let $Q_i^{(A)}$ be the quantity of cargo aboard the vehicle when the i^{th} discharging operation starts and, conversely, let $Q_i^{(B)}$ be the quantity of cargo remaining in the truck when the discharging operation terminates. The variables $Q_i^{(A)}$ and $Q_i^{(B)}$ are also expressed as a fraction of the full load. The mean quantity of cargo in the truck during the i unloading process is approximately

$$Q_i = (Q_i^{(A)} + Q_i^{(B)})/2. \quad (i = 1,2,\ldots,n) \qquad (16)$$

The following expressions hold:

$$Q_i^{(B)} = Q_i^{(A)} - m_{K(i)}, \quad i = 1,2,\ldots,n \text{ and} \qquad (17)$$

$$Q_i^{(A)} = Q_{i-1}^{(B)} \quad (i = 2,3,\ldots,n), \qquad (18)$$

with $Q_1^{(A)} = 1$ since it is assumed that the vehicle departs from the depot full loaded. Equation (16), together with recurrent relations (17) and (18), allow to compute the mean quantity of cargo in the vehicle during the various unloading stops. In order to calibrate equations (16-18) with the CoolVan simulation results, input data were extracted from the 12 delivery stages of the CoolVan simulation, as exhibited in Table 4. Temperatures at the beginning of the unloading process (θ_0) and at its end (θ_{unl}) were taken from the Coolvan simulation results. The values of Q_i were obtained via relation (16). Table 4 shows the input values to be used in the regression analysis.

Table 4 – Regression input data concerning the cargo unloading stages

Unloading stage *i*	Client number	Unloading time τ_{unl} (m)	Q_i – relative quantity of cargo aboard	θ_{ext} average external temperature (°C)	θ_0 – Initial temperature (°C)	θ_{unl} Final temperature (°C)
1	1	10	0.988	11.9	4.1	4.2
2	4	10	0.963	12.5	4.1	4.3
3	5	10	0.937	13.2	4.1	4.3
4	8	64	0.633	14.8	4.1	4.6
5	7	24	0.259	16.8	4.4	5.3
6	6	10	0.163	17.8	4.9	6.0
7	9	10	0.138	18.5	5.0	6.4
8	10	10	0.113	19.4	5.2	6.8
9	11	10	0.088	20.4	4.9	7.3
10	12	10	0.063	20.9	5.9	8.6
11	3	10	0.038	21.9	5.5	8.6
12	2	10	0.025	22.7	5.3	10.0

After simplifying equation (15) and applying logarithms one has

$$ln\left(\frac{\theta_{unl}}{\theta_0}\right) = \ln(a_1) + a_2 \ln(\theta_{ext}) + \beta_{unl}\left(\frac{\tau_{unl}}{Q_i}\right). \quad (19)$$

The results of the regression analysis are shown in Table 5. The regression fitting to the CoolVan data has shown a high R^2 value, close to one. Furthermore, with $n = 12$ and three parameters to adjust (19), one has 9 degrees of freedom. Entering into a *t* Student distribution table with 9 degrees of freedom, the critical value is 3.250 at a 0.005 significance level, indicating that the three coefficients are quite significant statistically.

Table 5 – Regression output data concerning the cargo unloading stages

	Value	*t* Student	*t* Significant at
$\ln(a_1)$(intercept)	-1.1290	-5.1497	0.005
a_2	0.4517	5.0773	0.005
β_{unl}	0.00081	5.5151	0.005
R^2= 0.965			

In Section 5, relation (19) will be used to estimate temperature variation along different discharging settings, considering diverse sequences of visits. Since the temperature values are calculated sequentially in the model, the temperature θ_0 at the beginning of the unloading operation is equal to the temperature observed at the end of the previous stage, and therefore known. Thus, from (19) one estimates $\theta(\tau)$ for any intermediate values of $0 \leq \tau \leq \tau_{unl}$ by applying the expression

$$\theta(\tau) = a_1\, \theta_0\, (\theta_{ext})^{a_2}\, \exp(\beta_{unl}\frac{\tau}{Q_i}), \quad (20)$$

with the values of a_1, a_2 and β_{unl} indicated in Table 5.

4.2.3 Local vehicle displacement stage

Upon terminating the unloading task at retail outlet i, the vehicle moves to client $i+1$ following the planned sequence of visits as indicated in Table 2. In order to calibrate a mathematical function for $\theta(\tau)$ with the CoolVan simulation results, the 11 vehicle local vehicle displacements were selected from the data, which are the links between two successive delivery points along the route. The quantity of cargo in the truck when it travels from point i to point $i+1$ is $Q_i^{(B)}$, defined in Section 4.2.2. The input data for the regression analysis are exhibited in Table 6.

An expression similar to (x9) was tested in the regression analysis:

$$\theta_{tvl} = a_1\, \theta_0\, (\theta_{ext})^{a_2} \exp\left(\beta_{tvl}\frac{\tau_{tvl}}{Q_i^{(B)}}\right), \quad (21)$$

where θ_0 is the temperature observed when the vehicle initiates its travel along the link, θ_{tvl} is the temperature when the vehicle arrives at the next client shop, and τ_{tvl} is the vehicle travelling time (Table 2). The external temperature θ_{ext} was not statically significant in this case. The best fitting expression was

$$\theta_{tvl} = a_1 \, \theta_0 \, (\tau_{tvl})^{a_2} \, (Q_i^{(s)})^{a_3} \quad (22)$$

The results of the regression analysis are shown in Table 7. The regression fitting to the CoolVan data has shown a satisfactory R^2 value. Furthermore, with $n = 11$ and three parameters to adjust (22), one has 8 degrees of freedom. Entering into a *t* Student distribution table with 8 degrees of freedom, the critical value is 3.355, indicating a_3 is significant at the 0.005 level; a_2 is significant at the 0.01 level, and a_1 at the 0.05 level.

Table 6 – Regression input data concerning local vehicle displacement stages

Vehicle displace-ment stage *i*	Link between clients	Travelled distance (km)	Travelling time (τ_{tvl}) (m)	Quantity of cargo aboard as a fraction of total load	θ_{ext} average external temperature (°C)	θ_0 – Initial tempera-ture (°C)	θ_{tvl} – Final tempe-rature (°C)
1	1-4	1.6	10	0.975	12.2	4.2	4.1
2	4-5	2.9	10	0.950	12.9	4.3	4.1
3	5-8	1.2	10	0.925	13.5	4.3	4.1
4	8-7	0.9	64	0.342	16.2	4.6	4.4
5	7-6	1.3	24	0.175	17.4	5.3	4.9
6	6-9	2.5	10	0.150	18.2	6.0	5.0
7	9-10	4.2	10	0.125	19.0	6.4	5.2
8	10-11	5.7	10	0.100	19.9	6.8	4.9
9	11-12	0.6	10	0.075	20.7	7.3	5.9
10	12-3	6.2	10	0.050	21.4	8.6	5.5
11	3-2	3.8	10	0.025	22.3	8.6	5.3

Table 7 – Regression output data concerning local vehicle displacement stages

	Value	*t* Student	*t* Significant at
$\ln(a_1)$ (intercept)	0.08940	2.3293	0.025
a_2	-0.07446	-3.0811	0.01
a_3	0.10159	6.7642	0.005
R^2 = 0.913			

5 RESULTS AND RESEARCH PROSPECTS

The fitting equations for the three stages of the process described in Section 4 were assembled in a computer program written in Turbo Pascal to estimate TTI values along a daily journey, considering different sequences of delivery visits, calculating the corresponding PCI values, and selecting the appropriate routing sequences that satisfy thermal requirements but reducing the travelled distance as much as possible. As previously mentioned, the time steps in the CoolVan simulation vary along the run. In fact, the average time step in the CoolVan simulation was 1.47 minutes. In our application a fixed time step of one minute was assumed, which showed to be sufficient for the purpose of this investigation.

The analysis of the results starts with the TSP routing sequence shown in Figure 1, with a minimum travelling distance of 204.1 km. The TSP vehicle tour sequence is

Depot – 1 – 4 – 5 – 8 – 7 – 6 – 9 – 10 – 11 – 12 – 3 – 2 - Depot. (23)

The methodology described in Section 4 is then applied to evaluate the thermal performance of the TSP shortest path travel circuit. Temperature values inside the vehicle are measured every minute, and the complete journey takes 444 minutes, starting at the depot, performing all the distribution tasks, and returning to the base afterwards. Figure 3 exhibits the histogram and frequency table of the 444 temperature observations, showing the distribution is not normal, being skewed to the right.

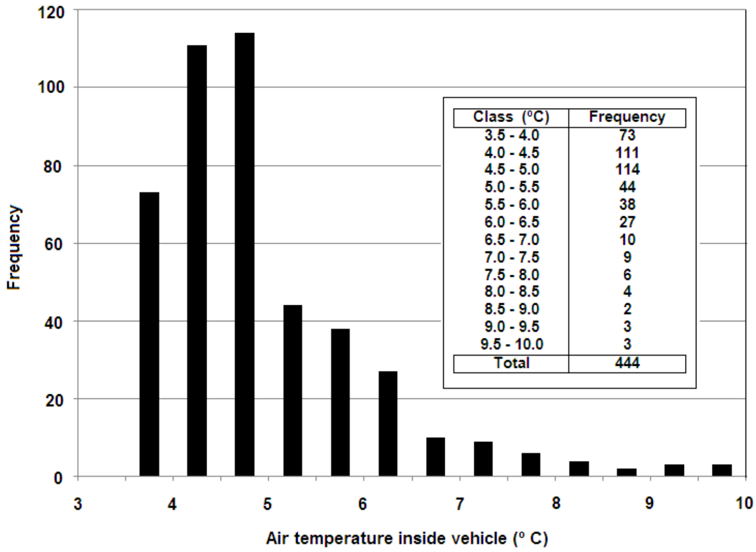

Figure 3 – Frequency table and histogram of internal vehicle temperature

Next, the PCI methodology (Section 3) is applied to the TTI data, obtaining $\bar{\bar{\theta}} = 4.66\,°C$, $\hat{\sigma} = 1.53\,°C$, $USL = 7\,°C$ and $LSL = 2\,°C$. A total of 218 observations of θ showed values smaller than the mean $\hat{\bar{\theta}}$, and then $P_\theta = \frac{218}{444} = 0.491$, leading to $D_\theta = 1 + |1 - 2\,P_\theta| = 1.018$ and yielding, through (12), $C_p = 0.535$. On the other hand, equation (15) yields $C_{pk} = 0.519$. Since $C_{pk} < 1.33$, the temperature variation along the route does not fit into the specified temperature requirements. It means that other vehicle routing sequences must be searched until one gets a route with $C_{pk} \geq 1.33$, in case a mathematical solution exists. The inverse of the TSP tour sequence (23) has the same travelled distance of 204.1 km, but showed an unsatisfactory C_{pk} value as well.

In case one of the TSP tours shows a satisfactory C_{pk} value, the problem is solved since its travel distance is at minimum. Otherwise, a greedy search routine can be applied to find an optimal solution where the objective is to get a sequence of stops with minimum total travelling distance, but maintaining the C_{pk} coefficient within the prescribed limits. The search routine comprises the following steps:

1) Let m be the searching stage number;
2) Initially do not impose an upper restriction to *D*, which is the total distance travelled in the vehicle tour cycle. Run the greedy search routine and get a first solution, registering the corresponding value of D_m;

3) Establish an upper tour length restriction equal to the last observed value of *D*: $D_{m+1} < D_m$, and run the search routine again;
4) Stop when no further solution is obtained.

Table 8 exhibits the results of the searching process showing the tested tours, the C_{pk} values, the tour length, and the observed distance increase as referred to the basic TSP tour. For the final tour solution indicated in Table 8 and depicted in Figure 4 it is observed a 18.6% (37.9 km) increase in the travelled distance over the TSP value (Figure 1). This result may represent a significant increase in vehicle operating costs but possible product losses due to unsatisfactory thermal conditions will possibly justify the extra effort. The zigzag sequence pattern of the final solution exhibited in Figure 1b might look non intuitive, but the increased distances linking some servicing points help the vehicle refrigeration equipment to reduce the internal temperature to acceptable levels. Of course, other operating solutions can be contemplated. For example, smaller vehicles could be used, which would perform shorter routes and, returning to the depot, would take another load of preserved product and then proceed to a subsequent distribution round as in Oswald and Stirn (2008).

Table 8 – Search results of tour sequences with decreasing travel distance

Vehicle tour sequence	Tour restriction (km)	C_{pk}	D (km)	Excess tour length (km)
7-2-6-8-1-12-4-11-9-3-10-5	free	1.716	258.4	54.3
7-5-9-2-8-10-1-12-4-11-6-3	$D < 258.4$	1.354	254.5	50.4
8-4-7-3-12-1-6-11-5-10-2-9	$D < 254.5$	1.343	251.8	47.7
8-4-7-9-6-1-11-2-10-5-12-3	$D < 251.8$	1.333	248.0	43.9
8-3-6-7-9-5-10-4-11-2-12-1	$D < 248.0$	1.367	246.1	42.0
7-8-10-5-9-1-6-3-11-4-12-2	$D < 246.1$	1.333	242.8	38.7
7-8-3-5-9-10-4-11-2-6-12-1 (final)	$D < 242.8$	1.332	242.0	37.9
1-4-5-8-7-6-9-10-11-12-3-2 (TSP)	-	0.347	204.1	0
2-3-12-11-10-9-6-7-8-5-4-1 (TSP)	-	0.150	204.1	0

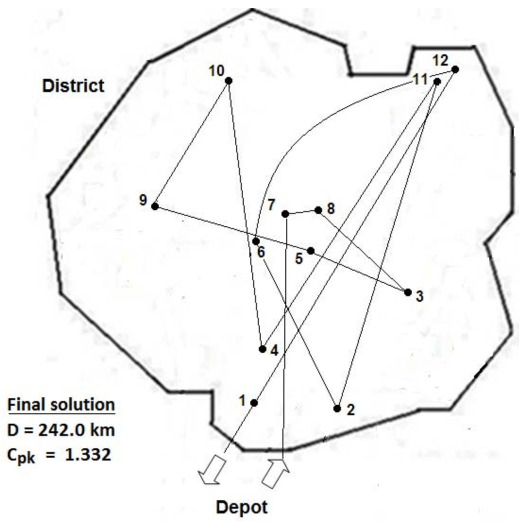

Figure 4 – Final vehicle tour respecting temperature constraints

This research continues in three ways. First, more efficient search algorithms are being developed, involving simulated annealing and genetic algorithm among others, with the objective of getting a vehicle tour that respects temperature variation requirements but, at same time, minimizing travel distance. Second, additional TTI data on the problem under investigation will be gathered in order to improve the regression fittings and the results. Finally, a dynamic version of this cold-chain distribution planning problem will be developed considering possible time deviations that might deserve routing revisions. For example, unexpected delays in the cargo unloading activities, traffic delays, and other fault occurrences will be dynamically incorporated into the problem in such a way as to devise corrective on-line measures.

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