Refrigerated Container Loading Problem (R-CLP) Models for Managing Arrangement of Smart Containers

Zara Safira Ramadhani[1], Ahmad Rusdiansyah[2*], Ratna Sari Dewi[3] , Fadila Isnaini[4]
[123]Department of Industrial and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
zarasafira12@gmail.com[1], arusdian@its.ac.id[2], ratna@ie.its.ac.id[3]
[4]Department of Business Management, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
fadilaisn@its.ac.id[4]
*Corresponding Author
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1. INTRODUCTION

Perishable products refer to goods whose quality or quantity gradually deteriorates with a maximum prespecified usable lifetime (e.g., pharmaceutical, dairy, blood, fruits, and vegetables) (Nahmias (1982) in Farghadani-Chaharsooghi *et al.*, (2021)). Deterioration of goods is regarded as the process of decay, damage or spoilage of items such that they can no longer be used for their original purpose. Perishable products are noted as one of the largest contributors of food waste and food loss.

In the fresh produce industry, cold chain management is essential for preserving the quality of perishable goods and reducing quality deterioration. A cold chain involves a series of controls aimed at maintaining products within a safe or optimal temperature range from production to the end consumer (Kim et al., 2015). A refrigerated container or reefer is an essential part of the cold chain, mainly used to keep perishable goods at low temperatures during transport (Getahun et al., 2017). However, the temperature inside a reefer is not uniform throughout. For example, areas farther from the cooling unit tend to be warmer than the reefer's set temperature. Managing temperature within a reefer is challenging due to various influencing factors (Defraye et al., 2015). This challenge becomes more complex with mixed products that require different optimal temperatures. Maintaining the temperatures of all products is crucial to avoid quality deteriorations.

In the literature, the assignment problem of packing cargoes into reefer involves aligning the required optimal temperatures of products with the internal temperature distribution within reefers to reduce product quality deterioration. This problem, known as the Refrigerated Container Loading Problem (R-CLP), builds upon models and algorithms from the Container Loading Problem (CLP) to address the two distinct temperature needs in reefers: those of the cargo and the container itself. The main goal of R-CLP is to minimize total loading costs while ensuring the quality requirements of the products are met. For example, Rusdiansyah et al. (2022) have introduced an R- CLP model for loading perishable products in reefer. They improve the classic CLP models to synchronize the required optimum temperature of products and the internal temperature distribution of reefers to minimize the quality deterioration of the products.

In this research, we enhance the R-CLP models to operate within the framework of the Physical Internet (PI). PI is defined as an open global logistics network built on interconnected physical, digital, and operational systems, enabled by encapsulation, interfaces, and protocols (Montreuil et al., 2010). A fundamental aspect of the PI is the use of PI-containers, which encapsulate goods within standardized, modular containers optimized for global logistics. There are three types of PI-containers: transport containers (PI-containers), handling containers (PI-boxes), and packaging containers (PI-packs) (Montreuil et al., 2014).

Our goal is to implement R-CLP models to manage PI-boxes equipped with IoT sensors for temperature and humidity monitoring. This technology will enrich the information available on smart tags, including transport details like origin, destination, and delivery timeframe, as well as other general data. The roles of the PI-boxes are to give information about the temperature distribution change inside the container and the condition of the product in the PI-boxes. Leveraging the real-time temperature and humidity data for each PI-box, we enhance the R-CLP algorithm to optimize the loading arrangement of PI-boxes within reefers, while dynamically setting the container's temperature and cold air velocity.

2. METHODOLOGY

The goal of R-CLP is to reduce the overall cost (penalty costs, quality loss costs, refrigeration expenses, and fixed costs), while ensuring compliance with quality requirements. The model have several constraints: basic geometric, weight limit, stacking, vertical stability, and internal temperature distribution. Temperature distribution inside the reefer is simulated using a Computational Fluid Dynamic (CFD). Readers may read the study by Xie et al. (2011) to know more about CFD and Rusdiansyah et al. (2022) for R-CLP models and heuristic algorithms.

The formula of R-CLP (Rusdiansyah et al., 2022):

$$MIN\left[\left[(m \times FC)\right] + \left[\sum_{j=1}^{m}\sum_{i=1}^{n}\frac{TT+N_i\left(SL_i-\left(SL_i e^{-k_0 TT e^{-\left[\frac{E_a}{R}\left(\frac{1}{TR_i}-\frac{1}{T_{ref}}\right)\right]}}\right)\right)}{SL_i}\times v_i \times p_{ij}\right] + \left[\left(\left(\frac{1}{s}kA\Delta t^*\right) + \frac{1}{TT}\left(\left(\sum_{j=1}^{m}\sum_{i=1}^{n} b_i p_{ij} \times C \times (T_{ext}-T_0)\right) + \left(\sum_{j=1}^{m}\sum_{i=1}^{n} b_i\, p_{ij} \times Cl\right) + \left(\sum_{j=1}^{m}\sum_{i=1}^{n} b_i p_{ij} \times C \times (T_0 - T_{int})\right)\right)\right) \times RC\right]\right] \tag{1}$$

$$\sum_{i=1}^{n} b_i p_{ij} \le B_{ij} u_j \tag{2}$$

$$\sum_{j=1}^{m} p_{ij} = 1 \tag{3}$$

$$x_i' \le \sum_{j=1}^{m} W_j p_{ij} \tag{4}$$

$$y_i' \le \sum_{j=1}^{m} H_j p_{ij} \tag{5}$$

$$x_{ik}^p + x_{ki}^p + y_{ik}^p + y_{ki}^p + z_{ik}^p + z_{ki}^p \ge (p_i + p_k) - 1 \tag{6}$$

$$x_k' \le x_i + \left(1 - x_{ik}^p\right)W \tag{7}$$

$$y_k' \le y_i + \left(1 - y_{ik}^p\right)H \tag{8}$$

$$z_k' \le z_i + \left(1 - z_{ik}^p\right)D \tag{9}$$

$$x_i' - x_i = r_{i11}w_i + r_{i12}h_i + r_{i13}d_i \tag{10}$$

$$y_i' - y_i = r_{i21}w_i + r_{i22}h_i + r_{i23}d_i \tag{11}$$

$$z_i' - z_i = r_{i31}w_i + r_{i32}h_i + r_{i33}d_i \tag{12}$$

$$\sum_a r_{iab} = 1 \tag{13}$$

$$\sum_b r_{iab} = 1 \tag{14}$$

$$r_{i21} \le w_i^+ \tag{15}$$

$$r_{i22} \le h_i^+ \tag{16}$$

$$b_i \le b_k y_{ik}^p \tag{17}$$

$$\sum_{v=1}^{4}\sum_{k=1}^{n} \beta_{ik}^v \ge 4(1 - g_i) \tag{18}$$

$$y_i \le (1 - g_i)H \tag{19}$$

$$\eta_{ik}^1 + \eta_{ik}^2 \le 2(1 - \beta_{ik}^1) \tag{20}$$

$$\eta_{ik}^2 + \eta_{ik}^3 \le 2(1 - \beta_{ik}^2) \tag{21}$$

$$\eta_{ik}^3 + \eta_{ik}^4 \le 2(1 - \beta_{ik}^3) \tag{22}$$

$$\eta_{ik}^4 + \eta_{ik}^4 \le 2(1 - \beta_{ik}^4) \tag{23}$$

$$x_k \le x_i + \eta_{ik}^1 W \tag{24}$$

$$z_k \le z_i + \eta_{ik}^2 D \tag{25}$$

$$x_k \le x_i + \eta_{ik}^3 W \tag{26}$$

$$\frac{SL_i-\left(TT+N_i\left(SL_i-\left(SL_i e^{-k_0 TT e^{-\left(\frac{E_a}{R}\left(\frac{1}{TR_i}-\frac{1}{T_{ref}}\right)\right)}}\right)\right)\right)}{SL_i} \ge QR_i \tag{27}$$

The objective function of the model is to minimize the overall costs (Formula 1). Formula 2 and 4-5 make sure that total loaded cargo weight and size cannot exceed the maximum capacity of the reefer. Formula 3 make sure that each cargo is allocated to exactly one reefer. Formula 6-9 makes the cargos cannot overlap each other. Another constraint is about the rotation of the cargos (Formula 10-16). Formula 17 make sure that heavier cargo must not be placed above lighter cargo. Formula 18-26 is the vertical stability constraint in which if cargo *i* is not on the ground, then the four vertices of the cargo must be supported by another cargo *k*. And formula 27 make sure that the product's quality level inside cargo must not be less than quality requirement.

In this research, we will assess the temperature distribution within the boxes using specified temperature indicators using CFD. By analyzing the temperature distribution in each box, we intend to establish the optimal temperature and velocity settings in the reefer for achieving an ideal temperature spread. Based on the temperature results, we can decide whether to rearrange the PI-boxes or adjust the temperature settings for certain PI-boxes. Figure 1 shows the differences between current R-CLP and R-CLP with PI-boxes.

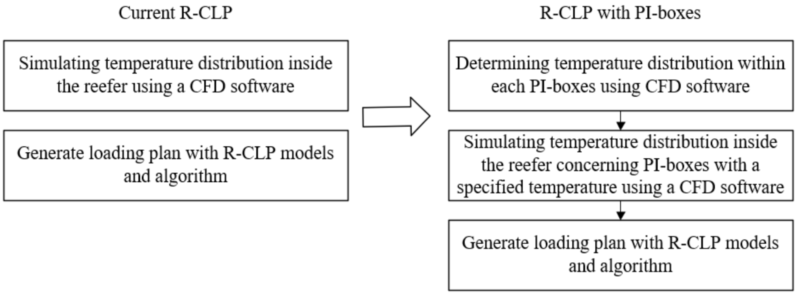
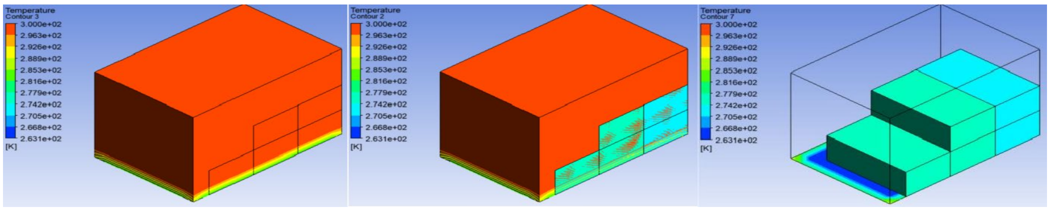


Figure 1. Differentiation of current R-CLP and R-CLP with PI-boxes

3. RESULTS

3.1 Experiment 1

This experiment aims to determine the effect of temperature distribution inside a container that holds PI-boxes at a specific temperature. We set the temperature with random number between -5°C to 5 °C for each PI-boxes. As for the refrigerated containers, we used 4 m/s for cold air velocity and -5°C for temperature. The optimal storage temperature can be determined using either the average or the weighted average of the optimal temperatures of the stored products. The results from the simulation using CFD are shown in Figure 2.



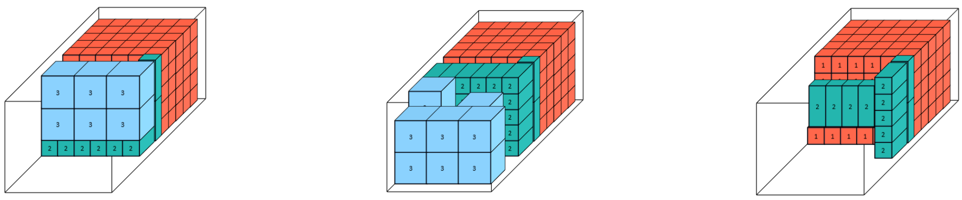
(a) Temperature distribution inside refrigerated containers (b) Temperature distribution inside containers and PI-boxes (c) Temperature distribution inside PI-boxes

Figure 2. CFD result of experiment 1

From the simulation results using CFD for temperature distribution within the containers and PI- boxes, the arrangement of PI-boxes according to optimal temperature can be determined. An additional experiment is conducted to examine the impact of cold air velocity and initial temperature on temperature distribution inside the container, using 2 m/s cold air velocity at -5°C and 4 m/s cold air velocity at -2°C.

3.2 Experiment 2

In Experiment 2, we arranged the cargo placement within the container to match the optimal temperature so that the quality loss is minimum. Figure 3. shows the cargo placement within the containers to ensure optimal temperature and minimal quality loss.



(a) 2 m/s cold air velocity and -5°C temperature (b) 4 m/s cold air velocity and -5°C temperature (c) 4 m/s cold air velocity and -2°C temperature

Figure 3. R-CLP result of experiment 2

The result of R-CLP based on the cold air velocity and temperature setting explained in Table 1.

Table 1. Comparison of R-CLP result considering cold air velocity and temperature

Performance Type	Performance Value of Temperature Distribution Parameter			Unit
	-5°C 2 m/s	-5°C 4 m/s	-2°C 4 m/s	
Cargo to load	210	210	210	units
Cargo loaded	174	205	167	units
Cargo left out	36	5	43	units
Filling rate	82.86	97.62	79.52	%
Total load volume	13355280	18370800	10439280	cm³
Volume utilization	47.22	64.95	36.91	%
Total load weight	1740	2050	1670	kg
Weight capacity utilization	5.97	7.04	5.73	%
Cost				
Penalty cost	2,742,021.00	858,065.00	3,816,051.00	IDR
Quality loss cost	771,101.03	841,283.19	726,657.78	IDR
Refrigeration cost	30,946.92	36,457.17	29,702.67	IDR
Reefer fixed cost	5,000,000.00	5,000,000.00	5,000,000.00	IDR
Total cost	**8,544,068.95**	**6,735,805.00**	**9,572,411.45**	**IDR**

4. DISCUSSION

This research examines how temperature settings in PI-boxes affect the temperature distribution within a refrigerated container. This insight guides decisions on whether to adjust the PI-boxes' temperature or rearrange them inside the container to preserve product quality. Numerical experiments demonstrated the temperature distribution within both the PI-boxes and the container. Once the temperature distribution was determined, a loading plan was implemented to ensure that all perishable products maintained both minimal quality loss and optimal temperature. Experiment 1 revealed the temperature distribution inside the container under a specific cold air velocity and temperature setting. Experiment 2 showed that setting the cold air velocity to 4 m/s and temperature to -5 ^{o}C resulted in the lowest cost compared to other temperature settings. This indicates that the air cold velocity and temperature setting in the container affects the amount of cargo that can be transported while maintaining the desired product quality, which in turn impacts the total cost.

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