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

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Abstract. This study advances the Refrigerated Container Loading Problem (R-CLP) model to create a decision support tool for optimizing fishery product quality and minimizing losses during transport. Utilizing physical internet containers (PI-containers) as cargo units (PI-boxes), the model maximizes space efficiency within refrigerated containers (reefers), reduces container usage, and ensures product quality through precise temperature control. Equipped with RFID and GPS, smart PI-containers provide real-time data on temperature, routing, and location, enabling informed, data-driven decision-making within cold supply chains. The study refines the R-CLP heuristic algorithm to incorporate real-time temperature data and applies Computational Fluid Dynamics (CFD) simulations to establish internal temperature distribution constraints. Through numerical experiments, the model's robustness is validated, offering insights to users for strategic decisions to optimize quality and reduce product spoilage.

Keywords: Physical Internet, PI-container, R-CLP, Perishable Product, Sustainable Logistics

1. INTRODUCTION

Perishable products refer to goods whose quality or quantity gradually decays or deteriorates with a maximum prespecified usable lifetime (e.g., pharmaceutical products, dairy products, fruits, vegetables, flowers, and blood products)(Nahmias, 1982)(Farghadani-Chaharsooghi *et al.*, 2021). Deterioration or perishability 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 is noted as one of the largest contributors of food waste and food loss. Food losses refer to the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption. Food losses occurring at the end of the food chain (retail and final consumption) are rather called "food waste", which relates to retailers' and consumers' behavior(Parfitt, Barthel and MacNaughton, 2010).

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 is an essential part of the cold chain (Getahun et al., 2017), mainly used to keep perishable goods at low temperatures during transport. However, the temperature inside a refrigerated container is not uniform throughout. For example, areas farther from the cooling unit tend to be warmer than the container's set temperature. Managing temperature within a refrigerated container is challenging due to various influencing factors (Defraye et al., 2015). This challenge becomes more complex with mixed products that each require different optimal temperatures. Maintaining ideal temperatures for each product inside the container is crucial to avoid quality degradation.

In the literature, the assignment problem of packing cargoes into refrigerated containers involves aligning the required optimal temperatures of products with the internal temperature distribution within containers 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 refrigerated containers: 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 refrigerated containers. They improve the classic CLP models to synchronise the required optimum temperature of products and the internal temperature distribution of reefers to minimise the quality deterioration of the products. The main objective of the R-CLP is to reduce loading costs while ensuring product quality.

In this research, we enhance the R-CLP models to operate within the framework of the Physical Internet. The Physical Internet is defined as an open global logistics network built on interconnected physical, digital, and operational systems, enabled by encapsulation, interfaces, and protocols (Montreuil, Meller, and Ballot, 2010). A fundamental aspect of the Physical Internet 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, Ballot, and Tremblay, 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 refrigerated containers, while dynamically setting the container’s temperature and cold air velocity.

2. METHODOLOGY

The current R-CLP model is basically an enhancement of CLP, where the internal temperature distribution inside the reefer will determine the appropriate placement strategy for perishable product cargoes in such a way that the products’ quality loss is minimised. The model will then have several constraints such as basic geometric, weight limit, stacking, vertical stability, and internal temperture distribusion. Temperature distribution inside the reefer is simulated using a computational fluid dynamic (CFD). Several fluid dynamics parameters, such as temperature and cold air velocity, will be used in the CFD simulation to obtain the temperature distribution data. Readers may read the study by Xie et al. (2011) to discuss about the study of temperature field inside refrigerated containers and Rusdiansyah et al. (2022) for R-CLP models and algorithm.

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 methodology flowchart.

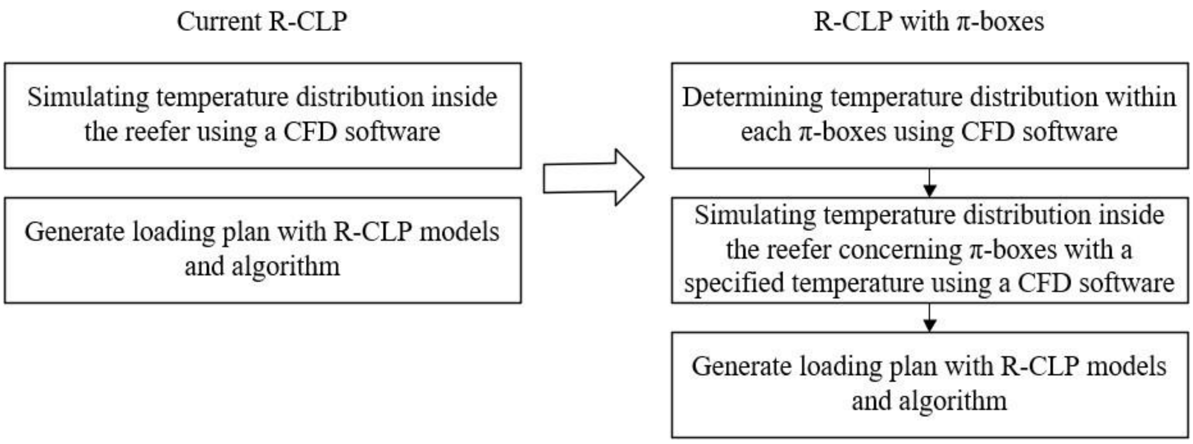
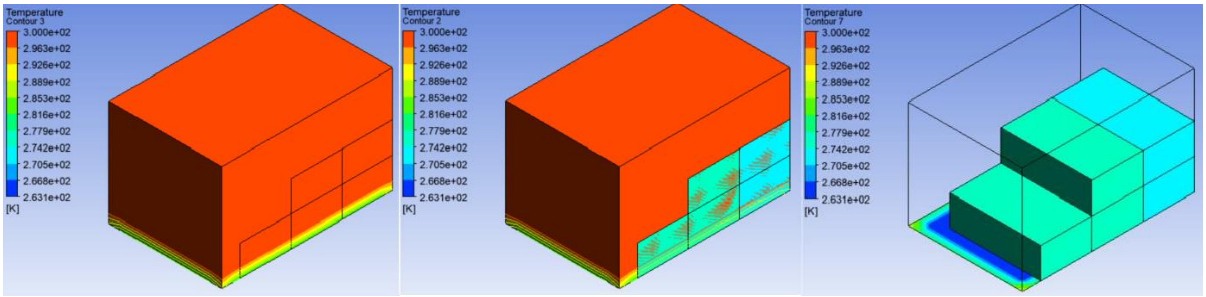


Figure 1. Methodology

3. RESULTS

3.1 Experiment 1

This experiments 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 and 4 m/s for air cold velocity and -10°C for temperature. The results from the simulation using CFD are shown in the Figure 2.



(a) Temperature distribution inside refrigerated containers

(b) Temperature distribution inside containers and PI-boxes

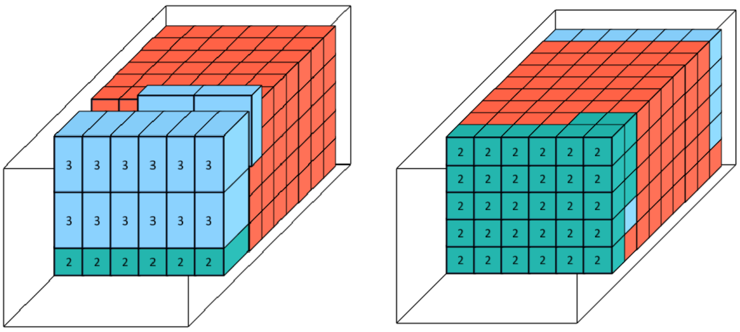
(c) Temperature distribution inside PI-boxes

Figure 2. CFD result

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.

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) R-CLP with multi size PI-boxes (b) R-CLP with one size PI-boxes

Figure 3. R-CLP result

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. If the temperature in the PI-boxes no longer meets the optimal level, the arrangement or temperature of the PI-boxes will be adjusted accordingly.

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