Cost-Effective Choice of Temperature-Controlled Transport of Fresh Food

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The application of a plethora of wireless technologies to support real-time food quality monitoring during transportation has significantly improved the performance of fresh food delivery systems. However, deployment of these technologies increases the capital and operational costs of food delivery and, hence, not all food delivery operations need to employ them. The research has developed a mathematical programming model to understand the trade-off involved in the increased capital costs and the opportunity to reduce food waste.

Internet of Things sensors | temperature control | temperature monitoring | food waste | fresh food supply chains

1. Introduction

Delivering fresh food products to the end user of the right quality while adhering to perishability constraints is of foremost importance in fresh food supply chain networks. Unlike other products, the quality of perishable fresh food degrades endlessly during the downstream activities in the supply chain, leading to food-borne diseases and food wastage. According to the Centers for Disease Control and Prevention (CDC), as many as 48 million people become sick due to food-borne illnesses every year in The United states (US) alone. However, tracing back the origin of these diseases due to food contamination is challenging [1]. According to the Food and Agriculture Organization, around one-third of fresh food is wasted throughout the supply chain post-production every year [2]. This is due to poor transportation and storage facilities and inadequate temperature and humidity control systems [3][4]. Several international standards, such as Hazard Analysis of Critical Control Points (HACCP), Good Agricultural Practice (GAP), and Good Manufacturing Practices (GMP) are implemented for quality assurance and a reduction in food wastage [3][5][6]. The threshold levels of temperature to safeguard food from quality damage vary depending on the type of food. For example, for frozen foods, the temperature range is between −18 and −24 °C (see [7]), while for frozen milk the range is 0–4 °C in fridges, and at or below −20 °C for long-term storage in freezers [8].

Owing to the growing need to reduce food wastage and increase quality preservation, several food quality monitoring and control technologies that enable tracking and traceability during transportation and post-harvest storage have recently evolved [9]. These technologies range from simple Internet of Things (IoT) enabled sensors, and radio frequency identification (RFID) systems, to sophisticated imaging technologies, such as spectroscopy, muti-sensor topologies, thermal imaging systems, and physics-based digital twins [4][7][9][10][11][12]. Traditional food supply chain retailers and logistics providers still depend on the use of dry vans without any temperature-controlled systems installed, usually due to the high cost of installation and maintenance of the RFID and wireless sensor network (WSN). Therefore, most of the small- and medium-sized enterprises [13][14] are unable to afford to adopt such systems despite the high level of technological maturity. Previous studies [15] have revealed that, compared to a non-temperature-controlled system, the shelf life of food can be increased by a factor of two or even three times in a temperature-controlled system. Thus, fresh food supply chain planning is seldom conducted looking at the trade-offs between the possibilities of cost reduction by preventing quality-affected food losses and the increase in total supply cost due to wastage from oversupply or overstocking. However, technologies for delivering fresh food faster with optimum quality and quantity reap financial benefits and can be perceived as a strategic asset to the organization [16]. Temperature-controlled systems with monitoring capabilities are designed to automate decision-making processes during transportation. In addition to their ability to remotely monitor food safety and commodity settings, some of these systems can also control in-transit ripening and pest-management treatments [17].

2. Technologies Used for Quality Monitoring of Fresh Food Transportation

Temperature control refers to the capability of the refrigeration unit fitted to trucks to maintain the pre-specified temperature, while monitoring refers to the continuous recording of this temperature using Internet of Things sensors whose outputs are made available via the Internet for further analytics, monitoring, and decision support. Several researchers have focused on developing and implementing technologies for monitoring quality. Imaging and thermography technologies have been deployed for temperature distribution studies on a pallet of fruits to evaluate and monitor food spoilage during storage using classification techniques [18][19][20]. Ref. [21] proposed a decision support method for quality monitoring by data acquisition from multi-sensor technologies. In any food supply chain, temperature control is essential for quality assurance and safety until consumption [22]. However, fluctuations in temperature are inevitable during the transportation and distribution of perishable foods due to their vulnerability and small inherent heat capacity [20]. Thus, most of the research on fresh food logistics primarily aims at temperature control [21]. However, a wide arena of research work exists on temperature monitoring and control using newer technologies, such as RFID, WSN, IoT, wireless networks, digital twins, and gas sensing, for improving tracking and traceability of the quality of fresh food. Ref. [22] developed a tribo-electric nanogenerator-based wireless gas sensor system for real-time spoilage marker gas monitoring.

3. Non-Temperature-Controlled Transport Systems

Non-temperature-controlled transport systems are low-cost dry vans which may not prevent food wastage during transit. They are relatively inexpensive transport options but can be used only over shorter distances because the food might become bad over time. Most of the studies concerning fresh food transportation deal with non-temperature controlled transport options and have made efforts to perform cost optimization and inculcate sustainability while addressing perishability and quality concerns using mathematical modelling. In [23], researchers deployed a three-objective linear programming model-based food distribution planner (FDP) to minimize cost, carbon emissions, and delivery time. FDP facilitates strategic planning of food distribution by considering perishability and multi-modal transport. In [20], the researchers optimized the cost of a fast-moving consumer goods (FMCGs) distribution network using scenario analysis. Ref. [16] presented a fast-moving consumer goods network design model with a consideration of greenhouse gases and other logistic leverages. Ref. [24] proposed a bi-objective food supply chain model for minimizing total cost and carbon dioxide (CO_2) emissions for a milk distribution channel in Ireland. Ref. [25] developed a hybrid approach of mixed integer linear programming and constraint programming to examine integrated production planning and scheduling for the case of the dairy supply chain. Ref. [26] addressed the problem of van route scheduling for fresh food transportation cost optimization using an NSGA-II meta-heuristic approach. Ref. [27] presented a model for a food supply chain to study the effect of temperature and storage on product quality, costs, and sustainability of the chain.

4. Temperature-Controlled Transport Systems without Monitoring Capability

According to a transport economics report by USTDA (2000), temperature-controlled systems or reefer vehicles can be more than twice as expensive as the traditional dry vans if purchased, although the cost might have reduced in the last two decades [28]. The temperature-controlled transport systems are advantageous in the sense that they can keep food produce fresh, thereby causing them to be transported over longer distances. However, these vans do not have the functionality of generating sufficient data for predictive modelling and informed decision making. If these transport systems do not have monitoring capability (in other words the temperature readings are not made available over the Internet for continuous monitoring), then there is some chance that the temperature control system fails and is detected only at the end of the journey. By this time, it would be too late to take any corrective action, and the entire food consignment would be wasted.

Quality and perishability concerns in fresh food transportation can still be addressed by installing temperature-controlled systems without the capability for monitoring. Various researchers have developed and utilized such technologies for dynamic shelf life determination and temperature control. Due to lack of remote and automatic control mechanisms, these systems fail to assist in the decision-making process in the event of disruptions and uncertainties [9] in real time; however, are useful for generating offline data and providing a route for retrospection. Post-harvest food loss management was given a fresh perspective by [29] in terms of studying technology adoption barriers and by conducting a feasibility study for the successful implementation of various temperature control technologies. Ref. [30] proposed a multi-temperature joint distribution (MTJD) for better handling temperature-sensitive food. The use of cold cabins and eutectic plates was adopted for operational cost reduction and to ensure food quality and safety during transportation. Ref. [20] developed an integrated critical temperature indicator (CTI)-RFID for maintaining the fresh cut fruit supply chain within the temperature range of 18–19 °C. Ref. [31] have developed a load-dependent vehicle routing model for optimal route decisions after accounting for emissions from the refrigeration system. Similarly, [32] have discussed the scope of IoT based systems to support food supply chains and suggested that simulation gaming could provide promise for studying the system in detail. Furthermore,

[33] have developed a mixed-integer network flow model that considers the rates of product quality decay of heterogeneous food products.

5. Temperature-Controlled Transport Systems with Monitoring Capability

An efficient cold chain logistics requires an automated temperature monitoring and controlling facility during transportation. Such a system can not only maintain appropriate temperatures to keep food produce fresh for longer but can also transport the produce over longer distance and, at the same time, provide confidence that the produce will arrive at the destination still fresh. The main advantage of temperature control and monitoring is that in case that the temperature control mechanism fails while the truck is in transit, the failure is rapidly identified, and corrective actions can be taken to preserve the quality of food, thereby minimizing the chance of it becoming waste. However, the downside is this would incur additional costs for installing and maintaining technologies to monitor and send alerts to decision-makers rapidly. These costs are slowly coming down as more and more companies are starting to use such advanced systems.

During the last decade, the use of IoT-based sensors for food quality monitoring and tracking temperature has become more and more operational in cold chain fresh food logistics. Furthermore, it is of great use to automate the decision-making process during transit. Numerous works have focused on developing and adopting these technologies. Ref. [34] utilized Electronic Product Code Information Services (EPCIS)-based online monitoring and a time–temperature maintenance system in a cold meat chain. This helped to decrease the losses caused due to temperature fluctuations. Similarly, [35] developed a real-time monitoring system based on RFID to improve the efficiency of a perishable goods delivery system. Additionally, it provides warnings when temperature, humidity, or any other environmental condition goes beyond safety limits. Ref. [35] proposed an “Intelligent Container”, which tracks and traces the temperature history and monitors the perishable food quality. Ref. [4] approached the problem of delivering perishable goods using wireless sensor node-based temperature control systems and proposed a smart cold chain management system. This framework enabled offline as well as online tracking and traceability through data centralization. Ref. [36] proposed an intelligent container-based framework for the shelf life prediction and remote monitoring of fresh food during transportation. Ref. [37] used RFID-based technology to gauge the quality and control the temperature in real-time throughout the supply chain. Ref. [38] introduced a real-time monitoring system based on the ZigBee standard, which sensed various environmental parameters, such as temperature, CO_2, humidity, vibrations, etc. Ref. [12] proposed a real-time smartphone-based monitoring system to ensure the quality and safety of food products. The system considers parameters, such as temperature, humidity, and location during transportation. Ref. [39] proposed an intelligent distribution strategy for perishable food considering the destination hub’s shelf life, transit time, and consumption rate. According to this strategy, pallets with low shelf life are transported to the destination with high proximity and a higher consumption rate and vice-versa. Ref. [40] proposed a methodology based on sensory and chemical attributes to predict and monitor the shelf life of perishables. Ref. [41] demonstrated an automatic freshness/quality monitoring and controlling tool based on predictive data transmission technology. The work also showed that the use of such technologies helps to reduce transportation costs. Ref. [42] proposed data-driven traceability tool highlighting the impact of logistics operations on fresh food.

The original paper has developed a mathematical programming model to understand the trade-off involved in the increased capital costs and the opportunity to reduce food waste. The model has found that the increased investments in technology can be justified (i) as the distance to be travelled by trucks increases and (ii) as the imputed costs of food waste increases.

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