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Cold supply chain logistics: System optimization for real-time rerouting transportation solutions

Sobhi Mejjaouli[a], Radu F. Babiceanu[b,*]

[a] Assistant Professor of Industrial Engineering, Department of Industrial Engineering, Alfaisal University, Riyadh, Saudi Arabia
[b] Associate Professor of Systems Engineering, Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA

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ABSTRACT

Transportation of perishable products is critical and imposes a series of challenges to the cold supply chain and logistics operations. The specific challenge to be addressed is the strict monitoring of transportation conditions. This paper provides insights in the logistics decision models associated with the cold supply chain of perishable products. The decision-making is performed in the cloud by temporary virtual machines (VMs) associated with every shipment or series of shipments. The VMs make operational decisions based on evaluating actual transportation conditions and location of shipped products against requirements and initial route and terminal market geographical location. The physical part of the logistics cyber-physical monitoring and control system is represented by integrated RFID-WSN sensor devices traveling with the product and reader checkpoints distributed along the transportation routes. Two types of decisions are considered in the proposed models: stopping transportation and/or rerouting the shipments to a closer location. The implementation of the optimization models for an actual case study, which considers shipments of fresh produce across the continental United States, shows significant savings that could be obtained if producers or third party logistics companies adopt the methodology.

1. Introduction

Transportation of perishable products is critical and imposes a series of challenges to the cold supply chain and associated logistics operations. The specific challenge to be addressed is the strict monitoring of transportation conditions. Even a small departure from the required transportation parameters can compromise the quality of transported products, such as produce, dairy, or meat products, resulting in big losses for the businesses involved. The consequences could be even more disastrous if human lives are in danger, as it is the case for transportation of pharmaceuticals and other bio products. Gunders [9] mentions that 40% of the food in the United States is wasted every year, which is equivalent to an amount of $165 billion. These losses get incremented at each stage of the supply chain from production and post-harvest losses, to distribution and consumer losses, resulting in estimated distribution and retail losses of 7% for meat and 12% for produce [5]. Losses in distribution are usually attributed to inadequate transportation and handling, such as keeping produce at improper temperatures. As such, Vigneault et al. [25] state that, proper packaging and shipping of produce in temperature-controlled containers could reduce the spoilage to just 5%.

In the last decade or so, industry practitioners concluded that preservation of products quality and reduction of spoilage risk may benefit from the adoption of non-conventional solutions. Technologies such as Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSN) are positioned to have significant impact on the way cold supply chains are operated. RFID applications can improve the decision-making process by providing real-time data and improve the performance of operations through increased visibility [12]. WSN also have the potential to positively impact the supply chain and logistics operations through sensing and data collection and processing along the transportation routes [24].

This paper considers a cold supply chain model and proposes an integrated RFID-WSN monitoring system architecture that combines the technological and coordination aspects of its logistics operations. The proposed system and logistics models are applied to a very common case of fresh produce shipped daily to local

* Corresponding author.
E-mail addresses: smejjaouli@alfaisal.edu (S. Mejjaouli), babicear@erau.edu (R.F. Babiceanu).

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markets in the United States, and it provides an indication of the benefits that can be obtained by adopting the solution.

2. Review of relevant literature

The use of integrated RFID-WSN devices for cold chain monitoring was reported recently in a significant number of articles. The technology side of it is represented by the design and placement of RFID and/or WSN tags on the shipped products across the cold chain logistics. The review of literature identified topics such as integrated antenna design [15], sensor tag functional requirements [11], hardware/software modeling [1], and compressed sensing techniques for cold chain operations [29]. Since monitoring the cold chain is performed using integrated technologies, a good analogy that can be useful for implementation arises from similar integrated systems already deployed in industries such as manufacturing and assembly. Meyer et al. [21] provide a survey of intelligent products and their integration for manufacturing and supply chain operations, while Lyly-Yrjanainen et al. [16] study the effect of combining product-centric control with direct digital manufacturing. In addition, Meyer et al. [20] also formulate a series of design principles in support of identifying field issues and promote the utilization of tracking technology for transportation logistics.

An integral part of prototype system design before deployment is the evaluation of expected performance including carrying out a realistic risk assessment. Kim et al. [13] propose an intelligent risk management framework for context-aware cold chain logistics, which uses RFID tags and various types of sensors for tracking shipment environmental conditions. A risk assessment approach for food safety analysis of produce chain logistics is proposed by LeBlanc et al. [14] in association with exercises for emergency preparedness planning. Xiao et al. [30] employ real-time monitoring of temperature fluctuation using WSN to determine critical quality parameters in the cold chain logistics of fresh produce. Xiang et al. [28] propose a wireless-multi-gas sensor system for produce cold chain monitoring tested in refrigeration trucks on distances similar to coast-to-coast United States. Other articles worth noting that discuss the sensor-based monitoring process of cold chain logistics include Shih and Want [22], Ting et al. [23], and Wang and Yue [27].

However, the design and successful prototype evaluation of monitoring and control systems are not enough for implementation decisions. Besides the technology side, the operational side is also important. Mathematical modeling for real-time transportation decision-making will ultimately make the case for the actual implementation of online monitoring and control systems. Distribution of perishable products requires cold chain management planning approaches, which include fulfilling customer requirements for different types of products, at a stated level of quality, and at the lowest cost. Hsiao et al. [10] follow this second operational path and use mathematical optimization techniques for temperature settings in multi-item-multi-temperature shipments, at the lowest distribution cost. Catala et al. [4] model the supply chain planning problem, including production, processing, distribution, and inventory decisions, considering the cost and product shortage objectives, in the face of changes during processing and transportation. Behzadi et al. [3] develop a two-stage stochastic programming model with profit/cost optimization objectives for supply chain operations purposes that includes an exponential perishability function to mitigate the disruption risks. Still, there is no real-time data collection and cloud computation for online re-routing of shipments approach included in any of the surveyed works. In other words, the technology and operational sides are seldom studied in coordination.

This current work builds on the RFID-WSN logistics framework presented in a series of previous papers. Mejjaouli and Babiceanu [17] propose a monitoring and control system for production and transportation operations. The proposed system is intended to provide more flexibility for production, logistics, and supply chain activities when unexpected events slowdown the normal course of operations. In another paper, Mejjaouli et al. [19] consider a multi-echelon supply chain model comprised of one manufacturer and several retailers and emphasize the benefits of employing the RFID-WSN integration architecture for the logistics operations between the manufacturer and the retailers. Though no formal mathematical models are derived, the simulation output analysis offers as much as nine good practice recommendations. In a subsequent work, Mejjaouli and Babiceanu [18] propose an optimization model to accompany the RFID-WSN logistics architecture. The model is shown to be effective in dealing with consequences resulted from equipment failures or other emergencies, which are simulated to alter the initial transportation conditions. The model can also accommodate backordering and provides savings for the “lost sales cost” metric.

From the technology point of view, this work, while using the previously defined multiple checkpoint logistics layout and RFID-WSN integrated tags traveling along with transported products, also adds the concept of cloud computation and virtual machines for improved real-time transportation decisions based on current outstanding customer orders and route and timing constraints. Then, from the operational point of view, this work accounts for several of the good practice recommendations previously obtained through simulation, and enhances the mathematical models defined for the logistics aspects of the RFID-WSN integration. While the previously models were based on demand scenarios, the current models are minimizing the expected cost based on shipment delivery success and failure events. In addition to stopping transportation, once dangerous safety conditions are identified, the current paper also considers real-time rerouting of shipments to other customers, together with inventory holding models for further improvement of shipment decisions.

3. The logistics RFID-WSN monitoring and control system

Monitoring the status of transported products is of utmost importance from the safety and security points of view on the customer side, as well as from the economic performance point of view on the producer and logistics service sides. The objective of the RFID-WSN system is to provide solutions for online decision making when unexpected events disrupt the regular transportation logistics for perishable products. These solutions take into account the demand, order, and inventory metrics of geographically dispersed customers, transportation cost, as well as failure timing characteristics. The solutions either stop or reroute entire product shipments such that the overall cost is minimized. The model presented in Fig. 1 considers the flow of goods and the flow of information occurring with the help of the RFID-WSN monitoring and control system. The RFID-WSN cyber-physical system includes the following components:

- Integrated RFID-WSN devices embedded on the unit shipped products for monitoring and control purposes. The RFID-WSN devices collect, store, and transmit data regarding the monitored transportation conditions.
- Distributed checkpoints deployed along the transportation routes. The number and location of the checkpoints is to be determined by using optimization models. The checkpoints include cyber-physical readers able to retrieve the stored data from the RFID-WSN devices and process it for re-transmission to the decision module.