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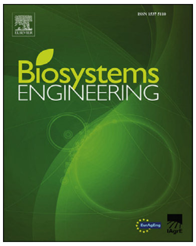

Research Paper

Data estimation methods for predicting temperatures of fruit in refrigerated containers

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Improving the capability and resolution of monitoring perishable products during their transportation and storage is essential, but there is a key requirement it is not to increase costs or the number monitoring devices. Currently there lies a knowledge gap in studies on the spatial prediction and mapping of determinant parameters (e.g. temperature) for the shelf life of perishable products. Through the viewpoint of different refrigeration failure scenarios this paper investigates and compares three data estimation tools (artificial neural networks, Kriging and capacitive heat transfer) for improved food safety. Results indicate that using these techniques makes it possible to reduce the number of sensors (through estimation of temperature distribution) within an industrial scale fully loaded strawberry-shipping container, thus reducing the overall commercial cost. Using a set of eight source sensors, an average error of 0.1 °C was achieved, which represents an improvement of 97.14% in regards to the absolute error between the ambient and product temperatures. Even when using only a single container sensor as a source for prediction, with an average error of 1.49 °C there still was an improvement of 62% with regards to the same baseline. This paper demonstrates that the adoption of these technologies not only presents significant industrial value-added potential but also the data obtained can further improve cold chain strategies and reduce product losses through more accurate shelf life calculations.

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1. Introduction

A recent study by the Natural Resources Defense Council (NRDC) has found that the US is losing up to 40% of its food from farm-to-fork (Gunders, 2012). Fresh fruits and vegetables have the highest wastage rate of more than 50% with at least one out of every two strawberries harvested being uneaten. The root cause of these loss figures has been mostly linked to insufficient temperature control (Pang, Chen, & Zheng, 2012). At a global scale such high losses are unacceptable and it is for

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Nomenclature

RFID	Radio Frequency Identification
WSN	Wireless Sensors Network
EPC	Electronic Product Code
UHF	Ultra High Frequency
ANN	Artificial Neural Network
Var	Variance (Kriging)
W_{ij}	Weights matrix for each source sensor relative to each destination sensor (Kriging)
Z_i	Estimated temperature (Kriging)
S_j	Measured source temperatures (Kriging)
V	Environmental temperature (Capacitive heat transfer method)
Vc	Container temperature (Capacitive heat transfer method)
τ	Time constant for Resistor Capacitor system (Capacitive heat transfer method)
RC	Same as τ (Capacitive heat transfer method)
T_{pal}	Pallet/container temperature (Capacitive heat transfer method)
$Tenv$	Environmental temperature (Capacitive heat transfer method)
N	Number of source sensors (ANN)
D	Number of time-delay elements (ANN)

this reason there is a need for a fully automated “intelligent” chain-wide monitoring sensor system for the chilled food chain. The primary aim of such a system is to monitor and record temperature across the stakeholder axis and ultimately facilitate a complete product “chain of custody”. Through increased transparency, such systems have the potential to directly target such high levels of food waste while also increasing the safety, security and integrity of global supply chains.

In order to address this problem various monitoring technologies – such as traditional data loggers as well as Radio Frequency Identification (RFID) and Wireless Sensors Network (WSN) – have been implemented across food supply chains. These systems can keep temperature record history relating to the product and provide accurate localised individual measurement results through an unbroken chain of calibrations to accepted reference standards (Opara, 2003). Regattieri, Gamberi, and Manzini (2007) states that in general an RFID system will reduce labour costs and increase profits, while providing more efficient control of the supply chain and thus improving the management of perishable items.

Both RFID and WSN technologies provide an enhanced level of transparency across the full supply network. The core information is delivered via real time data streams providing information to stakeholders on product quality, safety and integrity. This in turn will lead to more flexible, adaptable and responsive supply chains facilitating end-to-end production and supply chain integrity monitoring. From a commercial perspective this will lead to the formation of smart, sustainable and cost competitive global supply chains. These systems present the opportunity to generate large streams of “actionable data” on which important management decisions can be made and will also help to reduce product waste across the logistic chain.

Monitoring devices are used to ensure the temperature integrity in the cold chain. However resource limitations and cost factors prohibit their use to one device per pallet or even perhaps one device per container (Badia-Melis, Brecht, Lowe, & Uysal, 2013). Validations of these systems are being performed by many researchers, such as testing in refrigerated trucks during international transportation (Jedermann, Ruiz-Garcia, & Lang, 2009; Ruiz-Garcia, Barreiro, & Robla, 2008, Ruiz-Garcia, Barreiro, Robla, & Lunadei, 2010), using smart RFID tags which integrate light, humidity and temperature sensors to monitor intercontinental fresh fish logistic chain (Abad et al., 2009; Hayes, Crowley, & Diamond, 2005) and temperature mapping of the pineapple supply chain (Amador, Emond, & Nunes, 2009).

In relation to produce spoilage, temperature is an environmental attribute of the highest significance (do Nascimento Nunes, Nicometo, Emond, Melis, & Uysal, 2014). Previous studies have demonstrated temperature variations inside an individual cold room which were caused due to the on–off cycles of the refrigeration unit, resulted in open air temperature variations for each individual item within the cold room from 1 to 3 °C to as much as 3–6 °C (Jedermann et al., 2009). Other common sources of unwanted temperature variations during common logistical processes include loading/unloading of the produce to and from the refrigerated truck. As reported by Ruiz-Garcia et al. (2010), in a refrigerated truck with temperature set point to 0 °C, the thermometer registered a maximum of 8.52 °C and a minimum of −3.0 °C. Furthermore, on average 98% of the time the temperature was outside of the industry recommended range (set-point ± 0.5 °C). Similarly, temperature control of mixed produce freight containers also present significant challenges, as individual “ideal” holding conditions may also vary across products within a single container and this may be further exacerbated by the temperature within each individual container (or cold room) varying.

According to Ruiz-Garcia et al. (2010), ideal lettuce storage conditions exist in the middle of the trailer, given the fact that in this part of the trailer the optimum lettuce storage temperature of 0 °C is observed. A shelf life of 21–28 d can be expected at this temperature, whereas at 5 °C the shelf life is significantly reduced to 14 d (Cantwell & Suslow, 2002). However, it's worth noting that the ideal storage conditions of lettuce are far from ideal for other products such as tropical fruits, for instance, and these conditions could cause chilling injuries to these products (Jedermann et al., 2009).

The influence of all the factors discussed above would require a large number of sensors to detect the local variations throughout a single container, a practice that has proven cost prohibitive across the food industry, and thus creating a difficult jigsaw puzzle. If one could increase the monitoring capability and resolution inside a shipping container without necessarily using more sensor units and the added cost, all stakeholders could benefit.

There already is extensive research in this area and attempts to address and overcome the issues (Jedermann et al., 2009; Jedermann, Palafox-Albarrán, Barreiro, Ruiz-García, Robla, & Lang, 2011). However, the proposed methods in the

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