Intelligent Quality Control in Cold Supply Chains

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Abstract

Towards a sustainable and resilient digital cold supply chain, environment sensing technologies and Big data analytics combined with Artificial Intelligence can extract critical information and provide a systematic framework for product optimization and safety enhancement. Our research focuses on a descriptive analysis framework of a real-world dairy food distribution system, using historical data collected from embedded sensors inside refrigerated trucks. The dataset consists of 5,972 records that present the distribution schedule, the collected temperatures and the refrigerator's open door window in seconds. The measurements are taken both on-route and while loading/unloading from various vehicles for two periods one in the winter and one in the summer. A Big data analysis approach combining statistical analysis and heterogenous data manipulation was conducted to extract critical results regarding truck refrigeration efficiency and dairy products safety zone. Additionally, Pearson analysis was performed to evaluate the correlation between temperature differences and the open-door condition. The results indicated that in the summer period, temperature fluctuations are intensified both on-route and at the delivery point compared with the winter period, and the operating time of the refrigerator is extended. Moreover, refrigeration performance differentiated amongst the vehicles due to the truck's thermal characteristics i.e. inappropriate thermal insulation or even the human factor. The contribution of this research is to conduct a descriptive analysis of critical measurements comparing system characteristics between the summer and winter periods and to propose an effective analytical framework for optimizing the efficiency of the overall system in a real-world distribution use case.

Keywords
Digital Cold Supply Chain, Big Data, Sensing Technologies, Sustainability, Industry 4.0

1. Introduction
In the concept of Industry 4.0 Digital Transformation is enhanced by the integration of Cyber-Physical Systems (CPS) with state-of-the-art approaches namely Internet of Things (IoT), Big Data technologies, 5G in digital supply chains and Artificial Intelligence (AI) Dolgui and Ivanov (2022); Ivanov and Dolgui (2021); JRC (2019). Sensors commonly found in Heating Ventilation and Air Conditioning (HVAC) systems such as temperature and pressure Wan et al. (2021) collect critical historical data of high velocity, variability, veracity, volume and value Fosso Wamba et al. (2015) enabling Machine Learning, Deep Learning, Statistical or Stochastic algorithms to predict heat comfort and ventilation efficiency, energy consumption and upcoming malfunction. This research is a continuation of previous work regarding a state-of-the-art IoT monitoring system for dairy products Syrmos et.al. (2022) where internal sensors and GPS location devices were mounted on dairy crates and delivery trucks, to highlight the quality deterioration of the dairy products enhancing the concept of disruption risk management perspectives in supply chains Ivanov and Dolgui (2019).

Based on the selected information, the theoretical approaches commonly applied are descriptive analysis explaining the statistical characteristics of the historical data, predictive analysis predicting ''what will happen in the future'' and prescriptive analysis outputting ''what shall be done and how'' Bousdekis et al. (2022). Our research emphasized the descriptive analysis of critical parameters namely, the distribution schedule, collected temperatures while the truck is on route and standstill and the open door timelapse at delivering point. The contribution of this work is a comprehensive analysis of overall distribution characteristics comparing the refrigeration efficiency amongst various vehicles and the optimization of decision-making regarding food safety and open-door timelapse based on the analysis of the provided datasets. Two experimented datasets were selected depicting distribution measurements on the winter and summer periods. The remainder of the paper is structured as follows: Section 2 refers to the description of the use case. Section 3 presents a comprehensive analysis and overall results for the decision support process, while Section 4 provides the conclusions of this work and future research directions.

2. System Description
The main scope of the proposed research is improving the overall distribution efficiency and product lifetime through a dynamic process of data acquisition and analysis. The acquisition of detailed information depicting the complete transportation and distribution of dairy products from manufacturers to retailers is performed. The monitoring framework and embedded sensors will ensure the dairy products' safety and the reliability of distributors, collecting quantitative measurements regarding temperature differences and open door frequency and duration in the summer and winter periods. The architecture of the proposed system is characterized by two distinct sections depicted in (Figure 1). A kit named i-EAT Tag, contains acceleration gyroscope and altimeter sensors, a temperature sensor and an RFID tag for truck monitoring and identification. The specified kit is embedded inside the truck's refrigerator for product monitoring throughout the distribution process. Furthermore, the i-EAT Truck kit is deployed on the vehicle acting as a data logger for storing critical temperature measurements regarding products and the vehicle's condition inside the refrigerator either on route or while loading/unloading the products. The i-Eat Tag unit upon initial processing transmits the collected data to the i-EAT Truck units using Bluetooth Low Energy (BLE) technology for low energy consumption.

More specifically, the electronic equipment installed in each container consists of

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1) A 3-axis gyroscope capable of reading 4000 degrees/sec
2) A temperature sensor with +- 0,5 ° accuracy
3) A 3-axis accelerometer measuring up to 16g.
4) An atmospheric pressure sensor, reading up to 30cm of altitude difference.

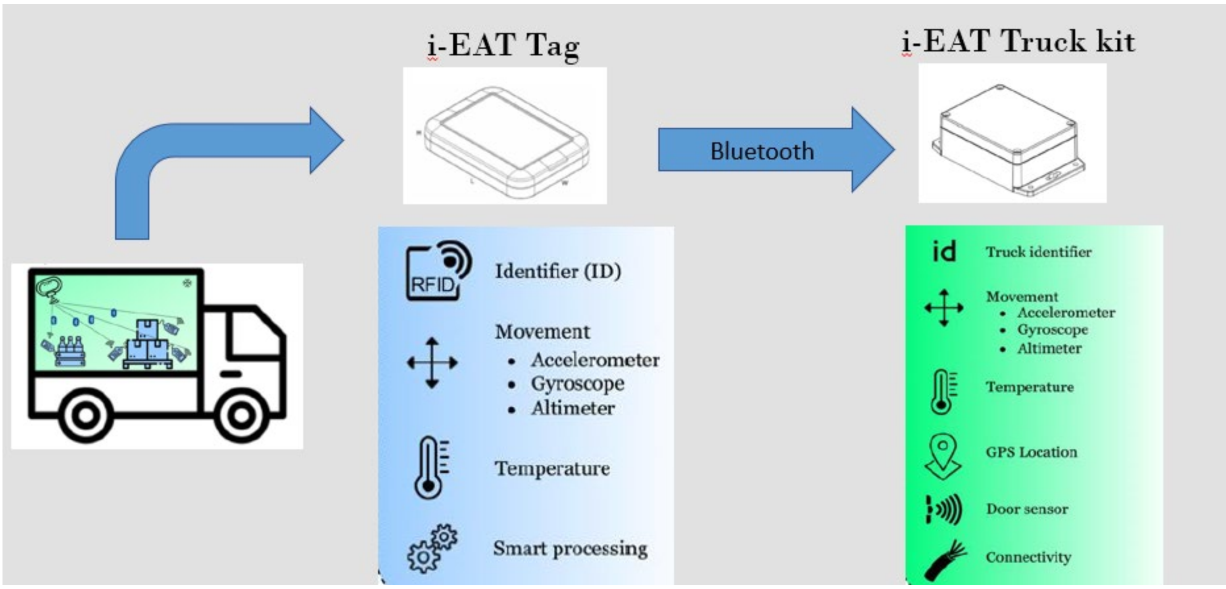

Figure 1. Architecture of the proposed system

Critical features regarding product condition and vehicle characteristics throughout distribution are provided by the embedded sensors. The next section presents a comprehensive analysis of the decision support system containing descriptive analytics and heterogenous data manipulation and finally a concise report depicting the overall results of product distribution and temperature behavior.

3. Decision Support System

A descriptive analysis of collected measurements from heterogenous data sources was conducted for systematic observation and decision support actions. The processed dataset contained detailed information regarding the complete transportation and distribution of dairy products from a warehouse to the retailers. More specifically, a total of 2,453 measurements describing vehicle_id, from location, to location, enroute temperatures, stop temperatures and open door timelapse were collected for a period of one week in summer and winter solstice respectively. Data analysis can be divided into subsections namely, data cleaning, data manipulation or data pre-processing and decision support or decision making, Broman and Woo (2018); Wickham RStudio (2014) presented extensively a data analysis framework for data organization and further manipulation.

3.1 Data Cleaning

As an initial stage of data analysis data cleaning involves identifying incomplete or inaccurate measurements in order to be replaced or deleted. Upon further processing of the collected dataset, it is essential the selected heterogenous values to be complete and in proper format. The authors identified a total of 5,792 Not a number values (Nan) a significant amount given on the volume of the overall dataset. In order to preserve valuable information about each instance the source of given Nan values has been traced. The manipulation of those values varies based on the significance and the origin (i.e. temperature values and door open values have been treated differently). The majority of Nan values are collected from a sensor describing a side door which rarely opens during dairy products distribution hence those values were deleted without affecting the overall decision outcome. However, the rest of the Nan values have been identified in specific temperature measurements where the respective sensor malfunctioned. Those instances can be crucial for the decision outcome and thus the selected approach was to fill the missing values with the mean of each given feature near the specific location. Instances of the inappropriate format were not identified throughout the dataset. NumPy and Pandas libraries of the Python programming language were applied for the data-cleaning process Mckinney n.d. (2011).

3.2 Data pre-processing

Following data cleaning, data pre-processing is the procedure of manipulating historical data and generating valuable information for further analysis. In our work data pre-processing is divided into procedures such as:

Data selection. The authors selected specific instances depicting the in-work timeline of each respective vehicle. That being said, this research is focused on the descriptive analysis of important features namely, vehicle temperatures and the timelapse of open doors while the vehicle is distributing the dairy products.

Data generation. Raw input sensor measurements regarding temperature, demonstrate the minimum and maximum collected value on each respective route. Two temperature sensors are installed throughout the vehicle outputting measurements depicting the vehicle temperature while moving and while at a delivery point. For a comprehensive understanding of the temperature changes throughout each trip and to improve decision-making regarding food safety, the authors generated new columns containing the difference between each maximum and minimum measurement. Additionally, in order to assist data selection, the duration of the open-door variable is divided into three supplementary columns hours/minutes/seconds for further processing.

Data organization. Finally, the dataset is divided into subsections of data frames where each subsection depicts the weekly route of a specific vehicle used for dairy product distribution. Moreover, the analysis and decision support are season-based for comparison between winter and summer solstice distribution. Additionally, a data frame containing the instances of specific measurements where the open door surpasses 20 minutes has been developed for further examination.

3.3 Data Visualization

In an industrial application data representation can be beneficial for an in-depth comprehension of data distribution, pattern recognition and outlier detection. It is essential for the processed measurements to be presented in a concise and understandable matter using the appropriate chart namely, (scatter plot, bar plot, heatmap, pie chart etc.) for each respective variable Ali et al. (2016). In our work, following initial pre-processing and data cleaning, line charts were designed containing crucial parameters of the dairy products distribution for data visualization and decision support. The visual data presentation is implemented using Python programming language and the Matplotlib library. In the particular paradigm, the deviation between the minimum and maximum distance is minimal with the highest mean value of 0.5. Additionally, for the same vehicle, a secondary set of charts (Figure 2) is designed to depict the generated difference between minimum and maximum temperature for each measurement and a combination of temperature differences with open-door minutes in each distribution point. Thus, it can be visualized at first glance whether the temperature differences and the open door timelapse are correlated. Assisting and verifying data visualization, the Pearson correlation analysis (Table 1) outputted that the correlation between the variable of the open door in minutes and the respective temperature differences in delivering point was up to 90%. Thus, it can be concluded that the differences between minimum and maximum temperatures are greatly affected during the summer period by the number of times and the duration that a door opens.

However, during the winter, the temperature differences are slight thus the correlation results do not provide specific information. It is worth noting that an instance was identified where Pearson analysis outputted low correlation value (Vehicle V3 – 8% correlation). Additionally, the temperature measurements in particular case depicted a linear increase during the distribution route differentiating from other vehicles where the temperature changes periodically. That being said, for the specific vehicle it can be concluded that most likely the refrigerator has been turned off by the driver for cost-effective reasons and thus the correlation between temperature differences and open door timelapse is slight. Moreover, in Figure 2 it is noticed that the door is open for more than 15 minutes for a couple of measurements in case of vehicle V6, inducing the authors to further investigate tracing back the origin of those outliers. Upon thorough examination, it is concluded that the aforementioned open-door delays originate from a specific distributor and this is indicated as a human-oriented outlier.

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Table 1. Pearson correlation analysis results amongst the variables temperature differences and open door timelapse for each respective vehicle

Vehicle_id	Summer period	Winter period
V1	0.90	0.68
V2	Off duty	0.46
V3	0.74	0.08
V4	0.86	0.72
V5	0.55	Off duty
V6	0.82	0.6

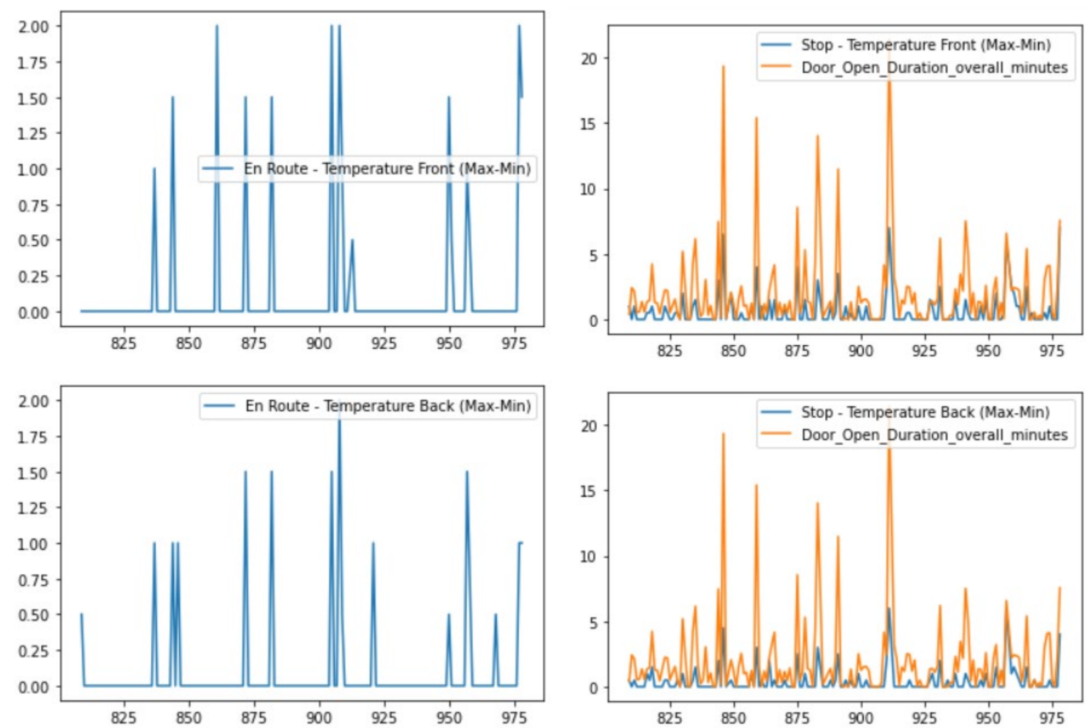

Figure 2. Temperature differences (left side) and combination of Temperature differences and open door timelapse while on route and standstill respectively for the weekly distribution of the same vehicle during summer period

Other than exploiting the data analytics performed on the initial measurement data set, a decision support framework has been developed to focus on potential use in the operational phase, aggregating, persisting, and utilizing sensor measurements as telemetry data. In particular priority has been given to the use case of conducting analysis of measurements along the transportation route. The operator can use the system (Figure 3) to discover the product's transportation routes and obtain a graphical depiction of temperature measurements where potential problematic conditions are emphasized.

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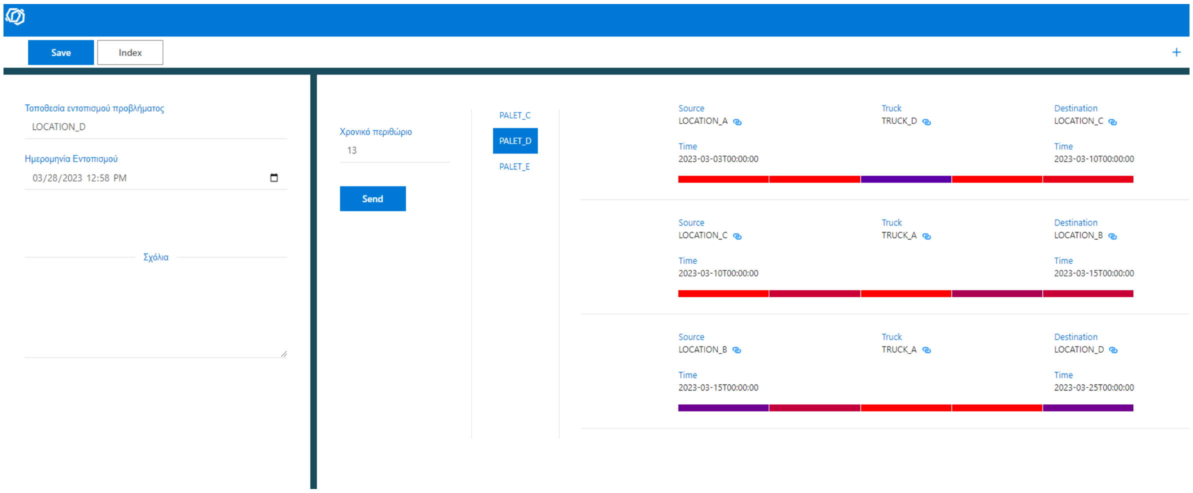

Figure 3. Decision support framework containing product's transportation routes and graphical depictions of temperature measurements.

3.4 Overall Results for decision support

Based on the descriptive analysis conducted by the authors several conclusions have been produced regarding dairy products distribution characteristics and temperature behaviour. Initially, as expected, in the summer period temperature fluctuations are intensified both on route and on the delivery points, and the operating time of the refrigerator is extended. Additionally, the refrigerators' operation in the majority of the trucks has some periodic characteristics (operates until a specific temperature is achieved) resulting in continuous temperature changes. However, in the winter period, a specific track did not have any temperature fluctuations due to the fact that the refrigerator was turned off. Moreover, in some cases, it is observed, that while the mean temperature difference when on the route is relatively low the same variable on a delivery point has a relatively high value. In the aforementioned cases, the total number and duration a door is left open at a delivery point is extended verifying the correlation between mean temperature differences and open door frequency.

Hence, it can be considered that this specific behaviour is triggered by a human factor and not by a refrigerator's malfunction. On the other hand, some instances in the summer period were identified where temperature fluctuations were intense on average, both in motion and at a delivery point. This occurred even without the door being open for a particularly long time. Thus, this may be due to insufficient maintenance of the cooling unit or issues of insufficient thermal insulation of the vehicle. During the winter season, even if the doors remained open for a long period, temperature differences in the chamber were not particularly affected. Finally, some distributors had low-temperature deviations and optimal performance due to the efficient refrigeration unit and thermal insulation but also due to the efficient use of the doors by the human operator.

4. Conclusion

A descriptive analysis and performance comparison in a digital cold supply chain environment is presented. The uprise of Cyber-Physical Systems, the Internet of Things, Big Data analysis, 5G technologies and Artificial intelligence enhance the implementation of smart decision support systems assessing the safety of dairy products and refrigeration efficiency during distribution. Following the system definition, a comprehensive framework of a data analysis approach combining data cleaning, data pre-processing, data visualization and result evaluation was developed enhancing the decision-making process. The results compared the efficiency performance of various delivery trucks during winter and summer periods and verified the excessive correlation between temperature differences and open door timelapse especially during the summer period. The future work of this research seeks to collect additional historical data containing deteriorated product measurements (measurements from products that do not have their organoleptic properties) in order to develop a predictive algorithm for product condition prediction and prescriptive approaches for system optimization and loss prevention. Another extension of this work is to enhance descriptive analysis focusing on dairy product temperature differences when on different crate positions inside the distribution vehicle (i.e. front row, upper side etc.). This can maximize system efficiency in environmental, and socio-economical aspects while optimizing the processes in digital cold supply chains.

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Biography

Panagiotis Mallioris holds a B.Sc. degree from the Department of Industrial Engineering and Management, School of Engineering, International Hellenic University (IHU). Currently, he is a Ph.D candidate conducting his research titled "Big Data Visualization and Analysis Methodologies in Production Systems and Value Chains". His work focuses on big data analysis, artificial intelligence, data mining and predictive maintenance. He has supervised numerous undergraduate thesis projects regarding predictive maintenance and artificial intelligence algorithms in modern industry. Mr. Mallioris participates in a national-funded research project as a research associate named Quality Control of Production Processes by Using an Integrated Decision Support System (ProDSS) National Strategic Reference Framework (ESPA) 2020-2022.

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Maria Papaspyropoulou (Female) is a Chemical Engineer who graduated from Aristotle University of Thessaloniki (AUTH) in 2020. She has been involved in laboratory research involving inorganic materials and industrial applications. She is currently working as an R&D Engineer, managing several research projects related to Industry 4.0 technologies, Big Data, Zero Defect Manufacturing, Circular Economy, and other fields..

Konstantinos Georgakidis He is a qualified Chemical Engineer from the Polytechnic School of AUTH (year of acquisition 1996). He completed postgraduate studies in Business Administration (MBA) (acquired year 2001) and obtained a second postgraduate qualification (MSc) in Waste Management (acquired year 2010) from EAP. As an executive at MEVGAL, he has been dealing with Research and Development Programs for the last 20 years, while for about 5 years he was in the Logistics department. Having been the Head of Research & Development Programs since 2002, he has participated in a number of approved projects (over 20 projects) both at the National level (PABET, SYNERGASIA, PEPER, ΕΠΕΤ II, INTERREG etc.) and at the EU level (FP5, FP7 & HORIZON), having the role of Coordinator in many of them.

Nikolaos Sfitis is a Mechanical Engineer, graduated from the Aristotle University of Thessaloniki, with a Master of Business Administration from Kingston University of London. Currently he is employed at MAKIOS LOGISTICS S.A. occupying the roles of the Head of Fleet Maintenance Dpt and the Head of Energy production dpt. He has experience of over 15 years in fleet management and from the last 5 years in renewable energy sources (Biogas and photovoltaic plants). He has also participated to European research projects (SUITS 2018-2021).

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