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Digital Twin for Inventory Planning of Fresh Produce

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Abstract: The management of perishable food inventory demands special attention. Fruits quickly lose their freshness and perish if they are not consumed within a specified period. It is critical to develop a management tool based on the Internet of Things that can efficiently integrate all the dynamic data associated with various types of resources in real-time along the supply chain. This research is part of a comprehensive supply chain framework developed to analyze food bank logistics supply chain interactions. The study will mainly focus on the use of historical time-series data to create a digital twin that can anticipate future events. The digital twin framework was built based on the operational trend of the Italian food bank to strengthen the decision support system related to the fresh food inventory. The SAP Analytics Cloud was used to create a solution that would help the organization better satisfy consumer needs by reducing fruit waste in the inventory.

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Keywords: Time-series, Digital Twin, Predictive Forecast, Inventory Planning, Fruits.

1. INTRODUCTION

In comparison to other food items, perishable food requires special attention due to its biological composition. Improper tracking and control of inventory levels can result in the loss of a large amount of food, which might benefit millions of people in need of food. The greatest amount of food lost in the fruit and vegetable supply chain due to poor quality and supply-demand mismatches (Raut et al., 2019). According to the study, the supply-demand mismatch is driven by both internal and external causes, including government policy, a lack of retail facilities, awareness, and transit infrastructure (van Donselaar et al., 2006).

Food waste can occur when products are still usable but approaching the end of their life. This problem occurs due to a lack of synchronization between demand and supply of the products. Developing solutions for this type of problem is seen as an important step in inventory management because it helps to avoid problems with the loss of fresh produce, especially fruits, which are very perishable.

In the past decades, various technologies have been implemented to improve the efficiency of the perishable food supply chain. Some of the technologies include radio frequency identification, the Internet of Things, blockchain, three-dimensional printing, autonomous vehicles, and unmanned aerial vehicles (Morrison, 2009). These technologies have increased the efficiency of the system. However, they are unable to reduce food waste to the extent that was anticipated. The use of reliable simulation-based digital twins can be considered one of the key approaches to monitoring inbound and outbound logistic processes in real-time. By definition, "a supply chain digital twin is a detailed simulation model of an actual supply chain which uses real-time data/snapshots to forecast supply chain dynamics" (AnyLogistix, 2020). Analysts can use the output to understand the behavior of a supply chain, predict abnormal situations, and propose an action plan. A digital twin is one of the industry 4.0 enablers that allows for deep synchronization and dynamic interaction between the physical and virtual worlds (Wang et al., 2020). Companies can use Industry 4.0 to improve interoperability, data transparency, technical support, and decentralized decision-making. A supply chain uses a digital twin to analyze and predict changes in real-time data about orders, supply, demand, approvals, etc. The data is collected by IoT devices (sensors), databases, users, and vendors. So, companies can better track their supply chain and react quickly to changes. Decisions regarding supply chain network architecture play a big part in optimizing a supply chain's operation since they affect total operational costs in the long term.

A few studies have investigated the issues with food bank supply networks. In the context of food rescue and distribution, this research has focused on real-time product monitoring (Melesse et al., 2022) as well as scheduling and routing issues for non-profit organizations (Mandal et al., 2021; Parker et al., 2020; Rodriguez, 2020; Santini & Cavicchi, 2014).

Inventory forecasting, which is also referred to as demand planning, is the act of anticipating inventory levels for a future period based on historical data, trends, and known upcoming events. Forecasting accurately ensures that businesses have enough products on hand to fulfill client orders while not wasting money on excess inventory. Forecasting is the analysis of data to identify patterns and trends that can be utilized to adapt to changing conditions and meet client demand.

In digital twin development, the use of accurate time-series and predictive analytics tools provides insights about future

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events. Forecasting is at the core of supply chain planning, and the outcomes are crucial in coordinating sourcing, production, and logistics (Wang et al., 2020). Using forecasting techniques, the model can provide insights about future phenomena based on trained historical events. The use of precise time series prediction can be used as an important tool in constructing a digital twin (dos Santos et al., 2020; Hu et al., 2021). Therefore, through the digital twin-led data integration, the stakeholders can get constant support from the system using real-time or near-real-time data.

The paper proposes the use of time-series-based digital twins in forecasting and the continuous decision-making process for planning perishable food inventory operations. For training the model, historical data on inbound and outbound logistics has been used from the food bank database, and the model has been implemented in the SAP Analytics Cloud. Section 2 discusses related works and the theoretical background of time series-based digital twins in supply chain planning, followed by the proposed approach in Section 3, and Section 4 discusses the case study of the Italian food bank. Finally, Section 5 provides concluding remarks on the work.

2. RELATED WORKS AND THEORETICAL BACKGROUND

Nowadays, supply chains are transforming themselves from traditional sequences to digital supply chain networks that can allow using of information from different sources during production and distribution phases. Companies will be able to provide synchronized scheduling, dynamic execution, intelligent supplies, smart monitoring, and a smart factory, making the environment more responsive for stakeholders (Barykin et al., 2020).

In the perishable food supply chain and saving the loss of food products, planning is the foundation for productivity, quality, and overall effectiveness of the supply chain network (Wang et al., 2020).

As a novel technology, the digital twin can synchronize the real and virtual environments in the supply chain by merging data from many sources, such as supply, demand, product quality, and planning variables. The digital twin paradigm can be used to link transportation management, supply chain management, ERP, business intelligence, demand forecasting, production planning, and inventory management. Forecasting, in conjunction with other approaches such as simulation, time series, qualitative, and informal methods, builds the foundation for supply chain digital twin creation (Wang et al., 2020). The application of these methods will answer questions about planning issues, including the quantity to be purchased, delivered, or produced. In particular, the time-series method of forecasting looks at the trends in historical data.

The use of simulation with forecasting methods can provide insights into certain supply chain phenomena. There are many use cases for time-series-based forecasts in operational planning. However, to be a digital twin, the forecast should provide constant decision support and integration with the virtual model. In the definition of a digital twin, it is common to see the term "real-time" and the use of sensors. But in the case of the supply chain, real-time might not be critical (dos Santos et al., 2020). The time scale of a digital twin is dependent on the type of goal. For instance, distributed control systems, model predictive control, online optimization, and process scheduling use time scales of seconds, minutes, hours, days, or weeks, respectively. In addition, sensors might not be able to collect supply chain data, and most of the time, manual processes are better.

In perishable food inventory management, forecasting will help to plan the amount of inventory level in response to different constraints such as storage space and product shelf life. The accuracy of these forecasts can be improved using tools of industry 4.0, such as big data analytics.

The development of a supply chain digital twin starts with mapping the process and determining the data source of the supply chain network (Figure 1). Then, using IT architecture, the internal and external real-time data sources will relate to the model of the supply chain that can enable simulation, optimization, and analysis of a system. Machine learning and analytics tools are useful in this context for learning about the system, experimenting with different scenarios, and responding to problems in the supply chain network.

The concept of the "digital twin" has gained popularity in supply chain management in recent years. The study by Marmolejo-Saucedo *et al.* (Marmolejo-Saucedo et al., 2020) has proposed a digital twin approach for an automotive company in Mexico to improve delivery times to customers. In this case study, the authors used anyLogistix supply chain software to develop a digital twin for decision support using enablers such as flexibility, agility, and real-time data exchange. Besides, a report has proved the application of digital twins in logistics networks as a non-destructive quality control method compared to traditional methods (Kapustina et al., 2020). The article also discussed the main differences between traditional and digital supply chains.

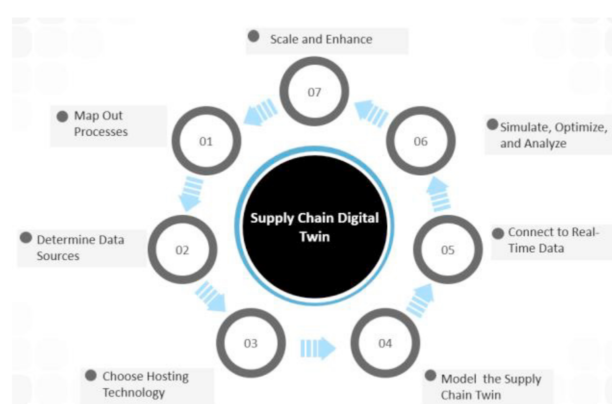

Figure 1. Steps to supply chain digital twin (Coupa, 2020)

Despite that, the implementation of digital twins has adverse effects on companies' business and visibility. Common obstacles to the successful implementation of digital twins include education (which causes management change and knowledge transfer), accurate representation, data quality, costs, IP protection (data ownership concerns, identity assurance procedures, and user access control), digital security, and interoperability (Kamble et al., 2022; Moshood et al., 2021). In the case of the agri-food domain, the application of digital twins is still at an early stage due to ethical issues and societal and safety impacts they may bring (van der Burg et al., 2021). However, reports are showing promising signs of progress in the sector (Agrawal et al., 2021; Pylianidis et al., 2021; Verboven et al., 2020).

3. PROPOSED APPROACH

As described in Figure 2, the approach uses operational data to develop a digital twin-based decision support system for fresh food inventory. The model leverages the food bank's incoming donations and outbound logistics data to generate insights for rescheduling the delivery process and controlling inventory levels. The approach illustrates the general framework of the supply chain that will be assessed in the next work. However, in this piece of work, we have specifically focused on the use of time-series data. The time series can be automated using SAP Analytics Cloud (SAP, 2022) and the model can be trained using a forecast algorithm.

Time series forecasting is useful for estimating a measure's future values. The training dataset is divided into two parts. The estimate dataset is used to detect cycles, whereas the validation dataset is used to validate cycle accuracy. It is critical to limit the scope of cyclic search to save computation complexity, especially for periodicities. The historical data is divided into two sections: A 75% of the dataset is allotted for change detection and model generation. The remaining 25% is the validation dataset, which is used to assess the quality of the prediction models and select the best one. The validation procedure compares the actual values of the measure to the anticipated values of each model. This subset is used to calculate the difference between actual and forecasted values over the time horizon specified by the user in the model settings. The difference shows the forecast model's error. The standard deviation from this series of errors is then computed using Smart Predict, which can explore relationships in the dataset.

The objective of the proposed framework is to ensure that the Food Bank has enough fruit on hand to fulfill the demand of small charity organizations while balancing the amount of fruit supplied by different donors (Figure 5) and the storage space required to minimize fruit waste.

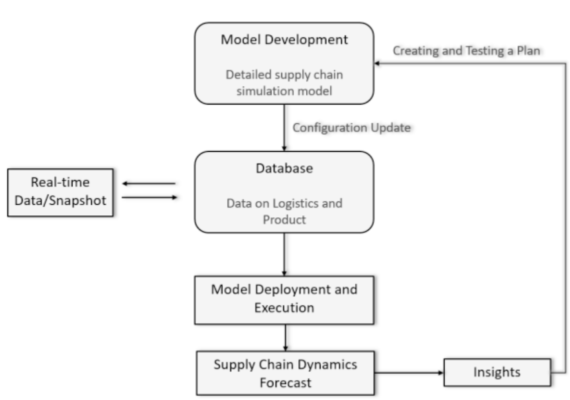

Figure 2. The general framework of supply chain digital twin

In contrast to traditional simulation models, the proposed model is constantly updated to adapt to the real process. As part of the supply chain, this will help the food bank make better decisions and meet the demand of small charity organizations.

4. CASE STUDY

A case study of Banco Alimentare Campania Onlus (one of the Italian food banks) is used to evaluate the proposed approach. A food bank is a non-profit organization that recovers and collects surplus food from different sources in the supply chain, including food processing, agriculture and primary production, distribution, food service, and retail (Silchenko, Simonetti and Gistri, 2019). Banco Alimentare Campania Onlus is among 21 regional food banks operating across Italy. The organization collects food from different donors and re-distributes it to more than 350 small charities located in the Campania region (Figure 3).

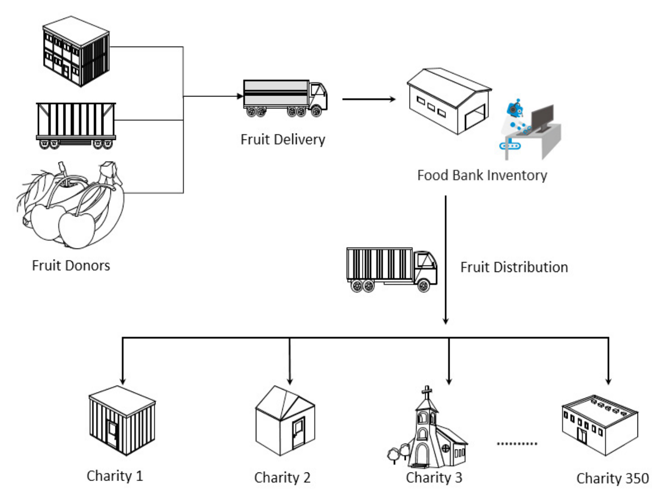

Figure 3. Structure of fruit supply chain network

Due to uncertainties in demand by charity organizations and incoming donations, the food bank is wasting huge amounts of fruit. This case study has focused on perishable food items, particularly fruits. In this supply chain network (Figure 4), there is uncertainty in the donation and distribution of fruits to charity organizations on an irregular basis. Similarly, orders are coming from different charity organizations operating in the region. Donors typically contact the food bank by mail within 48 hours to inquire about their availability to accept donations. In this case, the food bank does not order the products; it simply receives the items that are offered.

The delivery of the fruit is almost exclusively at the expense of the donor. However, the charity organizations collect the fruit at the food bank with their own means as well as deliveries by the food bank. Due to such a traditional way of communication, the food bank is facing challenges in managing its inventory to save perishable food items that are going to waste in a short period. The use of a digital twin, on the other hand, will make it easier for food bank operators to reschedule incoming and outgoing logistics.

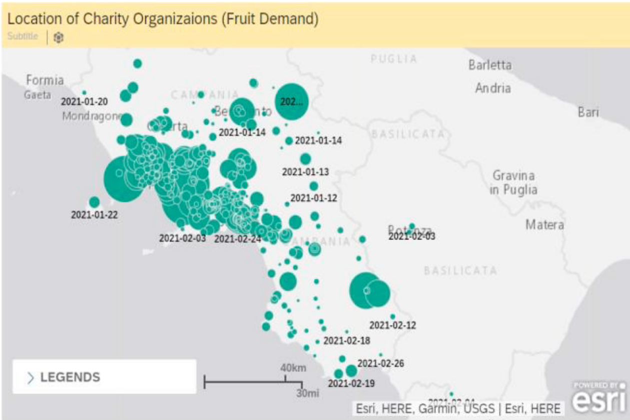

Figure 4. Geo map of charity organizations based on their demand

As shown in Figure 8, there is a big mismatch between incoming and outgoing logistics, which increases the risk of controlling the inventory level. A digital twin solution will be able to monitor disruptions and levels of perishable food inventory in real-time by synchronizing and predicting incoming donations and the amount of distribution. It's also possible to make sure that deviations from the plan are kept track of and that the logistical activities of getting fresh food from donors are rescheduled to meet the needs of small charity organizations. The model was created and trained in the SAP Analytics Cloud using historical data from the food bank. In the model, all the demand and supply quantities were expressed in kilograms. The experiment was done using annual data on irregular donations and distributions.

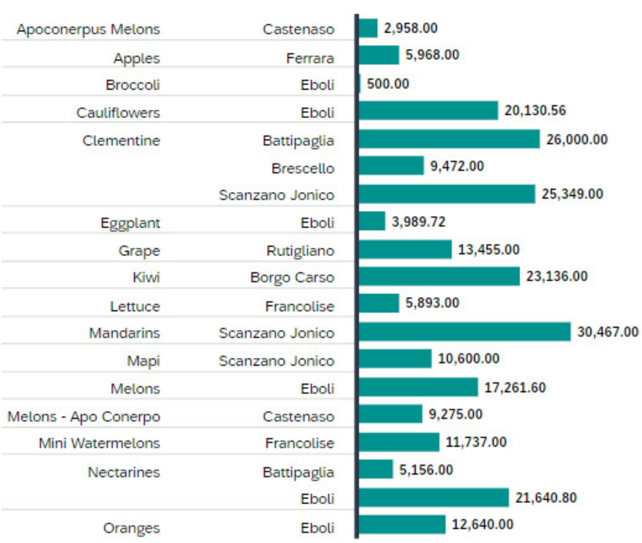

Figure 5. Historical data of incoming fruit donations and locations

As shown in Figures 6, 7, and 8, after the automation of time-series data from the food bank database, the digital twin predicts both the number of incoming donations and deliveries to charity organizations. Based on the forecast, the food bank can reschedule and perform quick modifications to the inventory. More adjustments can be made to solve issues related to storage space. Due to energy consumption, the food bank has limited refrigerated room capacity to store fruits. It is important to maintain a balance between distribution and donations of fruits.

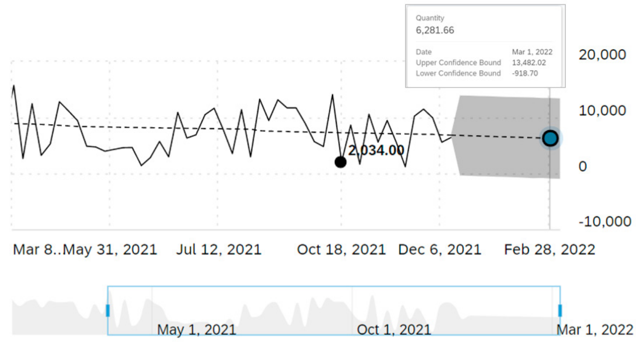

Figure 6. Daily forecast of incoming donations

Based on the traditional operation of the food bank, there is no way to have some insights to support the decision-making process. The digital twin empowered by the analytics tool will enable the food bank to take a proactive approach. Otherwise, after one week of storage, the fruits will be discarded.

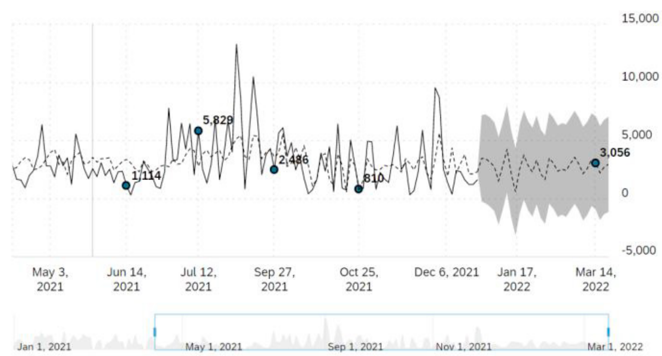

Figure 7. Forecast for the demand of charity organizations

A digital twin, as proposed, can synchronize the supply chain network, improving collaboration between donors, food banks, and charity organizations. The information is collected and analyzed in near real-time for quick decisions. Since the fruits are highly demanded by a charity organization, the information can be used as input for the inventory replenishment process. Typically, donors provide fruits that have already begun to degrade in quality. As a result, fruits that arrive in food bank stores have an extremely short shelf life. Besides, based on incoming donations, the food bank will be able to initiate a quick delivery of fruits to charity organizations if the storage space is not available.

Digital twins are living models that are constantly updated with current events. The proposed approach will assist the food bank in predicting what needs to happen with its fresh food inventory and how other factors are influencing supply chain activities. The model is continuously updated with the most recent operational data to obtain real-time or near real-time data to feed into the digital twin.

The food bank can forecast the volume of donations as well as the demand for charity organizations using an automated time series. As illustrated in Figure 8, the quantity of demand by the charity is less than the number of incoming donations. In this situation, storage space may not be an issue, and the food bank can still receive more fruits. If the incoming donation exceeds the outbound logistics, the food bank will reschedule the immediate delivery of fruits to a charity organization according to the predictive forecast.

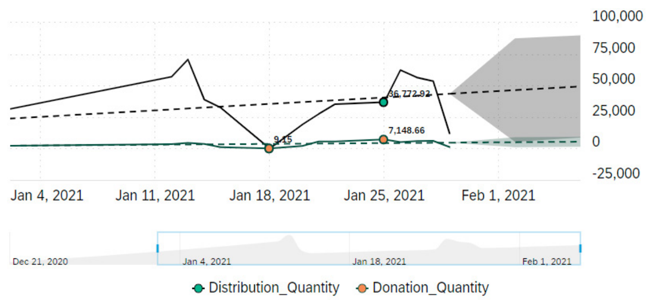

Figure 8. Forecast on the amount of fruit donated and distributed

Demand forecasting is critical for any firm. This involves having adequate inventory on hand to meet the demand of customers. A company that fails to estimate demand and orders insufficient inventory risks losing clients to the competition. A late order may cost more because supplier prices have risen in response to rising demand; this is yet another way the company loses money. If a company overestimates demand and orders too much inventory, there's a danger it will end up with underutilized inventory and must pay for extra storage. If the organization has a large inventory of perishable goods, it may incur financial damage on products that have already lost their freshness.

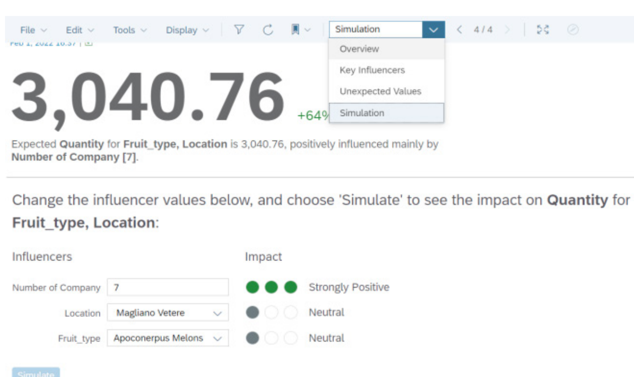

Figure 9. Simulation to view the impact of key influencers

Supply chain management is the process of matching supplies or inventory with customer demand. Because food banks are non-profit organizations, this logic does not entirely hold. Even so, they are unable to refuse to receive donations and orders from local charities that provide fruits to the needy. As a result, it might be best for organizations like food banks to use digital twins to coordinate their activities and keep an eye on their inventory levels to change their plans.

In addition to prediction, using the simulation, it is possible to discover how changing the influencers has an impact on the value of demand quantity for fruit type and location by changing the values, the food bank can perform what-if scenarios (Figure 9). This will allow the food bank to design action plans to help them confront anomalous events and evaluate those plans to verify they are effective.

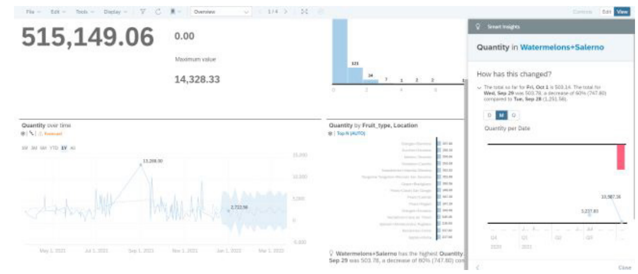

Figure 10. Interactive storyboard for digital twin

Overall insights into supply chain performance can be visualized through the storyboard as shown in Figure 10. The charts could depict additional key influencers based on real-time data to better comprehend the relationship between both key influencers and their impact on fruit quantity.

5. CONCLUSIONS

To summarize, this paper envisions a digital twin-based management and planning system for fresh food inventory that is driven by time-series data. By synchronizing demand and supply, the digital twin enables faster action and response times, thereby reducing product loss. The digital twin improves forecast accuracy by utilizing dynamic and comprehensive data from real-world operations. The use of predictive analytics tools can significantly improve the implementation of the proposed system. In the era of Industry 4.0, more predictive tools are becoming available, and the efficiency of the forecast has improved fast. Forecasting lets the food bank keep enough products on hand while not wasting space on products that aren't needed.

The proposed framework for a digital twin has been primarily focused on resolving the food bank's fruit waste problem. The next study will focus on vehicle allocation and routing to reduce fruit loss during delivery to other local charities. Furthermore, more effort will be made to create a general architecture for a fruit supply chain digital twin. This framework will include solutions for activities ranging from keeping track of how fruit quality changes to its delivery to customers.

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