

EMERGING TECH CONFERENCE – Edge Intelligence

Volume 03, 2024, Pages 98 – 103

**Proceedings of Emerging Tech Conference:
Edge Intelligence 2024**

Charting A New Course for Food Logistics:
Enhancing River and Ocean Transport Efficiency
with CFD-Based Digital Twins, with examples
from soybean logistics in the Amazon river

Sotiris Bantas¹, Miltiadis Xynopoulos¹, Alexandros Dimitriou¹, Antonis Sioutas¹, and Efstathios Kaloudis²

¹*Centaur Analytics, Inc., 1923 Eastman Ave, Ventura, 93003, CA, USA*

²*Computer Simulation, Genomics and Data Analysis Laboratory, Department of Food Science and Nutrition, School of the Environment, University of the Aegean, Myrina, Lemnos, Greece*

sotiris@centaur.ag, stathiskaloudis@aegean.gr

Abstract

Efficient grain transportation via barge along major waterways like the Mississippi and Brazilian Amazon is vital for global food security and economic stability. This paper presents a Computational Fluid Dynamics (CFD)-based digital twin methodology tailored for crop logistics in barge transportation. Integrating sensor data with predictive analytics, the digital twin continuously monitors temperature, humidity, and airflow dynamics to optimize grain storage conditions during transit. Case studies from commercial grain logistics show how this approach enhances efficiency, reduces costs, and ensures grain quality, demonstrating the transformative potential of IoT and digital twin technologies in global food supply chains.

1 Introduction

The efficient transport of grain and oilseeds such as soybeans by barge along major waterways such as the Mississippi River and the Brazilian Amazon is critical to global food security and economic stability. However, ensuring optimal storage conditions during transport presents significant logistical challenges. Traditional methods of monitoring grain quality during transport often rely on manual inspections or static sensors that only provide periodic snapshots of environmental conditions (Caixeta Filho and Péra, 2018). While these approaches are functional, they lack the adaptability and real-time insights required to effectively manage dynamic, long-distance grain logistics.

In recent years, emerging technologies have sought to address these challenges. Previously reported Computational Fluid Dynamics (CFD) models (Lawrence & Maier, 2011; Quemada-Villagómez et al., 2020) have been used to simulate airflow and temperature conditions in static storage environments. However, these models typically utilize predefined data and lack the ability to adapt to real-time changes. Another notable development is the integration of Internet of Things (IoT) technology in logistics management, allowing for real-time data collection and remote monitoring of grain conditions (Dyck et al., 2023). While IoT has enabled better traceability and monitoring, existing solutions often fall short in their ability to predict future conditions and optimize storage environments proactively.

This study presents a novel CFD-based digital twin methodology tailored to the unique challenges of grain barge logistics. Digital twin technology, which creates a virtual replica of a physical system, has been successfully applied in industries such as manufacturing and precision agriculture (Dyck et al., 2023), but its application in river and marine transport logistics remains relatively unexplored. By integrating real-time sensor data from IoT devices with advanced CFD models, our digital twin continuously monitors and predicts key environmental parameters such as temperature, humidity and airflow dynamics. This enables dynamic adjustment of grain storage conditions throughout the transport process, ensuring grain quality while reducing the risk of spoilage. As demonstrated by (Kollias et al. 2022), digital twin models can be instrumental in predicting and optimizing crop conditions in postharvest logistics, and our application of this methodology in barge transport marks a significant extension of its potential.

Several technologies are available in the same area, including static CFD models for airflow simulation (Lawrence & Maier, 2011; Quemada-Villagómez et al., 2020) and cable sensors for condition monitoring and weather stations that monitor the ambient conditions. However, these technologies typically operate independently and lack the predictive capabilities and real-time optimisation capabilities offered by the proposed digital twin approach.

In terms of market positioning, this digital twin solution occupies a unique space within the grain logistics industry. While traditional solutions focus on monitoring or simulation, the present approach provides a comprehensive system that not only monitors but also optimises grain transport conditions in real time (Kaloudis et al., 2024). This positions the proposed technology as an industry leader in predictive grain logistics management, offering significant cost savings, improved efficiency and enhanced sustainability.

2 Materials and Methods

2.1. Crop monitoring sensors and IoT system

To accurately monitor the storage conditions of grain, a network of IoT-enabled wireless sensors can be installed within the grain and move with it during transport (Figure 2). These sensors are designed to measure critical environmental parameters such as temperature, relative humidity, CO₂ and O₂ levels (Bantas et al., 2019). The high sampling frequency allows real-time data to be transmitted to a central database, enabling continuous monitoring (Centaur). The collected sensor data is integrated into advanced CFD models to simulate the airflow and heat transfer dynamics within the storage environments. These models solve the Navier-Stokes equations governing fluid flow and include additional equations for heat and mass transfer (Kaloudis et al., 2022). The simulation accurately represents the conditions within the storage systems, including potential hotspots for spoilage. Appropriate boundary conditions are imposed, including ambient temperature, relative humidity, solar radiation, wind speed and water temperature along the barge route. The CFD models are combined with other differential equations used to predict several critical quality metrics of the stored grain, including dry matter loss, the presence of visible mould and germination capacity. Validation of the CFD model is presented in Kollias et al. (2022).

For this study, a representative barge shipment of 3,000 tonnes of soybeans was analyzed, traveling from Miritituba to Bacarena, along the Amazon river. The barge dimensions were 8 meters in height, 30 meters in length, 12 meters in width, and a 5-meter draft. The voyage began on June 20, 2023, and concluded on July 4, 2023. Two wireless sensors were installed on the barge: one near the top layer of the soybeans at a height of 7 meters and the other near the bottom layer at a height of 2 meters.

2.2. Web-based IoT platform and predictive crop quality analytics

Additionally, a web platform (Centaur) enables users and grain managers to access real-time data and predictive insights from their smartphones. This platform displays the status of storage and logistics assets, including predictions of various quality metrics such as dry matter loss, the risk of visible mold, and the germination capacity of stored grain and oilseeds. The predictive power of the incorporated digital twin model, combined with the accessibility of the web platform, demonstrated significant potential to reduce spoilage and ensure the quality and safety of grain transport by barge through informed and timely decision-making.

The platform features a user interface (Figure 2) designed to provide comprehensive insights into the conditions within a grain barge, without requiring users to have advanced technical expertise. A visual representation of key metrics, such as a temperature map (showing product temperature) and a moisture map (indicating water content), allows for intuitive monitoring. Furthermore, the platform provides a detailed breakdown of maximum, average, and minimum values of product condition, for each day of the forecast period. Users can also simulate the entire barge journey, day by day, including potential demurrage periods. This predictive simulation uses the same model described below for real time analysis, projecting future conditions based on current data and trends.

A time-domain CFD simulation is being executed for each day of the journey, utilizing OpenFoam® CFD simulation software (OpenFoam) to model airflow and heat transfer dynamics. Boundary conditions for the simulation are defined by river water temperature and ambient weather conditions sourced from a weather API service, while internal conditions are derived from the real-time sensor readings. This integration of external environmental data and internal sensor metrics allows for highly accurate predictions of quality and storage conditions throughout the voyage.

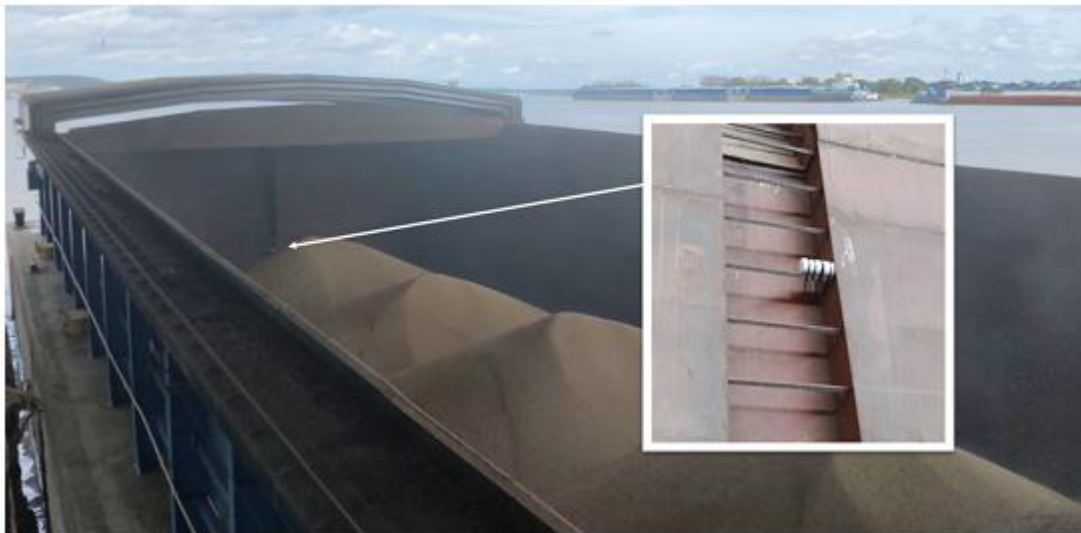


Figure 1: An example of a wireless sensor installation on a barge. The sensor is connected to a gateway to transmit information in real time to the cloud platform and feed the digital twin model.

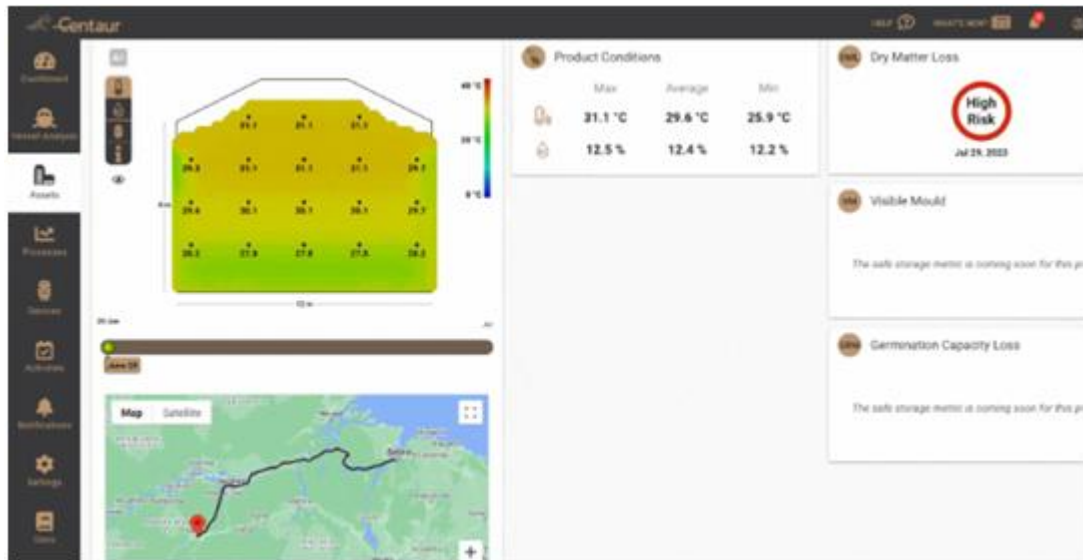


Figure 2: Barge logistics modeling UI

3 Results and Conclusions

Figure 3 shows the evolution of temperature and relative humidity as recorded by the two sensors installed on the barge. The monitoring period covers the entire duration of the barge's journey from Miritituba to Bacarena, along the Amazon river in Brazil. The temperature profile for both sensors shows relatively stable readings throughout the voyage, fluctuating between 28°C and 33°C. The data indicate that the temperatures of the top and bottom layers of the soybeans remained closely aligned, with minimal divergence. In particular, around 27 June 2023, there are fluctuations which correspond to the unloading process. The relative humidity readings from both sensors show consistent values between 65% and 75% throughout the voyage, indicating stable environmental conditions within the barge. Similar to the temperature data, a significant fluctuation is observed around 27 June 2023.

Regarding the number of sensors required for such applications, while increasing the number of sensors would undoubtedly improve the accuracy of the predictions by providing more granular data over the entire shipment, the validation of our model with experimental data has shown that for the volume of grain under consideration, two sensors provide a cost-effective yet reliable solution. These sensors are capable of measuring not only temperature and humidity, but also CO₂ and O₂ levels. Any abnormal conditions such as spoilage or localised hotspots occurring in areas remote from the sensor locations would likely be detected by changes in gas concentrations, as gases diffuse more efficiently throughout the grain mass than temperature or moisture content. Therefore, the combination of environmental and gas measurements ensures that even with only two sensors, the monitoring system remains robust and reliable for this specific application.

The integration of wireless sensors and CFD modeling provided a comprehensive understanding of the internal conditions of the soybeans in the barge (Figure 4). The CFD model identified specific zones within the barge where temperature and humidity levels were consistently higher. These conditions indicated a higher risk of dry matter losses, an important metric which is related to food loss during transportation and storage.

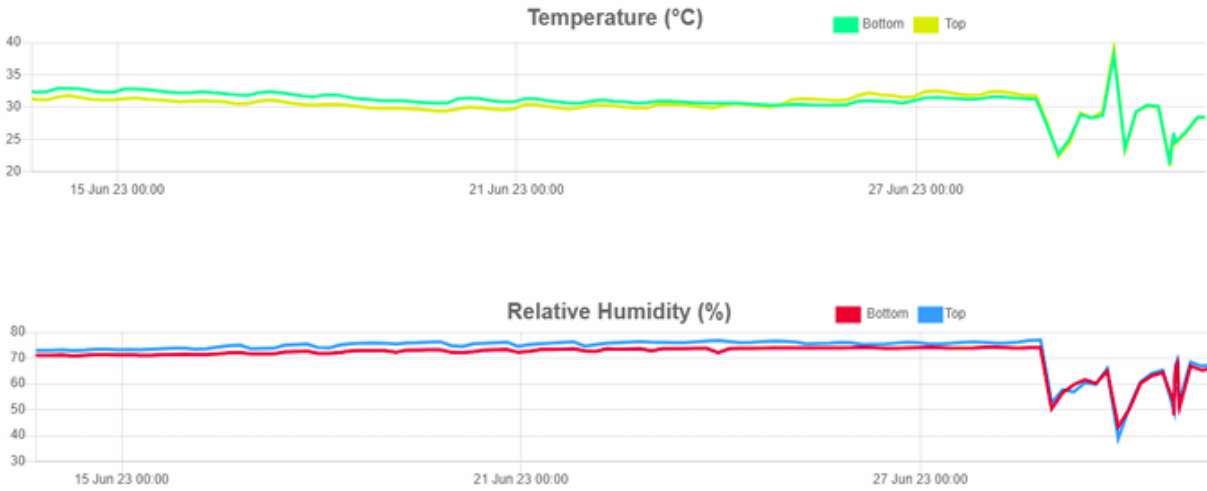


Figure 3: Temperature and relative humidity profiles of transported soybeans, recorded by two wireless sensors

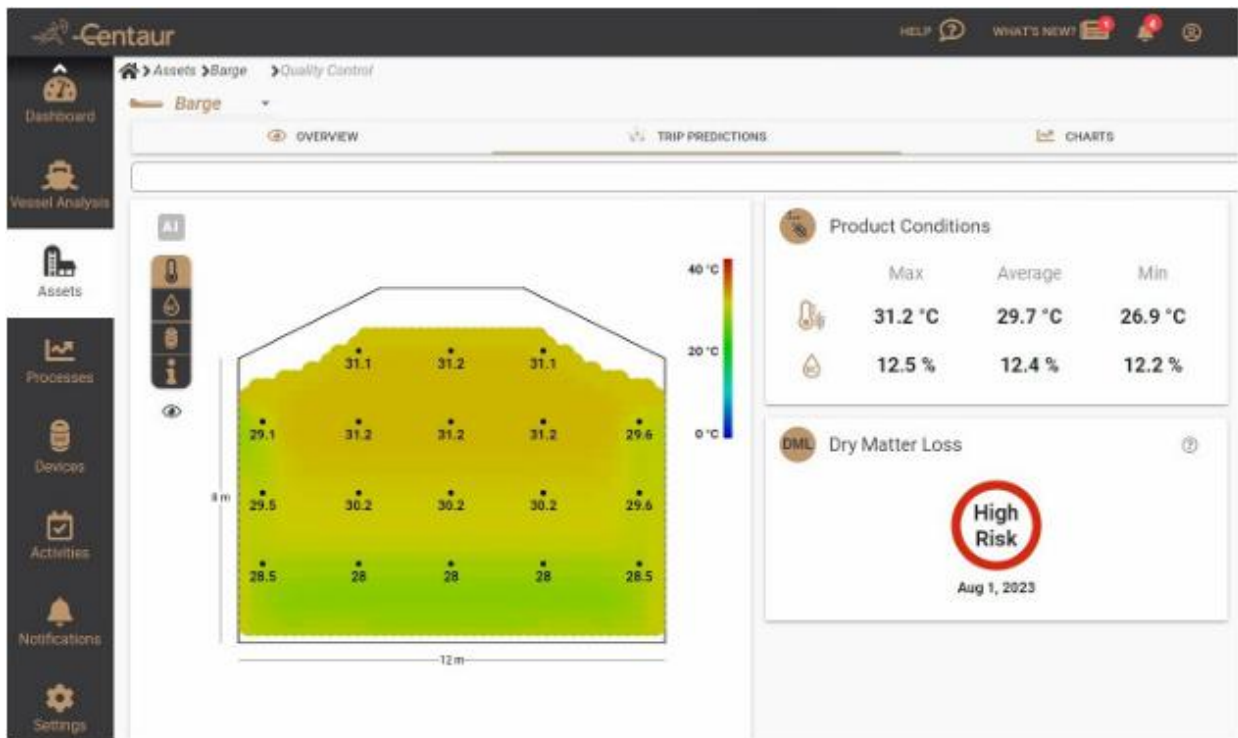


Figure 4: The web platform user interface showing soybean conditions at various points in the barge hold, including forecast values (left).

References

- [1] Bantas S., Sotiroudas V., Ham E.H. (2019) Wireless sensor devices for post-harvest crop quality and pest management (US Patent No. 10,296,863-B2). US Patent and Trademark Office.
- [2] Caixeta-Filho J.V and Péra T.G, Post-harvest losses during the transportation of grains from farms to aggregation points, International Journal of Logistics Economics and Globalisation 2018 7:3, 209-247.
- [3] Centaur (n.d.), Internet-of-Crops® product description. <https://centaur.ag>. Dyck G., Hawley E., Hildebrand K., Paliwal J., Digital Twins: A novel traceability concept for post-harvest handling, Smart Agricultural Technology, Volume 3, 0223, 100079, <https://doi.org/10.1016/j.atech.2022.100079>.
- [4] Kaloudis E., Bantas S., Leros A. (2023). Predictive post-harvest stored commodity management methods (US Patent No. 11,605,047). US Patent and Trademark Office.
- [5] Kaloudis E., Bantas S., Sotiroudas V., Ham R.E., (2024) Systems and methods for post-harvest crop quality management. US Patent 12,026,655.
- [6] Kollias G., Patsianotakis C., Sioutas A. and Bantas S., Digital twin approach for post-harvest crop protection, Emerging Technology Conference – Edge Intelligence (ETCEI) 2022.
- [7] Lawrence, J., & Maier, D. E. (2011). Three-dimensional airflow distribution in a maize silo with peaked, levelled and cored grain mass configurations. Biosystems engineering, 110(3), 321-329.
- [8] OpenFoam® (n.d.), available at <https://www.openfoam.com>.
- [9] Quemada-Villagómez, L.I., Molina-Herrera, F.I., Carrera-Rodríguez, M. et al. (2020) Numerical Study to Predict Temperature and Moisture Profiles in Unventilated Grain Silos at Prolonged Time Periods. Int J Thermophys **41**, 52