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A Sustainability-Driven Digital Twin for Optimizing Component Delivery in Piece-Type Manufacturing

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INTRODUCTION & AIM

Sustainable logistics has become one of the central pillars of modern manufacturing systems, as companies are increasingly required to reduce energy consumption, lower CO_2 emissions, and minimise resource inefficiencies throughout their supply chains. Inbound logistics, and especially the organisation of component delivery from suppliers to production facilities, significantly influences both environmental performance and operational efficiency. Transport activities contribute substantially to overall emissions in manufacturing systems, particularly through Tank-to-Wheel impacts, while delivery frequency, vehicle utilisation, and inventory policies directly affect warehouse capacity, handling operations, and associated costs. The growing complexity of production networks and fluctuating customer demand require advanced digital solutions capable of integrating heterogeneous data sources and supporting robust, data-driven decision-making.

Within the framework of Industry 4.0 and the broader green transition, digital twins are increasingly recognised as powerful enablers of transparency, simulation, and optimisation. A digital twin represents a dynamic virtual model of a real system, continuously synchronised with operational data and capable of simulating alternative scenarios without interfering with ongoing processes. The aim of this research is to develop and validate a digital twin framework for sustainable component delivery in inbound logistics. The proposed solution enhances organisational transparency, enables detailed "what-if" analyses, and supports the evaluation of trade-offs between economic performance and environmental responsibility. The study focuses on simulating various transport configurations, assessing the impact of vehicle capacity and delivery frequency on fuel consumption and emissions, and analysing the consequences for warehouse utilisation and storage costs.

METHOD

The digital twin was developed using a previously established five-stage methodological framework for modelling integrated production and logistics systems. The development process began with a comprehensive definition of the inbound logistics system, including transport routes, vehicle types, delivery schedules, production requirements, and warehouse capacities. Real production data, customer orders, and logistical parameters were integrated into a unified digital environment, ensuring that the model reflects actual operational conditions. The data are automatically refreshed after each completed production shift, allowing the digital twin to provide near real-time insights and maintain continuous synchronisation with physical operations.

A key feature of the model is the integration of algorithms that automate several critical processes. These include automatic recognition of the transport vehicle type, whether van, lorry, or lorry with trailer, automatic detection of production part types based on operational data, and automatic control and verification of delivered components against planned orders and production requirements. This automation reduces manual intervention, improves data consistency, and increases model reliability.

The virtual model dynamically represents material flows, vehicle utilisation rates, storage occupancy levels, and delivery frequencies. The simulation environment enables the analysis of different logistical configurations through structured "what-if" scenarios (Fig. 1). Fuel consumption and associated Tank-to-Wheel emissions are calculated using vehicle-specific parameters and transport distances, while warehouse utilisation is evaluated in terms of temporary storage requirements and potential external storage costs. Validation and verification were conducted using diverse test datasets designed to reflect realistic operational variations, including demand fluctuations and quantity changes, thereby assessing the accuracy and robustness of the digital twin.

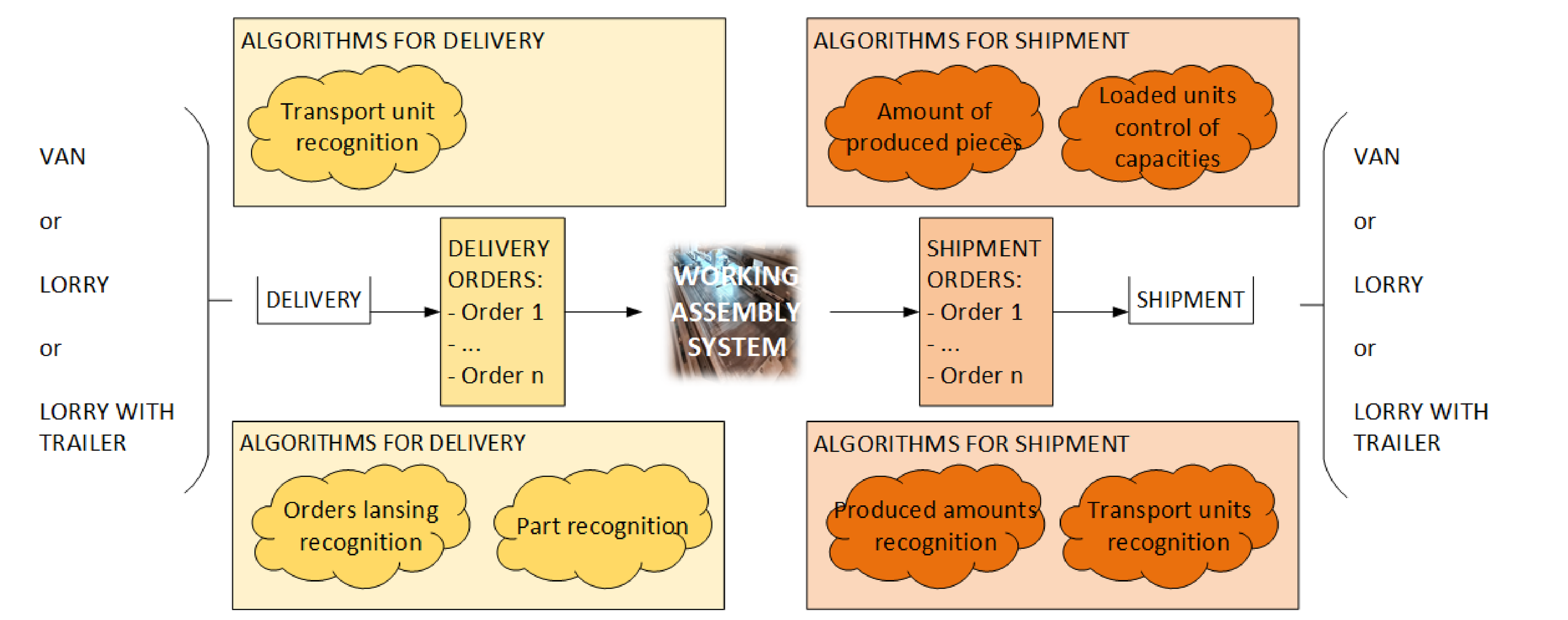

Fig 1. Logical schematic representation of a digital twin for component delivery in the production process and the final shipment of finished products.

RESULTS & DISCUSSION

The simulation results reveal significant trade-offs between transport efficiency and storage requirements. Scenarios involving larger transport vehicles, particularly lorries with trailers, achieved higher load factors and therefore required fewer trips to satisfy overall production demand within the given planning horizon. In the simulated cases, total fuel consumption was reduced by more than fifty percent compared to configurations relying on smaller vehicles, which led not only to improved energy efficiency but also to lower emissions and better utilization of available transport capacity.

As a direct consequence, Tank-to-Wheel CO_2 emissions were proportionally lower. These findings confirm that delivery consolidation and maximised vehicle capacity utilisation represent highly effective strategies for reducing transport-related environmental impacts.

However, the environmental advantages of larger vehicles were accompanied by increased batch sizes and less frequent deliveries, which led to higher temporary storage requirements at the production facility. In certain simulations, internal warehouse capacity constraints were reached or exceeded, creating a need for external storage solutions and increasing associated costs. This demonstrates that improvements in environmental performance may generate additional economic burdens in terms of inventory holding and space utilisation.

Conversely, the use of smaller vehicles such as vans allowed for more frequent and flexible deliveries aligned with just-in-time production principles. This configuration reduced on-site inventory levels and limited temporary storage needs. Nevertheless, the increased number of trips resulted in higher cumulative fuel consumption and greater energy intensity per delivered unit. Transport frequency rose substantially, which contributed to higher overall emissions despite lower inventory levels. The digital twin enabled a systematic comparison of these alternatives and helped identify intermediate solutions, such as medium-capacity lorries, that provide a balanced compromise between emission reduction and manageable storage requirements.

The validation process confirmed that the digital twin accurately reproduces operational patterns under varying demand conditions and quantity fluctuations. The integrated automatic recognition and control algorithms improved data integrity and reduced the likelihood of input errors. The ability to simulate alternative delivery strategies without disrupting actual operations proved particularly valuable for strategic planning and sustainability assessment. The results emphasise that transport decisions must be evaluated from a systemic perspective, as changes in vehicle configuration influence not only fuel consumption but also inventory dynamics, warehouse operations, and total logistical costs.

CONCLUSION

The presented research demonstrates that digital twins can serve as practical and effective tools for advancing sustainability in inbound logistics. By integrating real production data, automated recognition algorithms, and dynamic simulation capabilities, the proposed framework provides comprehensive decision support for balancing economic efficiency and environmental responsibility. The study confirms that the consolidation of deliveries using larger vehicles can significantly reduce fuel consumption and Tank-to-Wheel emissions, in some cases by more than fifty percent. At the same time, increased vehicle capacity utilisation may lead to higher temporary storage requirements and additional warehouse-related costs. Smaller vehicles offer greater operational flexibility and reduced inventory levels but result in higher energy intensity and transport frequency.

The findings highlight the importance of data-driven scenario analysis in achieving an optimal compromise between ecological and economic objectives. Digital twins therefore represent an important enabler of the green and digital transition in manufacturing, linking operational excellence with measurable environmental performance improvements.

FUTURE WORK

Future research will focus on extending the digital twin framework to include a broader environmental assessment perspective, such as broader emission analysis and life-cycle-based sustainability indicators. The integration of alternative fuel vehicles, including electric and hydrogen-powered transport, will allow the evaluation of additional decarbonisation strategies. Further development will incorporate multi-objective optimisation algorithms capable of automatically identifying optimal delivery configurations under varying constraints.

Another important direction involves deeper integration with supplier-side digital systems to achieve end-to-end supply chain synchronisation and enhanced transparency across organisational boundaries. The inclusion of predictive analytics and artificial intelligence methods for demand forecasting and adaptive logistics planning could further strengthen the model's decision-support capabilities. Additional validation in diverse industrial environments will enhance generalisability and confirm the robustness of the proposed approach. Through these extensions, digital twins can continue to support the alignment of manufacturing efficiency, economic competitiveness, and environmental sustainability.

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