Unified Modeling and Automated Scheduling for Manufacturing-as-a-Service: An Architecture for Dynamic, Trusted, and Sustainable Manufacturing Ecosystem

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Abstract

Manufacturing-as-a-Service (MaaS) seeks to expose distributed manufacturing capabilities as composable services, but its practical deployment remains constrained by fragmented data, heterogeneous resource descriptions, limited cross-company trust, and planning methods that do not jointly account for uncertainty, sustainability, and lifecycle traceability. This white paper presents UniMaaS, a reference architecture and validation blueprint for dynamic MaaS ecosystems. The architecture comprises three coordinated suites: a Data Management Suite for federated data spaces, semantic resource descriptions, trusted exchange, resource monitoring, and Digital Product Passports; a Modeling Suite for hybrid-system representations, intent interpretation, AI-based prediction, and Zero-X evaluation; and a Decision-Making Suite for resource selection, scheduling, digital-twin-assisted re-optimization, cloud-manufacturing orchestration, and circularity and sustainability optimization. The paper defines the roles of service providers and consumers, the interaction between distributed industrial data and platform-level metadata, and the closed-loop process from service intent and resource discovery to execution, monitoring, and reconfiguration. The architecture will be evaluated through four industrial scenarios covering aircraft maintenance, automotive-seat production, three-dimensional construction printing, and temperature-controlled logistics. UniMaaS therefore provides a common architectural framework for investigating interoperable, traceable, and adaptive manufacturing service chains across organizational boundaries.

Keywords: Manufacturing-as-a-Service, cloud manufacturing, manufacturing data spaces, digital product passport, digital twins, hybrid systems, dynamic scheduling, intent-based servitization, circular manufacturing, sustainable manufacturing, smart manufacturing, supply-chain orchestration.

1. Introduction

European manufacturing is being reshaped by shorter product cycles, volatile demand, constrained resources, and increasing expectations for sustainable, resilient, and human-centered production. These pressures are particularly significant for small and medium-sized enterprises (SMEs), which may require access to specialized equipment, production capacity, engineering expertise, or digital services without being able to justify the corresponding capital investment. At the same time, manufacturers are expected to improve resource efficiency, reduce waste and downtime, and respond more rapidly to changes in customer requirements and supply conditions. The European Industry 5.0 vision places these developments within a broader transition in which technological progress should support industrial resilience, environmental sustainability, and worker well-being rather than operational efficiency alone [Breque et al., 2021; European Commission and Directorate-General for Research and Innovation, 2023].

Manufacturing-as-a-Service (MaaS) provides one possible response to this setting. Building on service-oriented manufacturing and Cloud Manufacturing, MaaS treats manufacturing capabilities as services that can be described, discovered, requested, and combined through a digital platform. A capability may refer to a physical resource, such as a machine, production line, maintenance facility, warehouse, or transport asset, but it may also include software, data, process knowledge, human expertise, or decision-support functionality. Instead of relying only on fixed and vertically integrated production structures, a manufacturer can, in principle, compose a temporary service chain from capabilities offered by several providers. This model can improve access to specialized resources and make underused capacity available to a wider industrial network [Xu, 2012; Zhang et al., 2014; Moghaddam et al., 2015].

Realizing this model is more difficult than exposing a catalogue of available machines. A cross-company manufacturing service must satisfy process precedence, capacity, quality, delivery, workforce, safety, and regulatory constraints. Resource descriptions must be sufficiently precise to determine whether independently offered capabilities can be combined, while schedules must be revised when demand, availability, processing times, or logistics conditions change. Previous work has established important foundations for manufacturing-service management, resource matching, service composition, and Cloud Manufacturing scheduling [Liu et al., 2019]. Nevertheless, recent reviews show that MaaS research remains distributed across partially separate architectural, operational, business, and data-oriented strands [Karamanli et al., 2025]. As a result, the transition from an expressed production need to a trusted, executable, and dynamically adaptable cross-company service chain is still not adequately covered by a common architecture.

Data management is a central part of this problem. Manufacturing providers are unlikely to place all operational, commercial, and product data in a common repository merely to participate in a MaaS ecosystem. They require mechanisms for publishing selected capability metadata, controlling access to more sensitive information, applying agreed policies, and retaining authority over the data and services they provide. Contemporary data-space frameworks address this requirement through shared governance rules, interoperable catalogues, participant identities, trust mechanisms, and policy-controlled data transactions [Data Spaces Support Centre, 2026; Kalafatelis et al., 2025b]. Standardized asset descriptions, including those based on the Asset Administration Shell, can further support the exchange of structured information about industrial assets and their capabilities [Industrial Digital Twin Association, 2026]. These mechanisms provide useful foundations for MaaS, but they do not by themselves determine how a manufacturing request should be modelled, how a feasible service chain should be selected, or how operational decisions should be revised during execution.

Lifecycle information introduces a related requirement. Regulation (EU) 2024/1781 establishes the framework for ecodesign requirements for sustainable products and introduces the Digital Product Passport (DPP) as a mechanism for making prescribed product information accessible throughout the value chain [European Parliament and Council of the European Union, 2024]. Within a MaaS environment, lifecycle records may support material traceability, maintenance, reuse, re-manufacturing, and end-of-life decisions. However, a DPP is not equivalent to a production model, an operational monitoring system, or a manufacturing-resource registry. These information structures must remain distinguishable while being linked when a service chain creates, modifies, transports, maintains, or recovers a product.

A further challenge concerns the relationship between planning models and the physical manufacturing system. Digital twins can provide structured digital representations of observable manufacturing elements and support the exchange of information between physical assets, models, and decision-support functions. Their value in MaaS depends on how they are connected to resource monitoring, predictive models, scheduling decisions, and reconfiguration procedures. A digital twin that is isolated from the service-composition and decision-making workflow may assist local simulation, but it cannot support the coordinated adaptation of a cross-company manufacturing service chain.

Against this background, this white paper presents UniMaaS, a reference architecture for unified modeling and automated scheduling in Manufacturing-as-a-Service ecosystems. UniMaaS is intended to support the progression from a high-level manufacturing request to the discovery, composition, execution, monitoring, and adaptation of a distributed manufacturing service chain. The architecture is organized into three interacting suites. The *Data Management Suite* supports manufacturing data spaces, semantic resource descriptions, trusted data exchange, cloud-based resource monitoring, and lifecycle information management. The *Modelling Suite* provides dynamic formal models, intent interpretation, AI-based prediction, and the evaluation of measurable Zero-X properties. The *Decision-Making Suite* addresses resource selection, planning and scheduling, digital-twin-assisted evaluation, Cloud Manufacturing orchestration, and circularity and sustainability optimization.

The contribution of this white paper is fourfold: (i) it specifies an architecture that separates data management, system modelling, and operational decision-making while defining the principal information exchanged among them; (ii) it describes an end-to-end MaaS workflow connecting intent capture, semantic resource discovery, policy-aware data access, capability matching, service-chain composition, scheduling, execution, monitoring, and reconfiguration; (iii) it outlines an interoperability and trust approach that combines manufacturing data spaces, structured asset descriptions, access and usage policies, lifecycle records, and auditable cross-company exchanges without assuming that all operational data are transferred to a central repository; and (iv) it provides a common validation blueprint for four industrial scenarios covering aircraft maintenance, automotive-seat production, three-dimensional construction printing, and temperature-controlled logistics and warehouse management.

The remainder of the paper is organized as follows. Section 2 reviews the technological foundations of UniMaaS and identifies the integration gap addressed by the proposed architecture. Section 3 presents the three suites and their principal components and interactions. Section 4 introduces the four industrial pilots and the common validation framework. Finally, Section 5 concludes the paper.

2. Related Work and Positioning

This section reviews the main research areas that motivate the UniMaaS architecture. Rather than providing an exhaustive survey of each field, the discussion focuses on the technological foundations that are directly relevant to MaaS, namely formal modeling of manufacturing systems, intent-based servitization, trusted data exchange, circular and sustainable decision-making, and Cloud Manufacturing orchestration.

2.1. Unified Formal Modeling of Manufacturing Processes and Supply Chains

Optimization techniques have been a very active field in recent decades to model manufacturing processes and supply chains. Trying to solve material requirement planning (MRP) problems researchers achieved optimization of production systems by different mathematical programming approaches in a deterministic context. In relation to supply chain management, the advanced planning and scheduling (APS) has been developed to combine MRP with capacity constraints to achieve the creation of feasible production plans, with extensions based on robust programming models for production planning problems under uncertainty. In this regard, it should be noted that both digital optimization and simulation technologies are considered key in the cyber physical supply chain context Ivanov et al. [2019]. With the advent of MaaS, the mathematical behavior of the dynamical system consisting of the different part of a manufacturing process has massively gained in complexity: One has to depart from a paradigm where two postulates, namely 1) staticity; and 2) linearity are becoming the exception rather than the rule. As such, modern tools from Systems and Control that deal with complex dynamic nonlinear systems need to be imported. Aligned with this challenge, there have been some attempts on modeling of supply chains and production flows in manufacturing using Formal Methods from system theory, leading typically in discrete event systems such as Petri Nets and Finite State machines Campos et al. [2018]. Further to these efforts, the models have been enriched with refined dynamics, constraints, uncertainties.

Toward this, UniMaaS will form on-demand dynamical models describing the behavior of only the relevant agents/components, feeding knowledge and information from the Data Spaces of UniMaaS and the intent-based manufacturing module, using data-driven and control-theoretic methods. This is currently not possible as typically an expert team of engineers has to form manually such models, which are seldomly updated. We will employ hybrid systems, starting from linear hybrid automata Sanfelice [2021] that can incorporate phenomena present in supply chains (dynamicity, uncertainty of availability of resources and demand flows) and specifications, specifically circularity and sustainability entering as quantifiable time varying parameters. In stark contrast to the state-of-the-art, our models will be analytic and dynamic, evolving according to both continuous changes (e.g., time, demand flows, physical dynamics of components included in the chain) and discrete changes (e.g., change of providers, change of customer, logistical route, factory machine choice and configuration). This is currently not possible as typically models are static, or have only continuous dynamics, e.g., by assuming preselected interconnections between components. Furthermore, our modeling approach enables the analysis of important system properties, i.e., robustness and stability, and Zero-X properties such as zero defects and zero breakdowns

2.2. Intent-based servitization and AI-based prediction

The notion of intent has been recently introduced in the area of telecommunications, under the name of Intent Based Networking (IBN) Leivadeas and Falkner [2022]. The benefits and advantages of this approach quickly led to the adoption of intent in various domains. In terms of manufacturing, only a few elementary approaches have been proposed, targeting only networking resources, or cyber-physical attacks, neglecting any other part of the manufacturing pipeline. Regarding AI-based prediction it can be used to proactively predict the required manufacturing resources based on production performance prediction Wang et al. [2021], to forecast machines' activity states and their production capacities, or to automatically identify equipment malfunctions. In general, current trends of smart manufacturing tend to agree on the importance of introducing AI in the manufacturing process, which also should not only focus on a device level, but rather include the people, services, and data involved Sanchez et al. [2020]. Nonetheless, there is no concrete model or a complete architecture yet to address these requirements.

Toward this direction, UniMaaS aims to fully leverage the benefits of the intent concept, by proposing an intent mechanism that will provide a place for every actor of the MaaS ecosystem to interact with each other in a high-level and declarative language, vanishing any knowledge gap between the different involved parties (i.e., manufacturing providers, end-clients/SMEs, suppliers, etc.). Furthermore, through an automatic translation process based on large language models and state-of-the-art natural language processing (NLP) algorithms, the mechanism will provide the technical modeling of the entire process, reducing the time-consuming information exchange between the involved parties by automating the extraction and servitization of all the available assets and manufacturing processes. Moreover, AI techniques will be used to integrate the total set of information in the overall management, including the actors, devices, and data, while finding hidden correlation between all these assets. AI-based predictions will be used to predict service requests, asset availability, and to create a closed loop automation that will revert the manufacturing production in a compliance state whenever a production performance drift or fault is predicted or detected.

2.3. Secure, Interoperable, Trustworthy Data Spaces and Knowledge Graph for MaaS

The formal graph structure and semantic reasoning capabilities of KGs have been evaluated in the manufacturing sector as a semantic layer on top of heterogeneous data sources Meyers et al. [2024], or as a semantic layer on Data Spaces relying on the Web toolstack World Wide Web Consortium to leverage standards Li et al. [2023]. Nonetheless, the International Data Spaces (IDS) information model is limited to the generic goal of data exchange, having no specific notion of Manufacturing-as-a-Service concepts, where the need for relating product and production knowledge is acknowledged Hermann et al. [2020]. Gaia-X Gaia-X [2022] provides useful additions for MaaS like "Self-Descriptions" that can be used to describe services. Next to this, Asset Administration Shell (AAS) provides standardized means to provide access to an asset's data. The DPP will soon become the norm due to regulations, however requirements to build such a system and especially cross sectoral standards are still lacking. Recently, the use of data spaces for the implementation of DPPs was benchmarked CIRPASS [2024], indicating that no cross-sector interoperability standards exist. Trusted and secure data exchange are focused on novel specifications of Gaia-X Trust Framework and Trusted Data Spaces defined by DSBA Data Spaces Business Alliance [2023] to implement EU Industrial Data Space (EIDS) with decentralized Identity and Access Management based on Verifiable Credentials/Verifiable Presentations.

UniMaaS will create a standardized information model of MaaS services and products using AAS that provides the necessary high value information for flexible decision making, by building on existing standards. To this end, the project will implement a KG interface layer that makes data from data spaces available for the UniMaaS cross-organizational modelling and flexible decision support. Furthermore, UniMaaS will implement a cross-sector DPP system that provides the necessary interoperability mechanisms and information for tracking life-cycle data of products during the execution of a MaaS process, by closely monitoring of, and contributing to, the rapid advances in the research on defining DPPs in data spaces. UniMaaS will implement trusted and secure MaaS Data Spaces able to protect and governance access the cross-company data, MaaS services and to track individual products through DPPs.

2.4. Flexible Decision-Making, Circular and Sustainable MaaS

The concept of sustainable production, defined as the strategic, transparent integration and achievement of an organization's environmental, social and economic goals in the systematic coordination of key inter-organizational manufacturing processes for improving the long-term economic performance of the individual company and its supply chains, is evolving towards new economic and manufacturing models such as circular economy and industry 4.0. The evolution in the concept of sustainability is due, among others, to the fact that production systems are becoming increasingly complex and challenged to make operational decisions that meet the rapidly changing demands of customers and markets while maintaining a sustainable supply chain Zhang et al. [2022]; Kalafatelis et al. [2023b]. Then, an extensive set of indicators aligned to these new principles of sustainable production to accommodate these circular and smart strategies in manufacturing processes are provided Viles et al. [2024]. Additionally, the field of control systems offers a mathematical theory to describe and model interconnected systems Dolgui et al. [2019], with the goal of predicting and optimizing their behavior while meeting desired specifications.

UniMaaS will provide a new theory of optimal control of hybrid automata that capture specifically modern supply-chains, in a seamless, versatile, and agile way. Our theory will include techniques from Switched Systems control (as a specificity of MaaS is that systems are not static but switch from time to time as new requests are made, and reallocations must occur), Hybrid Automata (by leveraging recent modelling contributions), and more classical works in combinatorial optimization and Operations Research. Our techniques will be better fit to model and control modern manufacturing systems. In particular, data-driven automated control is a thriving topic, with many open avenues, in which UniMaaS will act as a pioneering work. Importantly, since the models introduced are dynamic, decision making will be continuous and adaptable in real-time to changes. UniMaaS will allow the quantification of objectives related to circularity, reusability, and sustainability.

2.5. Advanced Cloud Manufacturing Orchestration

The realization of MaaS is tightly connected to the convergence of manufacturing with cutting-edge digital technologies. CMfg Tao and Qi [2017] seamlessly integrates diverse and heterogeneous cross-company and cross-regional resources into manufacturing services and aims to transform the traditional rigid manufacturing activities towards a decentralized, flexible, and data-driven manufacturing approach. Moreover, in the transition to smart and autonomous manufacturing, a key-enabler is the convergence of both the physical and cyber world of manufacturing. To this extent, DTs provide a virtual emulation of physical systems, and allow advanced simulations and testing which are essential for optimizing the life-cycle of the manufacturing processes before the actual implementation. Furthermore, AI/ML algorithms enable predictive maintenance, flexibility in adaptation of the manufacturing processes, while ensuring the product quality and the adaptation to the dynamic manufacturing conditions. Fueled by the analysis of historical data, AI/ML algorithms are continuously evolving over time to ensure the resilience and efficiency and optimal reconfiguration of the manufacturing processes Leng et al. [2023]; Kalafatelis et al. [2023a, 2025c].

UniMaaS adopts the CMfg paradigm for the servitization of manufacturing resources. UniMaaS will use state-of-the-art orchestration mechanisms for all virtual resources and aims to provide an integrated and interoperable environment that is envisaged to undertake the role of efficiently coordinating the management of distributed manufacturing resources offered by the service providers and the workflow management of the UniMaaS decisions. DTs will be utilized for the simulation of the flexible decision making for providing feedback for optimal reconfiguration of manufacturing processes to meet both the clients' demands and the providers' high optimization goals. AI/ML-based technologies and algorithms based on real-time monitoring of the manufacturing resources and the data analysis of historical data will generate the necessary intelligence for fault detection towards Zero-X autonomous manufacturing.

UniMaaS vision is to deliver a platform for flexible, agile, and decentralized manufacturing, embracing the MaaS paradigm. UniMaaS will be built on five main technological pillars: (i) unified on-demand modelling of manufacturing resources and supply chains; (ii) intent-based servitization and AI-based estimators; (iii) Manufacturing Data Spaces facilitating the interoperable and trustworthy resource servitization; (iv) flexible decision making for reconfigurable, circular, and sustainable next-generation manufacturing execution systems (MES); and (v) cutting-edge digital technologies for Cloud Manufacturing (CMfg).

3. UniMaaS Reference Architecture

Figure 1 presents the UniMaaS reference architecture. The architecture is organized into three interacting suites: Data Management, Modelling, and Decision-Making. These suites are not independent software stacks. They participate in a closed-loop workflow in which service requirements are translated into structured constraints, candidate resources are discovered and evaluated, a service chain is scheduled and executed, and monitoring events trigger model updates or operational reconfiguration. The following subsections define the responsibilities, inputs, outputs, and principal interfaces of each suite.

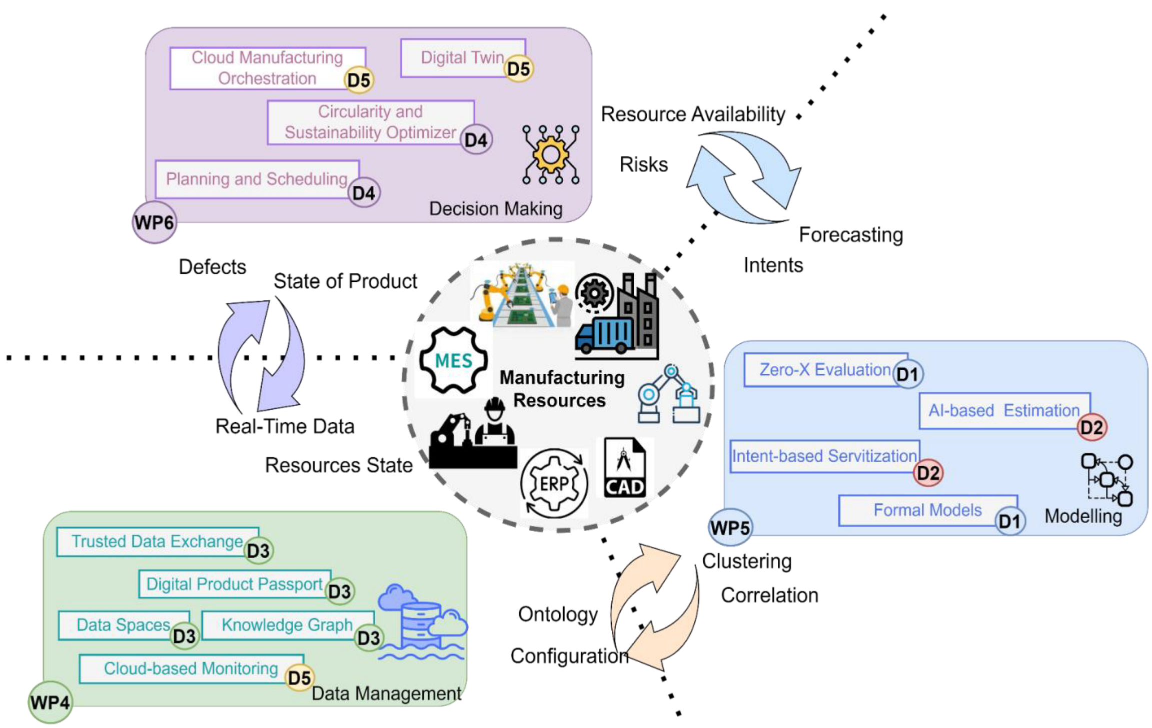

Figure 1: UniMaaS Conceptual Architecture

3.1. Data Management Suite

The **Data Management Suite** is responsible for building a data platform based on manufacturing Data Spaces for each manufacturing sector. This platform allows discovering and accessing the right data at the right time, from different data providers, in a trusted, secure way, so that data is available for the UniMaaS Modelling and Flexible Decision Making Suites, and so that data can be exchanged during the cross-company manufacturing process. The Data Management Suite is also complemented with Cloud-based Resource Monitoring for fast and real-time data exchange and the integration of DPP that ensures that products can be properly traced, the necessary information can be exploited throughout the manufacturing process, and to track life-cycle data of servitized manufacturing assets. Following, we provide information for the functionalities of each layer.

3.1.1. Data Spaces and Knowledge Graph Representation

The implementation of Data Spaces will be aligned with the specifications of Data Spaces Business Alliance (DSBA). In particular, UniMaaS will implement core building technologies (AAS, NGSI-LD, Smart Data Models, IDS Connectors) for solving DT data interoperability inside manufacturing data spaces. These technologies enable the crucial transport and semantic interoperability features defined in ISO/IEC 21823-1 and European Interoperability Framework (EIF) to achieve the creation of standard APIs for the cross-company interchange between data providers, consumers, and users in the manufacturing ecosystem. This data interoperability guarantees consistency across the entire manufacturing ecosystem independent of individual data type.

UniMaaS will create a software architecture and implementation of a data platform that firstly supports the discovery and mediation of services and resources (data and software) defined by AAS. Secondly, the platform supports real-time, cross-company transfer of data from UniMaaS users or “participants” (service providers and service consumers) to the UniMaaS Modeling/Decision Making Suites. Thirdly, the architecture will implement a digital thread to support the necessary trusted, secure data exchange between service consumers and service providers during a product (or batch) manufacturing process. The architecture will be based on data spaces for distributed, multi-company data storage and cross-company data exchange, where the UniMaaS platform will act as intermediary implementing a data broker. This broker will store and manage information about participants and their data in the form of KG, based on existing standards and ontologies. This KG provides a semantic layer for interoperability that relates data from multiple participants: product data (static e.g., CAD, BOM, and dynamic e.g., quality control results) as well as manufacturing service/resource data (both static e.g., service description, and dynamic e.g., availability data). This way, the KG allows populating the UniMaaS models with the right data.

3.1.2. Cloud-based Resource Monitoring

This layer is responsible for supporting the monitoring of manufacturing resources and supply chains and providing an interface between the manufacturing resources and UniMaaS platform. A cloud-based monitoring engine (e.g., Prometheus, Apache Kafka, Influx DB) will be realized to support the collection of historical or streaming data provided by the manufacturing resources. Seamless and secure connectivity will be implemented with IoT devices, robots, manufacturing equipment, with the respective IoT protocols (e.g., HTTP, CoAP, MQTT) to collect sensitive and real-time data for the state of resources and products. Energy-efficient data collection algorithms ensuring self-organizing and multi-technology wireless sensor networks will provide UniMaaS with IoT solutions for supply chain monitoring with various energy efficient technologies (Wi-Fi, LoRa, Bluetooth etc.) to enable the monitoring of key resources (e.g., inventory levels, transportation assets, environmental conditions, etc.). Accordingly, all necessary information will be propagated to the DPP. Device and process metadata e.g., location, status, events will be coordinated under the cloud-based resource monitoring system to provide alerts and notifications over critical KPIs and assist in the decision making of UniMaaS. This layer also supports the establishment of fast data exchange between the ERPs of manufacturing providers to manage the heterogeneous information and connection to the manufacturing Data Spaces. The monitoring engine will process the real-time data and propagate them to the Modeling and Decision

Making suites.

3.1.3. Trusted Data Exchange

UniMaaS will implement trusted management of cross-company data exchange in the manufacturing value chain. To develop trusted data exchange, it is essential to define data governance policies, classify data based on sensitivity and importance, implement access control and authentication, use secure communication protocols to comply with data protection standards and regulations. These cybersecurity mechanisms ensure data integrity, confidentiality, and availability across the manufacturing value chain. In UniMaaS, the implementation of trusted data exchange will be aligned with new protocols and standards proposed by ENISA Alamillo et al. [2023], including the Distributed Identifiers (DID), Secure DIDComm channel, OpenID Connect for Verifiable Credential Issuance, Self-Issued OpenID Provider v2 (SIOPv2), and other protocols for the issuance of verifiable credentials. Moreover, a decentralized ABAC (Attribute Based Access Control) based on Verifiable Credentials will be implemented to provide authorization mechanisms such as PEP, PDP, PAP/PMP, and PIP. Gaia-X cross-dataspace governance based on European values will be integrated. Implementing these protocols and standards, UniMaaS will ensure a decentralized Identity and Access Management (IAM), federated data governance, distributed control access and secure communications in order to protect and ensure trusted manufacturing data exchanges among cross-company participants and data sources (e.g., PLM/ERP/MES/SCADA system, etc.) using IDS Dataspace connectors.

3.1.4. Digital Product Passport

DPP will be developed for the manufacturing sector to enable EU circular economy and UniMaaS will create a comprehensive digital record to accompany a product throughout its lifecycle. The DPP will include key information such as materials used, manufacturing processes, energy consumption, and end-of-life considerations. The DPP data will be collected and stored using Blockchain (i.e. Hyperledger Fabric) and Trusted Data Exchange technologies to ensure transparency and traceability. Toward real-time DPP update, UniMaaS will use the data collected by sensors and IoT devices to monitor the product's usage and performance in the manufacturing facilities. The UniMaaS DPP implementation will be compliant with EU DPP directives (i.e. ESPR, Ecodesign for Sustainable Products Regulation) European Parliament and Council of the European Union [2009] to ensure that manufacturing products and their components can be properly traced and the necessary information can be found throughout the manufacturing process, and to track life-cycle data of servitized manufacturing in order to advance in the manufacturing circular economy. The DPP development will enable the recycling and remanufacturing processes and allow consumers to select resources based on a product's environmental impact to contribute to a sustainable and transparent manufacturing sector.

3.2. Modeling Suite

The **Modeling Suite** is the backbone of the formal approach of UniMaaS towards modeling of the whole supply and value chain within manufacturing. It is responsible for the (i) on-the-fly creation and adaptation of dynamic models,

3.2.1. Formal Models

Adoption of hybrid system models that evolve in the space of continuous flows as well as discrete events, will allow combining classical Operations Research based manufacturing techniques with modern dynamical systems models, including Timed and Hybrid automata. Accurate MaaS models require variable mathematical structures capturing the switching behavior triggered, for example, from choices on assets, time varying orders and demand, logistic routes, reconfiguration by software (e.g., CAD models) or hardware (e.g. machines in a factory). We expect that switched systems models will be key to tackling this modeling and analysis challenge. The various production, resource and environment agents will constitute a large, decentralized, multi-agent system, with stochastic or non-deterministic inputs (the demands), non-standard constraints (circularity, reusability, waste management) and dynamics. Moreover, adoption of formal methods in modeling will allow subsequent incorporation in the optimization problem of non-standard constraints, or even of common language statements via the use of AI-based intent interpretation component of the UniMaaS platform.

3.2.2. Intent-based Servitization

The intent-based servitization component of UniMaaS will create a mechanism that will act as a mediator between all involved parties of the envisioned MaaS ecosystem. It will allow any person or entity involved to express their intents in a natural language form leveraging a chatbot style interface. After a client issues a high-level description of the requested manufacturing service, an automated translation process will take place, which will map the service into a series of manufacturing assets that will be required to compose the final service. To do so, the intent mechanism will leverage an asset servitization approach that will be largely based on the formal models and KG representation components presented above. In other words, an asset servitization model is realized upon which the intent will be mapped, identifying all necessary assets and their interconnection to provide the requested service. This mapping of the intent to the asset servitization model will be performed through an NLP mechanism and specifically a name entity recognition approach that will classify qualitative service description keywords to quantitative manufacturing processes.

3.2.3. AI-based Prediction

A core component of UniMaaS will be the AI-based prediction that will allow the identification of a four-pronged set of prediction estimators to create a closed loop automation paradigm. The first set will target the self-configuration of the service by identifying hidden correlation between manufacturing assets for various service requests and by revealing both time and space affinity relationships between assets. Various ML techniques, such as linear regression and decision trees, along with statistical models will be investigated and deployed. The second set of estimators will allow the UniMaaS platform to exhibit self-optimization and self-scaling properties by dynamically predicting service demands and asset availability that can assist the overall planning, resource allocation and scheduling of the manufacturing resources. State of the art deep learning models and current trends of transformers will be used during this phase. The third set of estimators will target to create a self-protection environment by performing fault detection on all available assets (i.e., processes, devices, communication, data, etc.). The fault detection techniques will be largely based on anomaly detection techniques, both supervised and unsupervised, that will reveal current problems, while also predicting imminent failures. Lastly, the fourth set of estimators will aim to assure the performance through self-healing techniques. Specifically, through fault diagnosis techniques a root cause analysis will be performed while proposing corrective actions on how to remedy the situation towards Zero-Defect Manufacturing (ZDM). All these estimators will help to guarantee a high-quality assurance while allowing UniMaaS to exhibit the ever-wanted self-governing properties.

3.2.4. Zero-X Evaluation

Each type of specification under the 'Zero-X' umbrella will be the subject of formal analysis, quantifying the extent in which the specification is satisfied. We will work in two directions: (a) to create new system variables in the dynamics capturing sustainability, reusability, robustness, fragility, resilience, and subsequently identify their dynamic behavior, (b) to translate 'Zero-X' specifications to mathematical arguments, using algebraic functions, as well as first order and temporal logic statements. These costs are anticipated to be of a hybrid type, mixing logical formulae with quantitative algebraic expressions of the different variables. The formal models developed above will constitute a key asset to evaluate these specifications in a seamless way, by utilizing reachabiltiy and set-based methods for hybrid systems, as well as randomization and data-driven techniques. Since the former methods provide deterministic guarantees, however they require considerable computation resources, while the latter methods provide probabilistic guarantees with a tunable complexity, we will apply both interchangeably depending on the setting. Effectively, Zero-X evaluation will allow monitoring of the supply chain and quantifying critical properties for EU manufacturing, to be used as a decision criterion for supply chain reconfiguration, maintenance, risk management etc.

3.3. Decision-Making Suite

The **Decision Making Suite** is responsible for providing (i) the planning and scheduling of UniMaaS, (ii) the integration of the UniMaaS DTs to provide simulations and re-optimization capabilities of both the decision making and the modelling approaches, (iii) the realization of CMfg orchestration mechanisms to assist in the servitization of manufacturing resources and (iv) the provision of sustainable and optimized life-cycles for the products, manufacturing processes and supply chains. Following each mechanism is analyzed.

3.3.1. Planning and Scheduling

We will develop the theoretical framework that allows real-time decision making and planning and scheduling problems in supply chain optimization. Our suite starts from the classical techniques from Operations Research that had a tremendous impact for supply chains optimization in the last decades. We will enhance these mechanisms by incorporating the hybrid models from the modelling suite and address the emerging challenges of optimizing strategies over versatile environments with demand-based incoming flows, multi-constrained, interconnected processes, varying availability of assets with humans in the loop, sustainability specifications, and potentially malicious agents. We will thus evolve upgrade the manufacturing resource optimization suites from static, or even linear deterministic actions to complex, hybrid, decentralized actions, evaluating performance and behavior of the closed loop supply chain with formal methods, eventually enabling provably correct certificates of correct behavior (such as sustainability, resilience to unanticipated exogenous phenomena, minimal waste generation). Our arsenal of algorithms will be implemented accurately in software and will be interconnected with the Modeling Suite specified above, closing the loop of real-time optimization.

3.3.2. Digital Twin

During UniMaaS, a DT will be realized for each pilot to evaluate the performance of the Modelling and Decision Making suites. To achieve this, the DTs will be fueled with information by the Cloud-based Resource Monitoring and the Data Spaces and the IoT devices embedded within the supply chain. As a result, the goal of this component is twofold. First, the DT will simulate the decision making to provide feedback to the Planning and Scheduling component based also to the AI-based predictions. This will allow us to simulate the behavior of manufacturing processes and supply chains under (i) dynamic service demands and asset availability and (ii) provide fault-detection discovery and quality control to the manufacturing service chain and (iii) evaluate different reconfiguration options. This will allow the timely and predictive reconfiguration of the decisions of the UniMaaS framework towards autonomous manufacturing and customization of products. The second objective is to provide feedback to the Modelling Suite. Driven by the results of the Circularity and Sustainability Optimizer component and taking also into account the requirements of the supply chains and the manufacturing processes, the

DTs will act as a reoptimization feedback mechanism to the models to achieve high-level optimization goals such as: optimal resource utilization, power efficiency, and waste reduction. To this extent, based on historical data the DTs will be able also to simulate, benchmark and assess variants of the models in order to decrease risks, achieve cost reduction and ZDM for the service providers.

3.3.3. CMfg Orchestration

UniMaaS will follow the service delivery paradigm and provide scalable and on-demand computing resources. Edge/Cloud computing orchestration platforms (e.g., Kubernetes) to serve as the CMfg platform and to facilitate the hosting and orchestration of all virtualized resources needed for the manufacturing processes. To this end, the CMfg orchestrator will be integrated with existing solutions (e.g., Apache Camel Apache Software Foundation, MuleSoft MuleSoft and other open-source solutions), to provide interoperability (following the work of Trusted Data Exchange component) and communicate with the ERPs and MES of every manufacturing domain, interconnect the necessary APIs and propagate the decision making of UniMaaS. Dynamic orchestration mechanisms (autoscaling, load balancing and service placement) will be also implemented following a microservices architecture to provide scalable solutions and guarantee the required QoS for the virtualized resources (e.g., scale optimization algorithms of ERPs running in the Cloud). It should be noted that various tools for workflow management will also be utilized (e.g., Argo CD Argo Project) to coordinate the correct sequence of execution alongside the communication of processes during the lifecycle of MaaS service chains.

3.3.4. Circularity and Sustainability Optimizer

UniMaaS will provide business-oriented mechanisms that allow companies to draw their strategic, tactical and operational plans. The optimization of the company's internal and external logistics is guaranteed through the models, algorithms and optimizing processes of the manufacturing and logistics assets of the supply network and tools to support the collaborative processes of the supply network. The Circularity and Sustainability Optimizer will develop and standardize mathematical formulations (objective functions, constraints) and heuristic rules to model the main principles of circularity, which are primarily based on optimizing the use of available resources, materials and products while maintaining their value in the economy as a whole for as long as possible and minimizing waste generation. These standardized sustainable models, based on product and process lifecycle requirements, will identify high-level optimization goals for the upstream supply chain and will be incorporated into the manufacturing services where required. Thus, UniMaaS will contribute to fulfilling circular economy principles through waste minimization (overproduction, manufacturing times and costs, preparation and transport, inventory levels, etc.), advancing towards sustainability and its extension to all manufacturing processes provided as services. In addition, the connection with the company's systems and their interoperability will feedback models and algorithms with reliable and updated information. This aspect, together with efficient computing times, will provide companies with the necessary flexibility to adapt to the changing environment by making them more resilient and sustainable.

3.4. UniMaaS Platform Realization

UniMaaS envisages to deliver an open-source platform which acts as an intermediary broker for the realization of MaaS. All functionalities of the three suites of UniMaaS will be integrated in this platform. In detail, Manufacturing Service Providers (including SMEs, Industries and OEMs) will be able to provide, through the dashboard of the platform, a description of the manufacturing resources, data, and parts of supply chains, that will be used by all UniMaaS suites. The UniMaaS platform will store the static information in the Resource Registry, which is also used by the dashboard to provide visualization and search capabilities for the available resources. The Resource Registry is going to classify the offered resources into specific industrial domains. The entire information of the descriptors in terms of data spaces, existing production models and decision-support systems, is forwarded to the respective UniMaaS suite. Manufacturing Service Consumers submit their orders along with high level intents expressing their QoS requirements and configurations for the customized products or the use of decentralized cross-company servitized manufacturing assets and equipment. As a result, for each order a service chain request of any type manufacturing resources is formulated. Upon receiving a request by a Service Consumer, the platform triggers the Resource Selector component that is responsible for a two-stage resource selection process. Initially, based on the existing manufacturing resources in the Service Registry, a set of candidate resources is selected based on the order requirements. Then, during the second stage, the UniMaaS Agent is responsible for collecting all information for the candidate resources from all the UniMaaS suites. This information is forwarded to the Resource Selector to reserve the resources and formulate the manufacturing service chain, based on multi-criteria decision-making approaches. After the selection of resources, the UniMaaS Agent forwards the formulated service chain to the suites for the actual implementation. Then, the three UniMaaS suites are responsible for the actual implementation and realization of the requested service chain. During the life-cycle of the manufacturing service chain, real-time monitoring and visualization of the whole process will be provided through the dashboard of the platform. Finally, upon completion the manufacturing resources will be released and will be available for other requests.

4. Validation Blueprint: Early Adopter Pilots

The UniMaaS architecture will be evaluated through four early-adopter pilots covering aircraft maintenance, automotive-seat production, three-dimensional construction printing, and temperature-controlled logistics and warehouse management. The pilots were selected because they differ substantially in their production structures, resource constraints, planning horizons, data environments, and sustainability requirements. Together, they provide a basis for examining whether the proposed architecture can support Manufacturing-as-a-Service beyond a single industrial domain.

4.1. Pilot 1: Aircraft Maintenance as a Service

Operational Setting: Aircraft maintenance plays a pivotal role in ensuring the operational integrity of aviation fleets, involving tasks such as repair, modification, overhaul, and inspection. Sets of aircraft maintenance tasks are typically categorized into A-, B-, C-, and D-checks. A- and B-checks are considered light maintenance, while C- and D-checks are categorized as heavy maintenance. The former vary in duration, frequency, and associated tasks. A project is defined as a set of A-, B-, C- and D- maintenance tasks as well as standalone tasks. Projects are scheduled months in advance, with a planning horizon extending to 1-2 years. The efficiency of project schedules is crucial for airline companies as they rely on them to allocate resources effectively, including maintenance tools, workforce, and aircraft spare parts Shaukat et al. [2020]; Kalafatelis et al. [2025a].

Business Value: The aviation industry faces challenges in designing precise long-term project schedules due to the unpredictability of unscheduled tasks. Variability in workload extends maintenance projects, impacting subsequent schedules and leading to frequent adjustments. Moreover, the deadline for maintenance projects is contingent on aircraft utilization, and deviations from expected daily Flight Hours and Flight Cycles can accumulate, significantly affecting aircraft utilization and subsequent maintenance due dates. These uncertainties result in frequent revisions of schedule, leading to a backlog and increased maintenance costs. It is thus essential to tackle these stochastic issues to create maintenance schedules that are more resilient and dependable.

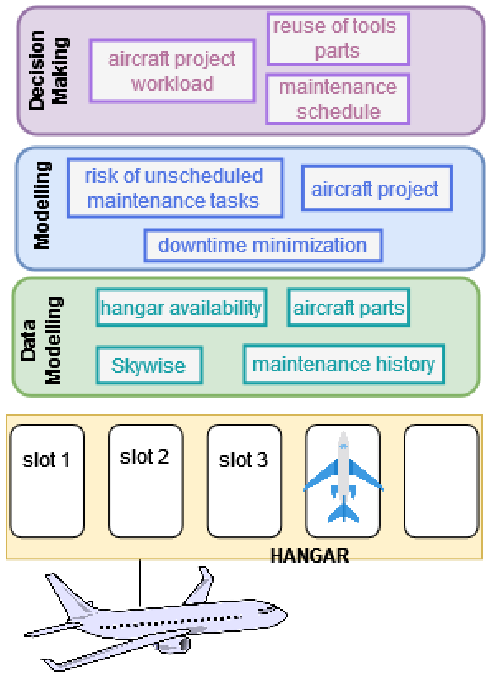

Figure 2: Aircraft-maintenance planning and resource coordination in the UniMaaS pilot. The scenario considers the allocation of maintenance tasks, hangar capacity, qualified personnel, tools, and eligible components under uncertain task durations and unscheduled maintenance findings.

UniMaaS added Value: UniMaaS suites and platform will allow to exchange data between different aircraft companies (e.g., with the use of Skywise) and optimally schedule the maintenance of aircrafts in Aegean's hangar. The DPP in this pilot will track the aircraft parts lifecycle. The modelling will incorporate the strategical scheduling of maintenance projects close to their due dates and considering space affinity relationships between different aircraft components. By understanding how the performance of one component may influence or be influenced by others and based on the customer intents, the model can assess the likelihood and cost of unscheduled maintenance tasks arising due to interconnected issues. Thus, the UniMaaS planning and scheduling component will leverage the insights gained from the former to enhance the efficiency of resource allocation (including cost-effective part exchanges between aircrafts), and workload promoting agility and responsiveness in the face of dynamic operational challenges. By leveraging machine learning techniques and statistical models, the AI-based prediction component of UniMaaS will analyze aircraft historical data, current operating conditions, and various factors influencing aircraft health to make predictions about potential maintenance needs. It will also examine patterns and relationships within the data to uncover potential indicators of wear, stress, or degradation in specific parts. By continuously learning from new data and adapting to changing conditions, the dedicated DT will provide a dynamic and proactive approach to estimate the probability of unscheduled maintenance tasks and promote the extended use of tools/equipment in the context of circularity and sustainability.

4.2. Pilot 2: Automotive seat manufacturing as a Service

Operational Setting: Automotive seat manufacturing includes a set of distributed production lines (leather, foam, and frame), while the final seat assembly is done in a different location. These manufacturing subsystems consist of a wide variety of enterprise applications (ERPs), mainly based on material requirement planning (MRP) and just-intime (JIT) production systems, originating from a multi-vendor environment. In such a complex supply chain environment, the real planning problems are dynamic with underlying uncertainties. Currently, supply chain applications development, customization and maintenance are very expensive and are not fully integrated in practice with the level of detail and collaboration that companies need.

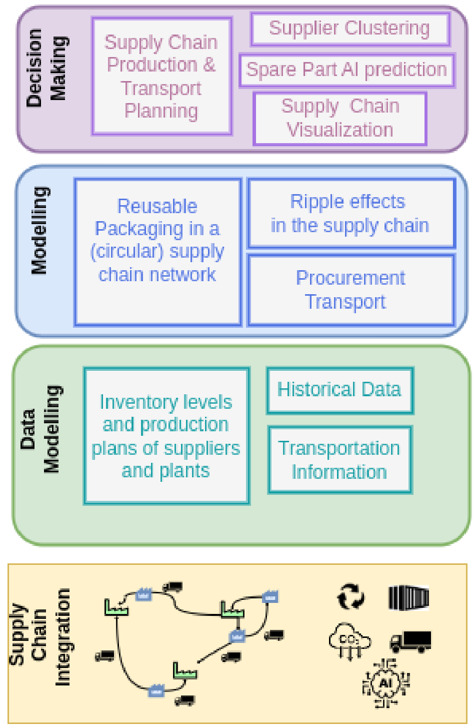

Figure 3: Distributed automotive-seat production and logistics considered in the UniMaaS pilot. The scenario coordinates production resources, component availability, transport operations, and reusable-container circulation across interconnected manufacturing sites.

Business Value: The lack of monitoring and visualization of the automotive seat supply chain problems can lead to an absence of agreement among the stakeholders. Thus, all system parameters should be modeled optimized, simulated, and visualized when defining supply chain production planning systems. In this sense, production planning in automotive first-tier suppliers has remained at an average lean manufacturing level, and in conditions of uncertainty and disruptions it is not effective, providing a gap between lead times of days and months. Thus, modeling is very important to plan real problems in an entire supply chain, which currently, is executed rather than planned. Monolithic approaches for solving all the supply chain decisions have been proven to be unrealistic and computationally expensive.

UniMaaS added Value: The UniMaaS open platform, which will be easily configurable and interoperable with enterprise applications, will facilitate the material requirement planning, and transport and container planning based on intents that focus on e.g., procurement transportation. The UniMaaS platform aims to be pluggable with enterprise systems to provide real-time monitoring, performance optimization and visualization. UniMaaS will realize the secure and reliable communication between supply chain nodes (e.g., demand, supplies and inventories) allowing also the real-time monitoring of the transportation. The DPP will track information regarding the seating parts and the reusable containers. The modelling will focus on the reusable packaging and circularity of containers in the supply chain (production and transport) towards minimizing the ripple effects. Based on historical data of the car models, the AI-based predictors will estimate the availability and the delivery time of spare parts and determine which parts can be manufactured in a sustainable way i.e., to make them easy to assemble and disassemble; and repair the product to give it a longer service life. The DT will simulate possibilities for (i) supplier clustering based on sustainability (optimization of trucks), (ii) circularity (return of containers) of the transportation process (iii) market research for sourcing products based on systematic search for commodities in or around the EU considering sustainability, social and economic aspects (e.g., generate more wealth and reduce carbon footprint).

4.3. Pilot 3: 3D Construction Printing as a Service

Operational Setting: 3D construction printing can greatly benefit from MaaS business model. As a digital manufacturing technology, it enables the production of parts from a file, and its workflow is data-driven. It also allows for greater flexibility and economy in on-demand manufacturing of small batches and single components. Thanks to the combination of 3D scanning, design and 3D printing, it is also possible to produce components withdrawn from circulation, which is particularly important in maintenance operation. Using 3D printing, manufacturers can get parts to customers and local markets faster, speeding up the delivery process.

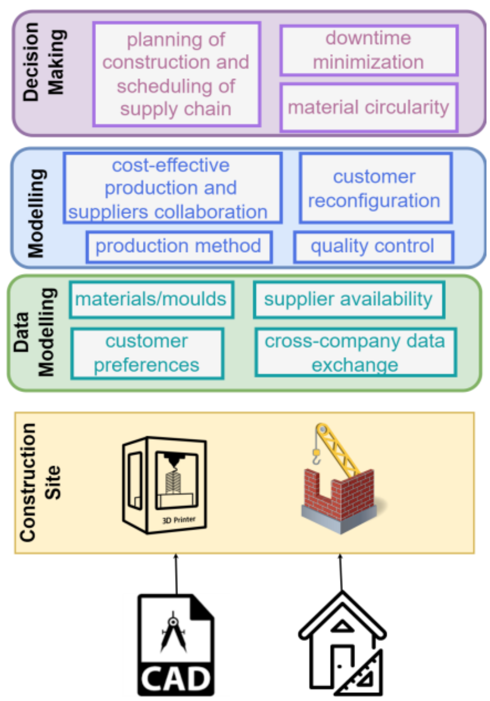

Figure 4: Three-dimensional construction-printing service considered in UniMaaS. Customer requirements are translated into a structured production request and evaluated against available materials, equipment capabilities, process constraints, provider workloads, and delivery requirements.

Business Value: Construction is a particularly conservative branch where customers are accustomed to traditional forms of manufacturing. Additionally, innovative technologies are not covered by existing legal norms and standards. In its European Industrial Strategy, the European Commission has set out to address these issues by mapping dependencies/vulnerabilities and investing in technologies enabling flexibility and agility, as well as promoting new business models that can support on-site production.

They involve shared infrastructure, in which equipment and other manufacturing capabilities are networked to enable more efficient manufacturing.

UniMaaS added Value: The UniMaaS platform will allow users to aggregate potential inquiries, and most importantly, it will show the recipient the best possible production method. The platform will indicate the alternative possibility of 3DCP (Concrete/Construction Printing), e.g. for objects where other methods force limitations on the ideas of designers and architects. The intent then will be utilized to map the customer's requirements to specific materials or manufacturing processes. The modelling will enable costeffective production and enable communication and collaboration among suppliers and manufacturing facilities located in different geographical regions. Data tracking and analysis can be conducted throughout the product's lifecycle. UniMaaS platform will allow a customer to submit an online order for a customized goods production, and then the decision making for the construction supply chain will be based on workload, material inventory, labor availability, location, and scale, to dynamically route the order to a given service provider to fulfil the request most efficiently. The DT will allow data-driven recommendations for recycling/reusability/refurbishment of components (Component Quality Control). The intent translation mechanism and the AI-based predictors will ensure the rapid production and reconfiguration and supply of customized products according to customer preferences, optimizing the weight and shape of products for better efficiency.

4.4. Pilot 4: Logistics and Warehouse Management as a Service

Operational Setting: Catone Group specializes in supply chain management, with a main focus on the management of the distribution chain of all goods at controlled temperatures (e.g. food products). In particular, Catone owns a fleet of over 200 refrigerated vehicles, all equipped with thermos-recorders and satellite-based security control in order to ensure reliability and the highest quality compliance with the HACCP (Hazard Analysis Critical Control Point) framework (SQS ISO 9001/2008 certified) all over the products chain. The acquired ability to fully respond to the customer's needs, has allowed Catone to be a leader in the frozen logistics sector.

Business Value: To improve its commercial offering, Catone is going to build a Hub Frozen for automatically manage around 35.000 pallets, to be stored, moved and delivered according to new and more efficient processes (in terms of time and cost, from order to storage and delivery), ensuring a reduced energy consumption (environment sustainability), and more accurate control of the overall logistics process (e.g. in terms of temperature control and waste). There are three main objectives to be considered when managing such a distributed management of pallets for specific frozen/ambient products: (i) ensure efficient planning at each level of the whole automated process, through an accurate management of the overall warehouse ecosystem; (ii) ensure quality of stored and delivered products, through an appropriate intra-warehouse pallet movement and a reliable refrigerated vehicle-based transportation; (iii) ensure quality of working conditions for workforce (e.g. dignity, satisfaction, motivation, safety) in such a highly-automated process, through appropriate KVIs.

UniMaaS added Value: The modelling of the warehouse ecosystem will allow the development of an innovative autonomous logistics and warehouse management to orchestrate and efficiently manage stacker cranes within the warehouse, and monitor fundamental indicators in real-time, towards high quality and storage minimization. The AI-predictors will be used to estimate critical KPIs (e.g., storage & delivery time) and assist for the re-planning of storage and delivery in case of deviations (e.g., exceeding capacity of warehouse storage, fault in refrigerated vehicles). The DTs will provide recommendations based on data for energy saving, material for pallets, costs and improving quality of workforce life and innovation. Human-in-the-loop will be a key factor during operations and storage of the pallets,

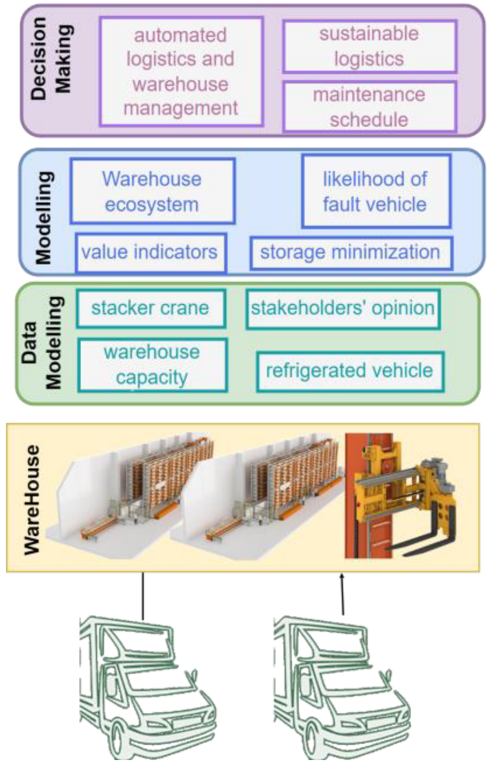

Figure 5: Smart logistics and warehouse-management pilot. UniMaaS coordinates pallet storage, internal movements, handling resources, loading operations, refrigerated transport, and responses to operational deviations.

ensuring well-being for workforce, respect of human rights, and regulatory compliance.

5. Conclusion

MaaS offers a means of making distributed industrial capabilities available through flexible and composable service chains. Its practical implementation, however, requires more than a digital marketplace for manufacturing resources. Providers and consumers must be able to describe capabilities and requirements consistently, exchange selected information under explicit governance rules, identify feasible combinations of resources, coordinate execution across organizational boundaries, and respond when operating conditions depart from the original plan.

This white paper presented UniMaaS as a reference architecture for addressing these requirements through three interacting suites. The Data Management Suite provides the foundations for semantic resource descriptions, manufacturing data spaces, trusted information exchange, resource monitoring, and lifecycle information management. The Modeling Suite connects formal representations of manufacturing systems with intent interpretation, predictive models, and measurable Zero-X properties. The Decision-Making Suite uses these inputs for resource selection, planning and scheduling, digital-twin-assisted evaluation, cloud-manufacturing orchestration, and circularity and sustainability optimization. Their integration defines a closed workflow that extends from the expression of a manufacturing request to service discovery, composition, execution, monitoring, and, where required, reconfiguration.

The principal contribution of UniMaaS is therefore not any individual technology considered in isolation. Data spaces, digital twins, formal models, predictive algorithms, scheduling methods, and Digital Product Passports already have established research and standardization foundations. UniMaaS investigates how these mechanisms can be combined within a common operational architecture so that manufacturing services can be composed under technical, temporal, organizational, trust, and sustainability constraints.

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