Designing a Manufacturing as a Service Ecosystem through Distributed Value Networks and Structured Volume-Variety Dynamics

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Abstract

This paper advances the Manufacturing-as-a-Service paradigm through the Tec4MaaSEs (T4M) project, where production and manufacturing processes are delivered as on-demand services using advanced Industry 4.0 and Industry 5.0 technologies, in order to create a resilient ecosystem of distributed value networks. This idea is based on a highly configurable Digital Twin architecture that dynamically adapts to fluctuations in supply and demand, enabling collaboration and optimization across diverse manufacturing scenarios and various stakeholders. Although Manufacturing-as-a-Service (MaaS) platforms promise to enable dynamic configuration of distributed production systems, most existing implementations exhibit limited ability to handle multi-actor processes involving diverse service types, heterogeneous data, and coordination needs. This work presents T4M, a MaaS framework that combines production planning, semantic interoperability, and service modeling to support the flexible composition of manufacturing value chains. A key innovation lies in its iterative feedback structure, allowing analytics and planning functions to co-evolve with service configurations. To structure the design space, we introduce a three-dimensional framework encompassing product–process variety, granularity, and Functional Integration Level (FILe). These dimensions guide the functional specification of platform services and determine where analytics and automation provide tangible value. The framework is instantiated through three representative value networks (VN1–VN3), each illustrating distinct demands in terms of information flows, coordination intensity, and decision complexity. Our analysis shows that effective MaaS ecosystems must align digital mechanisms not only with physical production resources, but also with the informational structure and functional logic of each setting. In particular, the volume–variety concept, and more specifically the notions of granularity and FILe, emerge as key enablers in identifying the level of platform integration and the appropriate scope in shaping MaaS ecosystems. These insights support the development of collaborative, resilient, and circular industry practices.

Keywords. Manufacturing-as-a-Service, Digital Twins, Resilient Value Networks, Functional integration, Granularity, Explainable AI.

1. Introduction

The current macroeconomic outlook is far from optimistic, with disruptive events driven by climate-related (up 96%), technological (up 113%), and geopolitical (up 311%) megatrends becoming the "new normal", placing unprecedented strain on global value networks (Hong and Betti, 2023). These networks, originally designed for more stable and predictable conditions, are ill-equipped to handle today's volatility (Kotter et al., 2021). As we transition into a supply-constrained world, resilience, i.e. the ability to "return to normal", has become a critical focus for businesses. However, resilience in its traditional sense is no longer sufficient. "Normal" now signifies the capacity to adapt, transform, and embrace sustainability and manufacturing companies cannot simply revert to their previous modes of operation, as these are increasingly incompatible with the emerging realities. Instead, organizations must adopt an expanded framework of resilience, one that anticipates and effectively navigates future disruptions and uncertainties. *To effectively navigate future disruptions and uncertainty, firms need to adopt a forward-looking mindset and embrace change as a constant by fundamentally reimagining and redesigning their global value network configurations and operations from end to end*.

One of the most transformative innovations for addressing these challenges is the Manufacturing-as-a-Service (MaaS) paradigm. MaaS uses cloud-based infrastructures, advanced digital technologies, and interconnected supply chains to provide scalable, on-demand manufacturing capabilities. Through virtualized access to distributed production resources, companies can utilize external capacity without the financial and operational burdens of ownership. Beyond cost efficiency, MaaS enhances the adaptability of manufacturing networks by dynamically reallocating production tasks among multiple providers, thus improving flexibility and redundancy, two key dimensions of supply chain resilience. In this respect, MaaS not only accelerates product delivery and enables customization but also mitigates disruption risks through diversified sourcing options and data-driven coordination across the value network (Koutrakis et al. 2025; Pero et al. 2025). Furthermore, by decoupling product design and development from in-house production, firms can scale operations without increasing internal capacity or fixed costs (Kusiak 2019; Hasan and Starly 2020; Zhang et al. 2022).

The implementation of MaaS is not without its complexities. Manufacturing typically represents one part of a broader value network and is often less dynamically reconfigurable compared to other components, such as logistics. Realizing the potential of MaaS requires attention on critical gaps related to capabilities, capacities and, more generally, in organizational structure. It demands a fundamental re-configuration of organizational roles, processes, and in some cases, the way individuals collaborate within the value chain. Addressing these challenges is essential to unlocking the full potential of MaaS (Usländer et al. 2021, Marinagi et al. 2023, Schöppenthau et al. 2023, El-Breshy et al. 2024) and technologies like Artificial Intelligence (AI) and Digital Twins (DTs) can play a crucial role. These technologies, when deployed within a well-defined governance framework, serve as key enablers for creating robust, adaptable, and efficient MaaS ecosystems. Digital Twins, in particular, allow detailed virtual modeling and simulation of manufacturing assets on different granularity levels and enhanced decision-making across value networks (Grieves, 2014). DTs, supported by advancements in cognitive analytics in a trustworthy and transparent environment, enable manufacturing systems to improve their ability to adapt dynamically to fluctuating conditions within the value chain (Bouguern, 2024).Also, Marra et al. recently proposed DT-enabled MaaS extensions in their work (Marra et al. 2024).

The objective of this paper is to present a conceptual methodological approach of a MaaS platform, referred to as *Technologies for Manufacturing as a Service Ecosystems (Tec4MaaSEs-T4M)*, and to substantiate its efficacy through three carefully selected use cases. These use cases not only span different domains but also vary in their volume and variety characteristics, reflecting the concept of product/service *granularity* and its extension concept, namely, FILe*,* a key factor influencing the structural elements of the proposed MaaS framework. T4M aims to enhance the adaptability of MaaS ecosystems across diverse manufacturing contexts, ranging from high-volume, low-variety production to low-volume, high-variety environments. By integrating FILe as a core principle, the framework addresses the challenge of aligning production capabilities and capacity with fluctuating demand and value chain disruptions, ensuring both efficiency and effectiveness under varying optimization objectives.

The remainder of the paper is organized as follows. It begins with a review of existing MaaS frameworks and highlights the need for more integrated approaches to managing volume–variety dynamics in platform-based manufacturing. It then introduces the Tec4MaaSEs perspective, which unites the structural notion of *granularity* with the functional concept of *FILe*, to address a wider spectrum of coordination and integration challenges. Building on this foundation, three value networks are examined—both as illustrative application cases and as distinct system configurations representing different positions within the volume–variety–FILe space. The discussion explains the rationale for their selection and concludes with a validation roadmap, along with reflections on broader implications and future research directions.

2. Literature Review

2.1 Cloud Manufacturing, MaaS Foundations and Implementation

Cloud Manufacturing (CM) and Manufacturing-as-a-Service (MaaS) represent an evolution of manufacturing systems towards a more flexible, service-oriented, and digitally interconnected paradigm. Their conceptual roots lie in cloud computing, service-oriented architecture, and the Internet of Things (IoT), allowing manufacturing resources to become virtual and delivered on-demand as configurable services. Tao et al. (2011) and Xu (2012) were among the first to propose layered architectures for CM, emphasizing modularity, scalability, and responsiveness through the integration of cyber-physical systems. These frameworks laid the foundation for virtualized resource access, platform interoperability, and real-time process monitoring, key elements of what later became formalized as CM and MaaS ecosystems.

Recent studies have extended this line of work into real-world applications (Wu et al. 2013, Adamson et al. 2017). Tedaldi and Miragliotta (2023) conducted a multiple-case study involving six CM platforms, analyzing the business-oriented dimensions of platform functionality, stakeholder roles, scalability, and orchestration. In an earlier work (Tedaldi and Miragliotta, 2022) suggested that Engineering to Order machine manufacturers should consider CM as a strategic option for their competitiveness and at the same time recognize that their internal resources and competences are not enough to build a CM platform completely on their own. In this respect, it is acceptable that any successful implementation of CM and MaaS is not merely a technical but also an organizational project, depending on trust, standardization, and governance.

Bulut et al. (2021) explored the transformative potential of MaaS for SMEs, identifying its capacity to democratize access to advanced production networks and enable digital servitization. Kladovasilakis et al. (2025) presented BladeWorks, a specialized MaaS application in the knife manufacturing sector, which exploits numerical simulation, AI-enhanced blade design, and online finite element analysis. The platform enables users to evaluate cost and delivery scenarios dynamically, exemplifying how MaaS can empower customization and “self-service” production.

Pulkkinen et al. (2024) focused on information modeling for additive manufacturing in MaaS contexts. Their contribution lies in developing data models that support usability and semantic expressiveness, both of which are essential for cross-platform integration. Similarly, the work of Yan et al. (2024)

introduced a federated learning-based supplier selection method, enabling privacy-preserving matchmaking based on geometric and material constraints without direct access to proprietary supplier data.

The decision-making dimension of MaaS has also received increased attention. Delaram et al. (2022) proposed a hybrid matchmaking mechanism based on Improved Fuzzy VIKOR and Deferred Acceptance, illustrating how stable and efficient allocations can be achieved under multi-stakeholder dynamics. Gong et al. (2023) emphasized analytics-driven collaborative contracting, combining predictive models with supplier performance histories to enhance both matching and trust in Industry 4.0 environments.

Within this distributed landscape, the role of stakeholder autonomy becomes central. Škulj et al. (2017) defined the MaaS ecosystem as a triad involving end-users, service providers, and industrial internet platforms. Chen et al. (2024) modeled interactions among these entities as autonomous agents engaged in decentralized matching. Landolfi et al. (2019) proposed a virtual MaaS marketplace architecture focused on optimizing underutilized capacity through integrated physical and digital assets. Reinforcing this, Pahwa and Starly (2021) utilized Markov Decision Processes and deep reinforcement learning to dynamically optimize order acceptance and rejection under capacity constraints. The importance of platform-level coordination has also been explored at a meta-organizational level. Schöppenthau et al. (2023) analyzed business models in large-scale innovation initiatives such as Catena-X, identifying key technical and governance requirements for scalable digital ecosystems that support distributed MaaS.

Kavre et al. (2023) conducted a comprehensive review categorizing MaaS adoption challenges into technical, organizational, and socio-economic dimensions, and emphasized the persistent gap between theoretical architectures and industrial reality. Kiatipis and Xanthopoulos (2024) highlighted cloud platforms as enablers of digital continuity, data-driven decisions, and supply chain integration, identifying digital twins, IoT, and real-time analytics as core pillars of cloud-enabled manufacturing.

Moreover, according to Tedaldi and Miragliotta (Tedaldi and Miragliotta, 2023) MaaS and the servitization of manufacturing are related but distinct concepts. MaaS is a business model for procuring manufacturing from a network of providers on demand, whereas servitization is a business strategy where a manufacturer shifts from selling a one-time product to selling a complete, ongoing service that includes the product. Thus, although MaaS too often relies on the effective design and governance of inter-organizational networks it can also be considered a powerful enabler for servitization. Table 1 provides a side-by-side comparison of these two concepts.

Table 1 Comparison of the concepts of MaaS and Servitization of Manufacturing

Feature	MaaS	Servitization of Manufacturing
Idea	Access to manufacturing capability. The customer buys the act of production as a service.	An outcome as a service. The customer buys a complete solution or performance guarantee, which includes a product.
Perspective	Primarily from the customer's point of view (an asset-light way to produce parts).	Primarily from the producer's point of view (a new way to sell and create value).
Business Model	Transactional, on-demand, often pay-per-part or pay-per-job.	Relational, based on long-term contracts, subscriptions, or performance metrics.
Key Asset	The digital platform and the distributed network of manufacturing partners.	The physical product bundled with service infrastructure (maintenance,

		monitoring, software, etc.).

Despite these impressive recent developments, challenges and open problems remain present. In fact, many frameworks remain proof-of-concepts with limited operational maturity. Interoperability across platforms is still weak, and matchmaking mechanisms often lack transparency, scalability, or the ability to support multi-period, multi-agent decision making. These limitations call for new frameworks that combine openness, modularity, actionable orchestration, and foster federal marketplaces.

2.2 Platform-Based Innovations in MaaS and Digital Manufacturing

Building on the theoretical foundations, this section focuses on implemented platforms that represent diverse approaches to MaaS and digital manufacturing ecosystems. Drawing from recent reviews (Tedaldi & Miragliotta, 2022; Kavre et al., 2023; Kiatipis and Xanthopoulos 2024) and the structured platform landscape presented in **Error! Reference source not found.**, we examine commercial, enterprise, and research-driven solutions.

The analysis covers platforms across multiple functions: on-demand production (e.g., Fast Radius, Xometry), additive manufacturing services (e.g., Sculpteo, Shapeways), integrated enterprise solutions (e.g., SAP, Oracle), federated ecosystems (e.g., Catena-X, Gaia-X), and scheduling and coordination infrastructures (e.g., SkyPlanner, Smart Factory Web).

In addition to previously mentioned platforms, we indicatively included SkyPlanner which is an advanced production scheduling solution using AI to create optimized plans rapidly, focusing on production-level orchestration. Weerg is a hybrid on-demand manufacturer offering both 3D printing and CNC machining, primarily for prototyping and low-volume runs, whereas, MagicMon is a consumer-oriented MaaS platform for custom products, offering low-volume, personalized manufacturing for individuals and designers. The Salesforce Manufacturing Cloud is a CRM-focused solution that integrates sales and order management with manufacturing operations, while FRIGATE offers a B2B MaaS platform that supports contract manufacturing. On the other hand, MANUFAST is a smaller-scale service provider integrating design-to-production support for SMEs and individual designers and Argonaut is focuses on pharmaceutical manufacturing, specializing in aseptic fill-finish. Factory X is a consortium-based initiative promoting open and collaborative ecosystems aligned with Industry 4.0 principles. EVIDEN is a full-service MaaS platform with blockchain-secured order tracking and strong integration features, while Screvle is another platform dedicated to electronics and IoT hardware development, combining manufacturing with early-stage product design support. The Rockwell Automation – PLEX is a cloud platform enabling full visibility and control over production processes. There is also the Microsoft Cloud for Manufacturing which integrates workflows and operations with digital assets for discrete manufacturing sectors. Focusing on PCBs is MACROFAB, a manufacturing platform using AI to personalize orders and optimize PCB production whereas, Fathom and 3D Systems, are vertically integrated hybrid manufacturing services covering additive and traditional production methods. Fictiv is a digital platform supporting rapid prototyping and small-batch production through CNC and additive manufacturing and similarly 3D Print Western is a service provider focused on tooling and rapid prototyping for custom industrial components. MFG and TECHPILOT are not typical platforms, rather a type of marketplaces, focused on supplier discovery, custom parts sourcing, and procurement optimization. DELMIA is a simulation and execution platform that supports end-to-end supply chain orchestration and digital twins. We note 247TailorSteelis which is a web-based sheet metalworking platform that enables the production of custom metal parts. Sybridge Technologies offers end-to-end solutions in tooling and molding, enhanced with digital cloud manufacturing capabilities.

Table 2 Existing platforms that do not address identified gaps

Platform	Description	Source
Fastradius	Additive manufacturing, offering a number of conventional manufacturing services, including injection molding, CNC machining, and cast urethane.	https://sybridge.com/ Visconti, P. et al., (2024)
GRABCAD	An open and enterprise-ready software platform for additive manufacturing at scale	https://grabcad.com/ Mets, T. (2021).
Skyplanner	SkyPlanner APS has built-in artificial intelligence for calculating complex production plans	https://skyplanner.ai/
Weerg	3D printing & CNC machining services	https://www.weerg.com/ Tedaldi, G., & Miragliotta, G. (2021)
OrderFox	Specialization in the CNC manufacturing industry	https://www.orderfox.com/
MagicMon	Manufacturing-as-a-service for brands and individuals (cups, bags, t-shirts, and pillows)	https://magicmon.com/get-started
SalesForce Manufacturing	Cloud-based CRM solution that helps manufacturing businesses with customer relationship, sales, lead, and order management.	https://www.salesforce.com/ap/manufacturing/
FRIGATE	B2B manufacturing company with partner networks (Frigaters) that facilitates New Product Development, contract manufacturing, parallel manufacturing, and Manufacturing as a Service.	https://frigate.ai/
MANUFAST	Manufacturing and product development services	https://www.manufast.be/en/
Argonaut	Full service contract aseptic fill finish manufacturing for drug products	https://www.argonautms.com/
EVIDEN	A platform that empowers customers and partners to create their own MaaS platform.	https://eviden.com/
Screvle	A hardware and software platform for smart electronics design and production.	https://www.screvle.com/
ORACLE Fusion	Oracle fusion cloud is an amalgamation of four different manufacturing solutions that includes Customer Relationship Management (CRM), Human Capital Management (HCM), Enterprise Resource Planning (ERP) and Supply Chain Management (SCM).	https://www.oracle.com/asean/applications/fusion-ai/ Muntala, P. S. R. P. (2023)
SAP Digital Manufacturing	A manufacturing operations management (MOM) platform that supports agile operations by providing cloud deployment on SAP and supports flexible execution coordinated with planning and logistics	https://www.sap.com/products/scm/digital-manufacturing.html Selvaraj, S. (2025)
Rockwell Automation – PLEX	Cloud-based manufacturing platform that manages production processes and supports functions such as inventory, shipping, supply chain management, quality control, accounting, sales, and human resources	https://plex.rockwellautomation.com/en-us.html
Microsoft Cloud for Manufacturing	Delivers capabilities that support core manufacturing processes, connecting workflows, people, business processes, and assets to enhance resilience and operational efficiency.	https://www.microsoft.com/en-us/industry/manufacturing/microsoft-cloud-for-manufacturing
MACROFAB	PCB assembly with personalized AI platform	https://www.macrofab.com/
Fathom	Additive and traditional manufacturing technologies to offer services such as 3D printing, CNC machining, and injection molding	https://fathommfg.com/
3d Systems	Additive manufacturing, including 3D printing, CNC machining, injection molding, and sheet metal fabrication	https://www.3dsystems.com/
Fictiv	Manufacturing services, including CNC machining, 3D printing, injection molding, and urethane casting, with a focus on rapid prototyping and production	https://www.fictiv.com/
Shapeways	Digital Manufacturing service for different industries	https://www.shapeways.com/ Kallisch, J. (2024)
3D Print Western	Additive manufacturing services.	https://3dprintwestern.com/
MFG	E-commerce marketplace connecting buyers of custom-manufactured parts with contract manufacturers	https://www.mfg.com/
TECHPILOT	Connecting matching suppliers, buyers and manufacturers and enabling them to determine the right price of drawing parts.	https://www.techpilot.com/en
DELMIA	Connecting the virtual and real worlds to empower customers worldwide to collaborate, model, optimize, and execute supply chains, manufacturing, logistics, and service to achieve strategic business results	https://www.3ds.com/products/delmia Jin, et al., (2024)
247TailorSteel	Tailor-made metal products	https://247tailorsteel.com/en/
Sybridge Technologies	Technology-driven cloud platforms for end-to-end design with expertise in tooling, molding and digital manufacturing.	https://sybridge.com/

2.3 Strategic Gaps in MaaS Platforms: Towards a Federated and Modular Meta-Architecture

The analysis of the above platforms (as summarized in **Error! Reference source not found.**) reveals structural limitations and challenges across the MaaS ecosystem. First, *most platforms exhibit a strong degree of domain specificity or vertical integration, focusing on narrow industrial segments or offering* *limited generalizability*. For instance, platforms such as Argonaut (biopharma), BladeWorks (custom knives) (Kladovasilakis et al., 2025), and 247TailorSteel (sheet metal fabrication) are designed for specific industries and lack general-purpose extensibility. While initiatives like Xometry and Protolabs broaden the scope by covering multiple processes (Tedaldi & Miragliotta, 2022), they still tend to favor centralized orchestration within specific service typologies.

Second, *cross-platform interoperability and the support of federal marketplace creation is largely absent.* The majority of platforms operate as closed systems, without APIs or federated data mechanisms for platform-to-platform interaction (Kavre et al., 2023). In fact, Smart Factory Web proposes a reference architecture that could support interoperability (Kiatipis & Xanthopoulos, 2024), and Catena-X aims to build a federated infrastructure for the automotive industry (Schöppenthau et al., 2023), yet such initiatives remain exceptions rather than the rule. Most platforms, such as Weerg or OrderFox, focus on self-contained transaction logic. In addition, among the few platforms that address interoperability, only Smart Factory Web (Usländer et al. 2021) or Factory -X[1] seem to be based on scientific research or a positional paper. Hence, although, platforms like Smart Factory Web and Factory-X are based on formal architectural proposals and research contributions (e.g. Usländer et al., 2021), others appear to prioritize practical business logic. Nonetheless, this distinction does not necessarily imply superiority, but actually it highlights different orientations and assumptions in platform development.

Third, *the matching processes are typically opaque, relying on proprietary algorithms with limited user feedback on how value chains (suppliers) are ranked or selected*. This is especially evident in platforms like Fathom or Shapeways, where users receive instant quotes without insight into backend logic. Some platforms like Xometry offer instant quoting but do not publicly expose how supplier prioritization is determined (Tedaldi & Miragliotta, 2023). Only a few research contributions, such as Delaram et al. (2022), address transparent and stable matching schemes. Furthermore, none of the platforms appear to support structured negotiation processes between providers and consumers as part of the platform infrastructure. While informal communication may occur off-platform or through messaging tools, negotiation is neither standardized nor embedded into the transaction logic, undermining a key part of how actual business is done in a day-to-day manner.

Fourth, the majority of these platforms are not open access that in combination with the closed, proprietary algorithms limits the transparency and explainability of the decisions made within them. Consequently, they remain “black boxes” for the end-users. The exceptions like Smart Factory Web or Factory–X and Catena–X, only underscore the lack of openness across the MaaS platform ecosystem.

Finally, modular capabilities are rare. Most systems implement tightly designed workflows, offering little space for adaptability or third-party service integration. For example, platforms like SkyPlanner or SalesForce Manufacturing support scheduling and CRM tasks respectively, but do not expose modular manufacturing workflows that can be recomposed dynamically. The concept of orchestrating production services through reusable modules, as envisioned in research (e.g., Tao et al., 2011; Xu, 2012), is not broadly implemented.

An emerging regulatory development that further complicates the MaaS platform landscape is the forthcoming EU Machinery Regulation (Regulation (EU) 2023/1230), which will enter into force in 2027. This regulation introduces stricter requirements around cybersecurity, software integrity, and system-level risk assessments for machinery, particularly those with embedded digital functions. Despite its relevance, none of the major MaaS platforms appear to acknowledge or publicly address this regulatory shift on their publicly accessible informational outlets. This is particularly concerning for platforms that operate as closed systems and rely on proprietary algorithms, as the regulation emphasizes

[1] https://factory-x.org/wp-content/uploads/MX-Port-Concept-V1.00.pdf, accessed on 24 April 2025

transparency, traceability, and demonstrable compliance in both physical and digital machinery components. Thus, closed architectures may face significant obstacles in proving conformance with the regulation's cyber risk and safety requirements.

In conclusion, the following gaps have been identified in the existing platforms:

Gap 1/Generalizability: Most existing platforms are highly domain-specific or vertically integrated, targeting narrow industrial segments at a fixed level of granularity with limited capacity for generalization or cross-sector deployment.

Gap 2/Interoperability & Federation: (a) Interoperability across platforms and support for federated marketplace architectures remain largely unaddressed, (b) with current efforts restricted to conceptual studies or position papers.

Gap 3/Transparent Matching & Negotiation: (a) Supplier matching and value chain composition processes are typically opaque, relying on proprietary algorithms with little user insight into ranking mechanisms or (b) negotiation processes.

Gap 4/Transparency & Explainability: The transparency and explainability of decisions generated within these platforms are underdeveloped, limiting user trust and actionable oversight.

Gap 5/Regulatory Compliance: Existing solutions do not systematically address compliance requirements stemming from EU Machinery Regulations and related legal frameworks.

Table 1 summarizes the platforms that were studied in the context of the current paper that were found to not address any of the identified gaps and Table 2 summarizes the platforms which were found to partially address one or more of those gaps. Note that since Gap 3 and Gap 5 are not addressed by any of the existing platforms are therefore excluded in the summary given in table 2.

Table 3 Existing platforms summary that partially address the gaps.

Platform	Description	Gap 1	Gap 2		Gap 4
			a	b	
Sculpteo	Additive manufacturing production center (professional 3d printing service)			✓	
Gaia-X	A collaborative cloud ecosystem designed to promote data sovereignty, transparency, and trust in the digital economy.		✓	✓	
Factory X	A consortium that aims to build an open and collaborative digital ecosystem for factory outfitters and operators, based on Catena-X and Platform Industry 4.0 concepts		✓	✓	✓
Smart Factory Web	Blueprint architecture for open sustainable and resilient production ecosystems.		✓	✓	✓
MACROFAB	PCB assembly with personalized AI platform				
Xometry	On-demand manufacturing of parts, including CNC machining, 3D printing, injection molding, and sheet metal fabrication	✓			
Protolabs Network	On-demand access to a global network of over 250 manufacturing partners, offering services such as 3D printing, CNC machining, injection molding, and sheet metal fabrication.	✓			
Catena-X	A digital MaaS ecosystem for the automotive industry.		✓		✓

These observations reveal a number of constraints that motivate the need for novel architectures, which aim to address these exact challenges through domain-agnostic services, platform interoperability, and transparent composable orchestration making them future-proof in the constantly evolving landscape.

In this respect, Tec4MaaSEs addresses these limitations through a design based on openness, flexibility and the ability to create a federated marketplace. In contrast to vertical or sector-specific implementations, Tec4MaaSEs enables domain independence, allowing cross-sector applications, scalable collaboration and federated MaaS networks, linking isolated platforms through interoperable services. In addition, transparent decision mechanisms will be integrated, using multi-criteria ranking models, mathematical programming and AI-driven optimization techniques. These methods will not only enhance explainability and user trust but also serve as a foundation for compliance with the EU Machinery Regulation (Regulation (EU) 2023/1230), which emphasizes traceability and risk assessment in cyber-physical systems. Finally open APIs and semantic models will be incorporated, enabling third-party service integration. As such, Tec4MaaSEs is not only a MaaS platform, but also an enabling framework for interconnecting and orchestrating MaaS ecosystems in a way that promotes trust, agility, inclusiveness, and innovation.

3. Evolving MaaS by rethinking the Product-Process Matrix and the granularity concept

While existing MaaS platform ecosystems provide a functional foundation, the gaps identified in the previous section highlight the need for a fundamentally new methodological approach. Designing next-generation MaaS platforms that are both robust and adaptable requires more than incremental or surface-level adjustments; it calls for a re-examination of the core assumptions that guide platform architecture and design. To initiate this shift, we begin with the Product-Process Matrix (PPM), introduced by Hayes and Wheelwright (1979a, 1979b). It aligns product characteristics, specifically variety and volume, with appropriate production processes. Its primary aim is to help organizations strike a balance between the often-conflicting objectives of flexibility and cost efficiency. Hayes and Wheelwright found that most organizations position themselves along a diagonal path on the matrix (see Figure 1), progressing from flexible, low-volume processes to standardized, high-volume ones as industries mature.

Moreover, the different types of processes based on the original PPM are:

1. *Continuous Flow:* Products move continuously without division into discrete units, like mixing and pouring concrete in construction. This category exhibits high-volumes with low variety of production.
2. *Connected Line Flow (Assembly Line):* Used for high-volume, uniform products, such as fasteners or automobiles, produced on a continuous, highly automated line. This category exhibits repetitive tasks producing high-volume standardized products.
3. *Disconnected Line Flow (Batch Production)*: Suitable for repeated production of similar items in moderate volumes, like cooling units for data centers or industrial compressors. It exhibits medium- to low-volume production with high variety.
4. *Jumbled Flow (Job Shop):* Designed for low-volume, highly customized products with significant variation, such as bespoke machinery or engineered-to-order components. So in this case we have highly flexible, usually small-scale and customized, or even one-off production orders that might also call for low re-configuration times.

Deviations from the diagonal of the Product-Process Matrix (PPM) can arise for valid strategic reasons, but they may also result from the introduction of new technologies that significantly reshape the production environment and fundamentally alter the nature of the trade-offs inherent in the PPM framework. It is worth noting that in the literature, another category is often distinguished, that of Project Process (Slacks et al. 2010). This category refers to one-off, large scale and customized projects/products/services. In the context of the current paper, we treat projects as the extreme case of the label Job Shop.

In this discussion, we highlight three papers that examine the continued relevance of the PPM through the lens of Manufacturing as a Service (MaaS). We begin with Kumar et al. (2020), who explore the concept of Distributed Manufacturing (DM) within the context of Industry 4.0 and employ the PPM to propose strategies for implementing DM. MaaS can be viewed as an operationalization of DM, enabling businesses to access manufacturing capabilities and capacity on demand, without the need for large capital investments in their own facilities. Next, Eyers et al. (2022) investigate the impact of Additive Manufacturing (AM) and its implications for the PPM in a MaaS context. AM challenges the traditional volume-variety trade-offs at the core of the PPM. By enabling on-demand production of customized parts regardless of volume, AM-based MaaS platforms exemplify a practical deviation from the conventional PPM structure. Finally, the evolution of the PPM towards Industry 5.0, referred to as PPM 5.0, is discussed in Jiménez - Partearroyo et al. (2024). Based on the same paper, Industry 5.0 emphasizes human-centricity, sustainability, and resilience. In this context, MaaS solutions will likely need to reflect these values, for example, by offering access to sustainable manufacturing processes or enabling collaborative customization, where human expertise is blended with advanced technologies.

The above discussion supports that the classic volume-variety trade-off, which is based on product and process characteristics, still matters in a manufacturing as a service environment but this trade-off is not as rigid as it used to be. For example, in a traditional setting, high volume typically implies low variety (e.g. automotive production lines), and high variety results in low volume (like job shops, customized machinery etc.). MaaS on the other hand, enables access to distributed capabilities beyond fixed facilities, and supports high variety without sacrificing entirely economies of scale, (at least to some extent). Yet, these developments bring forth new challenges which call for processes that are standardized in a way that enables reconfigurable manufacturing which can subsequently be servitized, and thus accessed dynamically. Thus, the volume–variety trade-off turns into something much more dynamic and flexible in a manufacturing as a service environment and this should somehow be captured within the PPM framework.

In the Tec4MaaSEs project, the Product–Process Matrix (PPM) served as a conceptual guide for selecting use cases across a broad spectrum of manufacturing contexts. By positioning each case within the PPM landscape, we were able to compare requirements, integration mechanisms, and constraints across distinct production modes. This helped ensure that the platform design remained domain-independent, adaptable to both job-shop and continuous flow environments. At this point we believe that the discussion is mature enough to introduce a notion that will be relevant and fundamental to the conceptual link between general MaaS environment and the Tec4MaaSEs contribution.

We define the *"Functional Integration Level" (FILe) of a product/service as the metric that expresses how close it is to forming or constituting a final usable product/service with respect to a specific domain. It reflects the degree to which the item in question contributes to the realization of a complete, standalone product or service that is functional and ready for end use.*

We argue that the concept of MaaS is closely connected to the principles of the PPM and FILe is playing a critical role in defining this relationship. It is important to recognize, that the Functional Integration Level is not an absolute or universally quantifiable property, but rather a context/industry/domain/product - dependent construct. What qualifies as a complete, functionally autonomous product or service varies significantly across industrial domains. In this sense, the notion of product or service functional integration "maturity and completeness" is not inherent to the product per se, but emerges from the specific role it plays within a broader value network and the PPM matrix. After all, every product or service can be understood both as an outcome and as a subsystem of a more complex system suggesting a nested (recursive) structure, in which functional integration is always relative to a defined scope. This underlines the need to interpret FILe within each specific operational and strategic context, taking into account how completeness, usability, and autonomy are realized, each with respect to the registered domain in T4M (for relevant discussion, see Eyers et al., 2022; Lu et al., 2020). In practice, FILe translates into a registration threshold for platform providers, defining the minimum level of product or service completeness required for participation:

- ***High FILe:*** *The provider is expected to deliver a complete, self-contained product or service, fully integrated and ready for deployment.*
- ***Medium FILe:*** *The provider may offer either full solutions or modular components, depending on capability and context.*
- ***Low FILe:*** *The provider contributes only specific parts or subsystems, requiring external contribution to form a complete solution.*

Therefore, in the context of MaaS, the concept of granularity (Figure 1), originally referring to the level of decomposition of production activities, finds a more functional and integrative expression through the notion of Functional Integration Level. While traditional granularity captures how finely a production task can be broken down, FILe reflects how these decomposed elements must interact to deliver a coherent and complete product or service. In this sense, FILe can be seen as a MaaS-oriented generalization of granularity, one that not only accounts for task decomposition but also embeds the degree of interdependence and coordination required among providers within a distributed manufacturing network. This shift from structural to functional granularity enables more nuanced orchestration of service-based manufacturing systems, where flexibility, modularity, and integration must co-exist dynamically.

In addition, it is deemed important to discuss the relationship between the FILe concept and two important notions in MaaS, those of customization and modularity. High customized production requires tight cooperation and synchronization among specialized providers, hence higher functional integration. On the contrary, low customized or standardized) products rely on existing and/or modular configurations which typically involve minimal coordination, thus have lower FILe settings.

In a further distinction, modularity typically refers to the ability to separate components structurally; FILe acts complimentary to modularity and refers to the degree of functional synchronization/coordination that is required when these modular components are reassembled to create a complete product or service. In that sense, high modularity could co-exist either with high or low FILe depending on the level of customization of the final configuration might be.

Figure 1, presents the extension of the classical Product–Process Matrix with a vertical dimension of granularity, capturing the level of decomposition in manufacturing tasks.

Nonetheless, within MaaS environments, this structural view is further enriched by the notion of Functional Integration Level, which generalizes granularity to account not only for task size and scope, but also for the degree of functional coordination required to compose a complete product or service. FILe thus serves as a MaaS-specific evolution of granularity, reflecting both decomposition and integration dynamics across distributed value networks.

This tiered FILe framework ensures that registration criteria are precisely aligned with both the complexity of the offering and the expectations of the value network it supports. In practice, FILe serves as a guiding principle for provider registration on the platform.

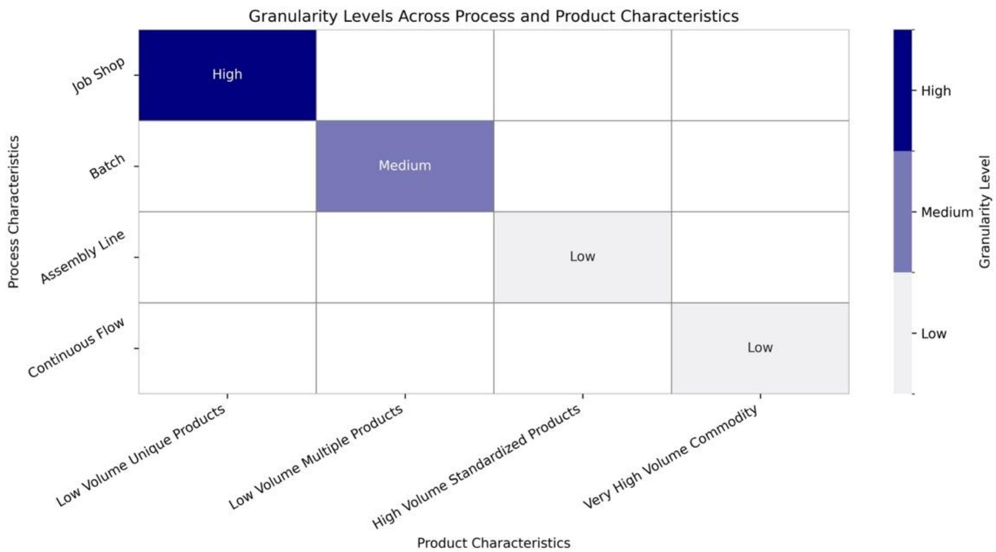

Figure 1 The product process matrix as proposed by the Spearman and Choo (2018) enhanced with the Granularity dimension[2]

Consider, for example, the broader domain of white goods and its various specializations. One such specialization is contract manufacturing of consumer washing machines, a clear case of high FILe. Here, each provider is expected to demonstrate the ability to produce specific washing machine models at scale. The consumers are major white goods companies that source large volumes from multiple providers under contractual agreements. In contrast, the production of highly specialized washing machines for industrial applications represents a medium-to-low FILe context. The exact FILe level depends on the degree of customization involved in the final product and whether a single provider can manufacture the entire machine or collaboration among multiple suppliers is required.

More specifically, in the example of white goods domain (e.g. washing machines) we have that:

- In **high FILe** settings, such as contract manufacturing for consumer-grade washing machines, each provider is expected to deliver fully assembled, market-ready units at scale, typically serving well-known appliance brands under strict quality and delivery requirements.
- In **medium** to **low FILe** contexts, such as industrial or specialized washing machines for niche applications, providers may focus on specific components or subsystems (e.g., control modules, high-capacity drums), necessitating the coordination of multiple suppliers to complete the final product.

Within the traditional Product–Process Matrix, batch production is particularly well-suited for low-volume, high-variety manufacturing scenarios. Such configurations align closely with MaaS applications, where production tasks are decomposed into subtasks and distributed across multiple providers of a supply chain. These scenarios often correspond to a medium-to-high Functional Integration Level: although individual components are produced independently, integration is required to assemble a complete, usable product. A notable example is Additive

2 the job shop category encompasses project-type processes (Slack et al., 2010)

Manufacturing, where highly customizable parts are created in discrete stages and then integrated into a final product. This interdependence of elements and the need for structured coordination indicate a relatively high FILe, reflecting the advanced capabilities needed to compose a functional final product. Conversely, assembly line production is designed for high-volume, low-variety output and typically involves a low FILe. The production process is rigid and standardized, with limited variation or integration effort. In such contexts, MaaS platforms do not focus on decomposition, but rather on enabling efficient large-scale coordination. The platform acts as a collaborative means, supporting the discovery and orchestration of partners within the supply chain to fulfill bulk orders efficiently (Schöppenthau et al., 2023). This model is particularly valuable for smaller firms or startups that wish to access industrial-scale production lines without heavy infrastructure investments. Moreover, when integrated with reconfigurable production lines, MaaS can offer limited product-mix flexibility, enhancing responsiveness to demand shifts while preserving operational efficiency.

This analysis emphasizes the dual functionality of MaaS: it enables task allocation and customization in job-shop and batch production, while also promoting large-scale coordination and efficiency in assembly line production. By adapting to varying levels of Functional Integration Level, MaaS provides a versatile framework capable of addressing the diverse needs of different manufacturing scenarios. In essence, MaaS can help reduce the cost of transitioning along the diagonal of the product-process matrix, from low-volume, high-variety to high-volume, low-variety, or vice versa, by offering adaptable and scalable production solutions.

Moreover, the level of FILe, in conjunction with process and product characteristics, significantly influence the complexity of decision-making models in any practical MaaS framework. For instance, in job-shop applications, which typically operate at high FILe, the recursive decomposition of the production process becomes especially challenging, both theoretically and practically. These environments often require significant customization and flexibility, making automated steps such as decomposition or task matching difficult to fully automate within the MaaS platform. As a result, some of these steps may need to be handled manually by the user. In such cases, the platform’s information model becomes crucial. It plays an essential role in streamlining what would otherwise be time-consuming and error-prone service operations, allowing users to efficiently coordinate tasks and integrate components. In particular, the platform's information model should be essentially supported by the appropriate semantics that would enable the representation of the complex relationships between requests, infrastructure, and resources, enabling interoperability among system components through standardized data structures and interfaces. The result would enhance the automation of decision-making processes and the integration of heterogeneous manufacturing services, which is particularly crucial in high FILe domains where customization and flexibility are important.

Medium to high FILe settings, such as additive or batch-based manufacturing, require dynamic integration of customizable components, making decomposition and task matching central to the MaaS value proposition. Conversely, in low FILe environments such as assembly lines, the emphasis shifts toward coordination and throughput rather than flexibility. In such cases, MaaS platforms serve primarily as orchestration layers that streamline large-scale production workflows and facilitate efficient resource utilization across partners.

In conclusion, the notion of FILe, building on the foundational idea of granularity, provides a more practical way to understand modularity and system complexity in MaaS environments. It supports the need for MaaS platforms to sustain a wide range of volume–variety scenarios by allowing different degrees of integration among service components. In this respect, the platform is no longer just a transactional layer, but operates as a meta-platform, capable of adjusting its coordination mechanisms to match the structural and functional requirements of each manufacturing setting. The connection between FILe and process structure plays a key role in shaping platform design, as reflected in the general-purpose semantics defined within its information model. The following sections present how these ideas have been applied in the Tec4MaaSEs architecture, using three value networks that represent distinct positions across the volume–variety–FILe space.

4. The Tec4MaaSEs Methodological Approach

The Tec4MaaSEs methodological approach is outlined in Figure and represents a strategic response to the main research gaps identified in Section 2.3.

It is important to note that the methodological schema shown in Figure 2 was designed to address these key research gaps and clearly, at this stage, we are not presenting a full architecture but a structured way to organize the elicitation process in order to define and clarify the pilot configurations in Tec4MaaSEs.

In this respect, let us provide in this paragraph, a mapping between the identified challenges and the components included in our approach. More specifically, high domain specificity and vertical integration is addressed by the use of service decomposition together with the definition of three value networks (VNs) targeting different levels (operational, tactical, strategic), which allows us to generalize the approach across different manufacturing domains. To handle the lack of cross-platform interoperability, the approach includes an open resource registration stage using standardized capability descriptions. Of course, the notion of "capability" varies across providers depending on their available assets and the specific domain in which they operate. This is further explained in the following text. The inclusion of governance interfaces supports connectivity between different platforms and data spaces, which is important for enabling a federated MaaS ecosystem. Regarding the gap of opaque matching, the proposed schema includes a service decomposition stage based on semantic matching, followed by an analytics component. These support transparency by allowing matching to be more traceable and explainable, avoiding a black-box decision-making process. The issue of restricted access and low transparency is addressed by the inclusion of a governance layer, which enables platform-level coordination and configuration. This supports controlled openness and accountability, while still respecting security requirements. Finally, the issue of regulatory compliance, particularly in relation to EU Machinery Regulations, is supported through the traceable structuring of service components and the explicit definition of capabilities, roles, and provider responsibilities. By embedding these elements within the platform's information model, the architecture facilitates alignment with formal certification and audit processes, thus enabling providers to meet legal and safety requirements more efficiently.

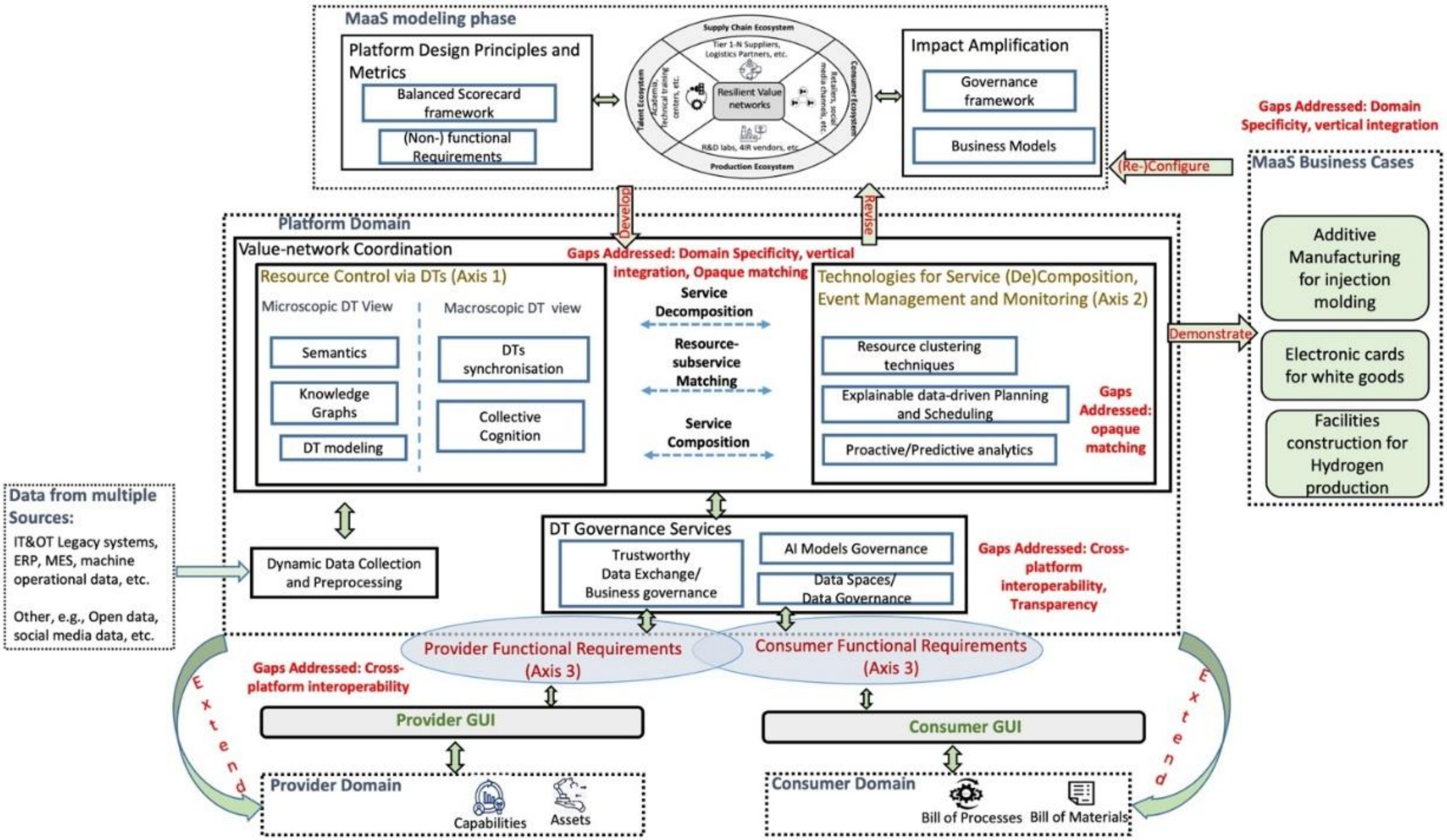

Figure 2: The Tec4MaaSEs methodological approach

Therefore, the components included in Figure 2 are not arbitrary but are carefully selected to respond directly to the barriers that limit the scalability and adoption of MaaS platforms. As we will further elaborate in the pilot presentation, the proposed Tec4MaaSEs approach will guide the design of an elicitation process for a set of carefully selected use cases, based on the principles discussed in Section 3. This methodology is structured around three core axes, which will ultimately inform the detailed design of the Tec4MaaSEs architecture in subsequent phases.

Axis 1: Open Resource Registration and Integration: Involves the systematic registration and integration of available resources, including physical assets (e.g., factories, manufacturing equipment, materials), digital tools (e.g., software), and associated capabilities, using standardized descriptions. Capabilities refer to both *what* the assets can produce (e.g., molds) and *how* they perform the transformation (e.g., using 3D printing).

Axis 2: Resource Encapsulation and Selection: Focuses on the encapsulation of resource characteristics and the intelligent selection of the necessary components to fulfill a requested service. This enables the dynamic (de)composition of services tailored to specific production requirements based on semantic matching and facilitated by the analytics component.

Axis 3: Service Monitoring and Operations Management: Covers the monitoring, evaluation, and operational oversight of the composed service, including the coordination and lifecycle management of the selected resources involved in service delivery. Consequently, the proposed schema is grounded upon an agile *Governance Framework* with three key components:

- *Business Governance*: Defines operational strategies for resource sharing, actor roles, product lifecycle, and DT modeling decisions. It covers interactions, constraints, AI-based decision-making, and DT automation levels.
- *Data Governance*: Establishes data handling policies per DT, including confidentiality, ownership, accountability, security, privacy, metadata management, and risk planning for interconnected DTs.
- *AI Governance*: Ensures the trustworthiness of AI models through explainable and human-in-the-loop AI services, supporting transparency, feedback, and ethical use.

These models will incorporate *design principles for resilient value networks*, guided by non-functional requirements such as: interoperability, domain adaptability, openness to standards, business model flexibility, scalability, security, data sovereignty, and extensibility. At this stage, the reference to Explainable AI systems is conceptual rather concrete. The specific operationalization of these elements that will ensure the explainability can be selected at a later stage given the context of the platform's implementation or the type of usage/demand/orders that dominate. In this respect, future iterations of the T4M platform will integrate explainable AI mechanisms such as surrogate models and local interpretability (e.g., LIME, SHAP) to enhance decision transparency in matchmaking and scheduling modules.

To enhance architectural resilience, Tec4MaaSEs introduces *a modeling framework for MaaS*, enabling the matching of service requests with provider capabilities across the selected business cases. Modern manufacturing demands resilient value networks, which Tec4MaaSEs addresses by adopting *platform economy principles*. These promote fair participation, incentive alignment, and fulfillment of both *functional and non-functional requirements* across all stakeholders, that is, resource providers, service consumers, and platform operators.

We now proceed with a detailed explanation of the Tec4MaaSEs methodological approach by analyzing the components shown in Figure 2 through the identified axes.

4.1 Axis 1: Open Resource Registration and Integration

Tec4MaaSEs builds on the *Smart Factory Web (SFW)*, developed by Fraunhofer IOSB and KETI in starting 2016. It adopts the three core axes while focusing on two main actors—resource providers and service consumers—and introduces a Platform Domain that serves as a service broker. This broker role enables Tec4MaaSEs to operate within a federation of industrial marketplaces, expanding its reach and capabilities. SFW provides a reference architecture for open industrial marketplaces, offering assets *as a service* and supporting supply chain integration. Tec4MaaSEs enhances this framework with technologies that address key design challenges and will be validated across three strategically selected industrial domains. More specificallyTec4MaaSEs will develop:

- Interconnected digital twins, standards, and semantics to encapsulate resources and manage supply chains.
- Explainable technologies, including prescriptive analytics for supply chain composition, descriptive analytics and visualizations for summarizing data in various stages of the decision-making process and refining the final selection of supply chains.
- Semantic rules and reference libraries for flexible, domain-independent resource modeling. These will capture key attributes, such as asset capabilities and supply chain properties, to enable efficient service decomposition and dynamic production configuration.

4.2 Axis 2: Resource Encapsulation and Selection

Nonetheless, demonstrating manufacturing capabilities across different levels of granularity, supply chain, asset, product, and property, calls for the adoption of a *functional requirements set* for MaaS. Those include resource registration based on open standards (e.g., Platform Industrie 4.0), service decomposition into subservices, and the discovery and matching of resources to production requirements. This approach will also lead to an architecture that should support real-time availability tracking, visualization of shop floor and network data, disruption detection, and value network analysis. Additionally, resources should expose both static and dynamic attributes to convey quality of service and operational status, supporting informed decision-making and coordination.

To guide the decomposition of services at different granularity levels, we adopt a Balanced Scorecard perspective as a way to capture multi-dimensional performance views. The Balanced Scorecard Framework is proposed to complement the defined functional requirements by supporting the monitoring and management of resource-sharing strategies. The primary function of this monitoring instrument is to enable quantitative assessment of circularity potential and impact, grounded in the understanding of causal relationships and the performance of individual resources and services. The framework also informs strategic decision-making by evaluating and prioritizing necessary actions. It is expected to comprise two components: (i) a generic set of criteria aligned with established frameworks for assessing circularity and supply chain performance, and (ii) pilot-specific KPIs tailored to the contextual needs of each scenario.

The Tec4MaaSEs platform operates through two primary actors: providers and consumers. Providers register via the *Provider GUI*, uploading models of their services and products aligned with the platform's data model, which captures production assets, capabilities, and properties as defined in the MaaS modeling phase. To ensure seamless resource integration, Tec4MaaSEs employs syntactic interoperability tools proposed in SFW, including standard communication protocols, common data formats. Integrated resources are digitally represented as DTs, which encapsulate attributes and behaviors for communication, storage, and processing. Each DT comprises (i) resource data, (ii) behavioral models (e.g., physical or data-driven), and (iii) services leveraging these elements. DTs are developed in alignment with a defined meta-model—such as the Asset Administration Shell (AAS)—to ensure consistency, interoperability, and structural integrity. The application and service layer of each DT supports advanced cognitive functions through optimization, and predictive analytics. Building on individual DT cognition, Tec4MaaSEs facilitates *Collective Cognition*—the coordinated learning and optimization across multiple DTs within a value network. This capability supports the dynamic reconfiguration of value networks, integrating new DTs into existing models. Combined with the Balanced Scorecard, this framework enables the evaluation of alternative MaaS scenarios and their systemic impacts.

The *Dynamic Data Collection and Preprocessing* component ensures seamless connectivity with dynamic data sources (e.g., IoT) and legacy systems (e.g., ERP, MES), enabling transparent data integration within Tec4MaaSEs. It addresses data uncertainty and incompleteness through a comprehensive process of profiling, preprocessing, integration, validation, and monitoring, thereby reducing errors and ensuring data fitness for platform use.

Data sharing among verified industrial partners presents a significant challenge for Tec4MaaSEs, particularly regarding proprietary information such as price thresholds, lead times, and supply chain risks. While consumers seek detailed insights, manufacturers are often hesitant to disclose data to unfamiliar entities. To address this, Tec4MaaSEs will be integrated with *Trusted Data Spaces* that ensure data sovereignty and address governance and privacy concerns. These spaces will utilize standardized data connectors to enable secure and transparent data exchange between providers and consumers. Achieving truly *Trustworthy Data Exchange* will require further modeling and integration of Balanced Scorecard metrics and sustainability KPIs, in line with OECD guidelines and Tec4MaaSEs' governance framework. Upon registering with Tec4MaaSEs, consumers will be able to submit search queries for registered resources (e.g., factories) and composite configurations (e.g., supply chains) capable of delivering the required services. In alignment with the SFW approach, Tec4MaaSEs will bridge the semantic gap by employing unified data semantics and developing reference models tailored to multiple industrial domains. These models encompass attributes such as production assets, capabilities, properties, and supply chain characteristics relevant to the business case.

4.3 Axis 3: Service Monitoring and Operations Management

Through the advancement of semantic interoperability across the platform's three core Axes, Tec4MaaSEs will enable the registration of capabilities and production processes. Following the submission of a service request, the platform will validate the input using semantic rules and structured models from the reference library, and then generate a *Service Decomposition Model,* a flow graph representing the subservices (i.e., finer-grained capabilities) needed to fulfill the request. The quality of this decomposition is central to Tec4MaaSEs' objectives, as it directly impacts product development speed, cost-efficiency for providers, and production reconfigurabilty by modularizing process steps. Once the decomposition model is established, Tec4MaaSEs takes advantage of its DT view to match subservices with registered resources. This is achieved using advanced *Resource Clustering Techniques* that account for cross-industry diversity and variable levels of resource and capability granularity, providing a robust and flexible foundation for resource sharing. To support this, a *multi-granularity resource model* will be developed, incorporating dimensions such as geographical and physical constraints, production processes and steps, and a wide range of Quality of Service (QoS) parameters. These include service time and cost, idle time ratio, throughput, scalability, response time, reliability, environmental impact (e.g., GHG emissions), manufacturing efficiency, IoT integration compatibility, and quality reputation.

To complete the requested service composition, Tec4MaaSEs performs the selection, planning, and scheduling of suitable sub-services and resources capable of delivering the desired service, considering a range of Quality of Service (QoS) criteria. This process is grounded in *Explainable Data-Driven Planning and Scheduling*, which supports both (a) a *reactive approach,* where capacity demands and disruptions dynamically evolve, and (b) *a proactive approach*, where scheduling must be adapted to handle uncertainty in critical parameters such as resource availability, processing times, pricing, machine reliability, and stakeholder requirements. Once the service composition is finalized, the corresponding service offer is returned to the registered consumer. The output includes comprehensive resource information such as: selected factories within the supply chain, their individual capabilities, input and output product descriptions, associated properties, and the matched service capabilities. These results will be presented *through interactive visualization components* specifically designed for Tec4MaaSEs, enabling both consumers and providers to interpret, analyze, and validate the data supporting the composed service.

Visualizations and analysis tools will be embedded in both the *Provider and Consumer GUIs*, developed according to the functional requirements defined under the Tec4MaaSEs framework. These functionalities will include modules aligned with the *Balanced Scorecard* framework to support effective monitoring, evaluation, and strategic decision-making for registered resources, their associated supply chains, and the composed services themselves. Notably, certain functionalities—such as real-time availability monitoring, capacity planning under temporal constraints—will be shared between providers and consumers to support seamless and transparent collaboration.

5. The Tec4MaaSEs Business Cases and mapping to the evolved Product-Process Matrix

The Tec4MaaSEs methodological approach, as outlined in Section 4, establishes an iterative feedback loop between the T4M platform real world implementation and its foundational modeling principles. In this framework, the T4M platform is initially configured during the modeling phase and subsequently demonstrated and further developed through the selected business cases. In this respect, insights gained from these demonstrations inform the reconfiguration and refinement of the modeling principles, leading to continuous improvement. The following subsections detail the three selected value networks and their distinct characteristics, which are most relevant to our discussion.

5.1 VN1: Electronic cards for white goods

The first value network (VN1) comprises four organizations operating within the manufacturing of white goods and electronic components sectors. In the white goods industry, appliances such as washing machines and refrigerators require electronic boards (EBs) that are tailored to each product's specifications. These EBs are assembled by two providers (VN1P1 and VN1P2), which integrate various components including printed circuit boards (PCBs), microcontrollers, and other electronic elements, into functional units. Subsequently, these EBs are supplied to two consumers (VN1C1 and VN1C2), which incorporate them into their final white goods products. Note that while certain types of EBs are commonly produced by both providers, their specific characteristics may vary depending on the individual requirements of each consumer.

In this context, the production capacities of providers are perceived as shared resources that EB-consuming plants can dynamically utilize to boost both throughput and supply chain resilience. Each order then typically consists of multiple identical units, classified by specific EB types. In the envisioned to-be scenario, the T4M platform facilitates collaborative engagement between stakeholders during the so-called composition phase, a stage in which the system consolidates the requested EBs from the first-tier providers to meet consumer demand efficiently (see Figure 3).

Therefore, VN1 illustrates how the T4M platform supports the dynamic allocation of shared production capacities, enhancing operational responsiveness and enabling more efficient use of existing manufacturing resources. By promoting collaboration between multiple stakeholders and reducing idle capacity, the platform contributes to the circular use of production assets and supports agility across the value chain.

A significant challenge within this network stems from the asynchronous and unpredictable demand patterns of the consumer companies. This variability leads to production bottlenecks and inefficiencies for the providers, who struggle to align their manufacturing schedules with constantly shifting requirements. To mitigate these issues, the T4M platform enables enhanced coordination between providers and consumers through real-time data exchange and collaborative planning. This integration aims to synchronize production activities, reduce lead times, and improve the overall efficiency of the value network.

Since the implementation of T4M heavily relies on the use of digital twins, it is essential to identify the assets and their corresponding capabilities within each value network. Based on our discussion thus far, the assets in VN1 refer to the facilities of the various providers at the factory level. Their capabilities are defined by the different types of EBs that each asset (i.e., provider) is able to produce. These capabilities are specified, among other means, during the provider registration phase and through the provider GUI. Apparently, a provider can register itself in the domain of PCBs only if it has the capability to produce certain types of EBs. Since EBs serve as the final product in this domain, two key implications arise: (1) decomposition is not relevant within this value network, and (2) the VN exhibits a relatively high FILe, as outlined in Section 3

The Tec4MaaSEs platform will be accessible to consumers via the consumer GUI, enabling them to submit requests for EBs with different specifications (i.e., capabilities) from various providers (i.e., assets). Data sharing considerations, such as EB price thresholds, time constraints, and routing-related risks are incorporated into the platform's decision-making logic. By considering the location of the different facilities and a variety of QoS criteria that will be agreed in advance (e.g., service time and cost), T4M will be able to match the service demand for EBs with what is offered by the providers' facilities. The selection planning and scheduling of the requested service for EBs will be realized through explainable data-driven optimization methods which should consider disruptions (e.g., unexpected demand fluctuations, machine breakdowns etc) via suitable proactive and predictive analytics. The final search result is expected to return detailed information for the selected assets and capabilities used for fulfilling the requested service.

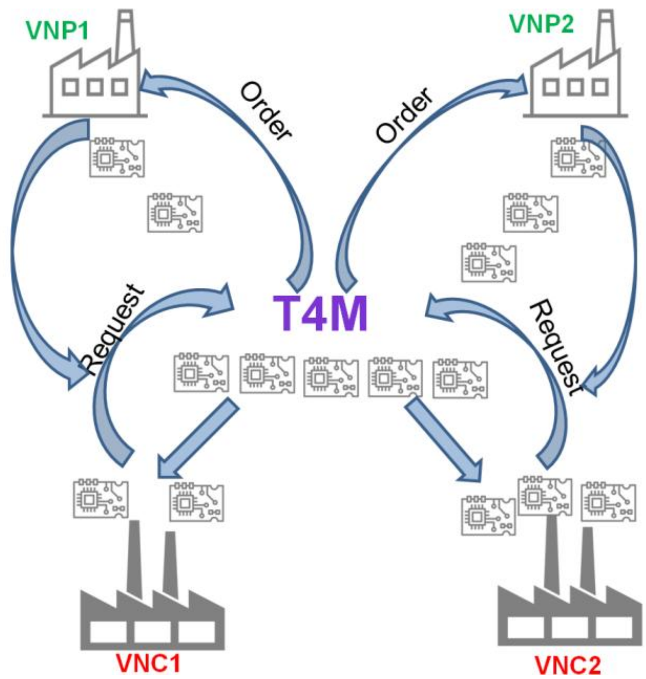

Figure 3: Value Network 1 Schema and the place of the T4M platform within its process

5.2 VN2: Parts for molds used in plastic injection molding

The second value network (VN2) operates within the domain of mold part production for plastic injection molding. It comprises three organizations specializing in plastic injection molding, machining (Mach), and additive manufacturing (AM). We refer to each participating organization using the label VN2U#, where 'U' stands for decision making entity (unit) within the value network. The first organization, denoted as VN2U1, is an original equipment manufacturer that designs and produces plastic injection components across multiple industrial sectors. Within this network, VN2U1 functions exclusively as a consumer of mold parts. The second organization, VN2U2, is an SME that specializes in mold design, feasibility evaluation, and subtractive manufacturing for various applications. The third entity, VN2U3, is a manufacturing provider operating a hybrid shop floor equipped with both AM and Mach resources. Notably, while VN2U1 serves solely as a consumer in this network, VN2U2 and VN2U3 may alternate between consumer and provider roles, contingent on the specific use case.

Additive manufacturing presents compelling advantages over conventional mold production techniques in the injection molding sector. Its integration can reduce lead times, improve production and storage costs, and enable on-demand fabrication of complex components. In particular, AM can replace the need for extensive spare part inventories by enabling the rapid production of mold inserts or specialized parts as needed. However, these benefits come with trade-offs, including high initial investment costs and the requirement for downstream processes such as machining and surface finishing to meet functional specifications.

Figure 4 illustrates a representative scenario in which VN2U1 submits a request for mold parts through the T4M platform. In response, T4M orchestrates a composite supply chain involving VN2U2 and VN2U3 as service providers. Specifically, VN2U3 performs the additive manufacturing of the part, after which VN2U2 completes the process via subtractive finishing (machining) and arranges delivery to VN2U1. Although either VN2U2 or VN2U3 may possess the full capability to fulfill the request independently, the T4M platform determines the most suitable composition of service providers based on multi-criteria decision-making principles, Including (but not limited to) the tradeoff between additive (AM) and machining (Mach) manufacturing processes.

Furthermore, VN2U2 and VN2U3 may also assume consumer roles in scenarios where manufacturing requests originate outside the T4M ecosystem. In such cases, these organizations can use the platform to identify and procure complementary services (e.g., AM or Mach) offered by other participants within the domain. For instance, VN2U3 may receive an external order requiring machining operations and subsequently utilize T4M to source those services from VN2O2.

Value network 2 demonstrates how T4M supports the flexible and modular composition of manufacturing services across organizational boundaries. Unlike VN1, where providers deliver complete products without intermediate hand-offs, VN2 introduces a decomposition phase, in which different production steps may be distributed among multiple providers. This indicates a medium FILe, as defined in Section 3, in which no individual provider is solely responsible for delivering the complete product, even if technically capable.

Another key distinction lies in the granularity of asset representation. While VN1 considered digital twin representations at the factory level, VN2 requires for individual machines. During the registration phase, each provider organization must specify its shop-floor assets along with their supported capabilities. During the matching and composition phases, T4M requires real-time data on resource availability (e.g., current capacity and valid time windows). This information allows the platform to (re)configure the supply chain dynamically and ensure timely fulfillment of service requests. A significant challenge associated with this approach is the scalability of value network composition. As the number of registered entities and assets increases, the complexity of service matching and scheduling rises exponentially. To address this, T4M integrates efficient and explainable analytics (e.g. data driven and automated Bill of Process generation from CAD files) and optimization procedures that support distributed manufacturing scenarios. These methodologies are further supported by preprocessing and post-processing analytics aimed at reducing computational complexity and improving the value chain rankings, while ensuring transparency and timely decision-making.

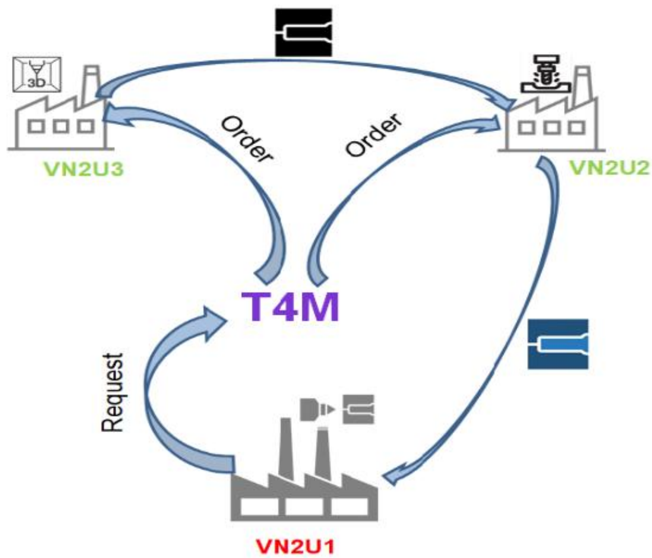

Figure 4: Value Network 2 Schema and the place of the T4M platform within its process

5.3.VN3: Hydrogen Facility Construction

The third Value Network (VN3) focuses on the construction of hydrogen production facilities, emphasizing the negotiation and contracting processes required to assemble complex systems from multiple component providers (e.g., compressors, electrolyzers). In typical projects, the facility owner delegates overall project responsibility to an Engineering-Procurement-Construction (EPC) contractor, who acts as the sole consumer in this network (VN3C).

Hydrogen facilities are composed of distinct equipment packages, each requiring specialized components. T4M maintains a registry of qualified providers for each package. VN3C initiates a manual matching process by selecting a subset of these providers to submit quotations. One provider is ultimately awarded the contract for each equipment package. This selection and negotiation process is repeated iteratively for all required packages and actually, this iterative contracting structure reflects the somehow decentralized nature of the network, where no predefined end-to-end production chain exists and coordination occurs at the level of modular procurement coordinated by the VN3C. In the current use case, two providers—VN3P1 and VN3P2—compete for a single equipment package. Therefore, in the examined case, the network consists of the consumer (VN3C) and two competing providers (VN3P1 and VN3P2), each associated with specific equipment capabilities.

Notably, the Functional Integration Level (FILe, see Section 3) of this network is relatively low, as no individual provider can deliver a complete facility. This low level of integration necessitates a central coordination role, assumed by the EPC contractor, who decomposes the overall project into modular equipment packages and manages their technical and timely integration. This orchestration involves bilateral negotiations between the contractor and various suppliers, typically based on extensive and often complex technical documentation.

VN3 illustrates how T4M supports these interactions by enabling the use of standardized and semantically rich Information Models (IMs). Providers register their Digital Twins (DTs) in T4M, representing their equipment and associated capabilities. Once selected by VN3C, providers engage in a quotation process, followed by an extended negotiation phase culminating in formal contract agreements. In this context, the value of T4M lies in its ability to support semantic clarity and interoperability, thereby accelerating negotiations and reducing misunderstandings in the assembly of complex, multi-supplier projects (Figure 5).

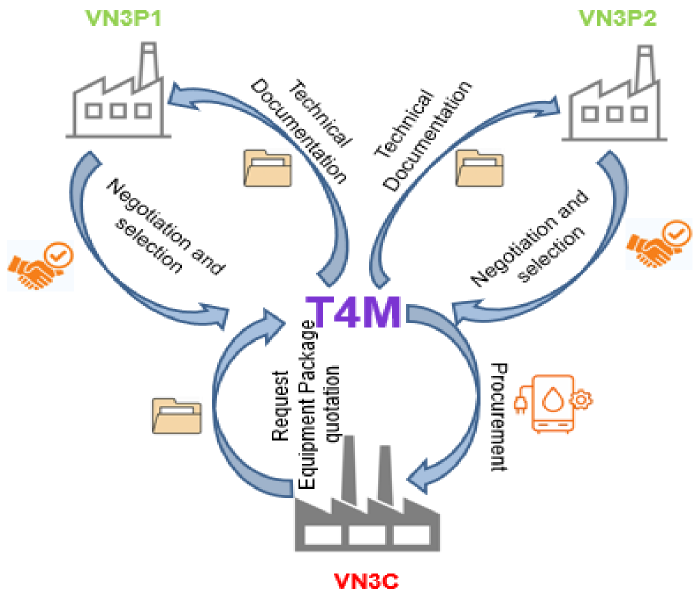

Figure 5: Value Network 3 Schema and the place of the T4M platform within its process

The description of the three value networks presented above, highlights an interesting feature inherent in T4M. Specifically, one could map the three Value Networks, VN1 to VN3, onto the three fundamental levels of planning in operations management; that is, operational, aggregate, and strategic planning. In particular, VN1 focuses on operational planning at the most basic level of operations, specifically for the production of a single type of product, the electronic board for white goods (albeit, under various variations). The four involved factories (stakeholders, including two consumers and two providers) aim to coordinate their actions to improve the alignment of supply and demand for electronic boards on a daily basis. On the other hand, VN2 involves three stakeholders, each of whom may have multiple roles as consumers and/or providers within the manufacturing sector, particularly in additive manufacturing. In this case, the emphasis is on the planning and production of mold parts, an intermediate process related to aggregate planning. Additionally, VN2 is highly interested in the available production capacity, whether in machining or additive manufacturing, with the goal of reducing idle periods at the aggregate planning level. Finally, in VN3, there is a single stakeholder, an EPC contractor, which constructs large energy production facilities on behalf of third parties. In this case, the challenge is at the strategic planning level, as T4M is intended to facilitate negotiations after contracts for the construction of the facility have been signed. The aim is to streamline, standardize, and digitize the negotiation process with various suppliers of both standard and customized equipment. These bilateral interactions between the contractor and the supplier(s) should be transformed into specific agreed-upon Information Models, thus positioning the entire process of the specific VN at the upper (strategic) level of operations management.

In conclusion, the three value networks presented in this section represent different types of granularity and volume-variety dynamics (as discussed in section 3) within the Manufacturing-as-a-Service (MaaS) framework. In particular, VN1 is characterized by medium granularity, as it focuses on coordinating the production and distribution of electronic boards (EBs) across a 1-tier supply chain. In this case, the platform is used to enable synchronization of medium-volume, medium-variety production processes in an effort to achieve a balance between flexibility and standardization. The T4M platform offers the possibility to optimize allocation of resources based on production capacities and availabilities. On the other hand, VN2 exhibits high granularity by emphasizing the reconfigurable nature of additive manufacturing for injection molding, which deals with low-volume, high-variety production requirements. The platform offers the ability to dynamically decompose services into subtasks and allocate these specific subtasks to specialized providers, ensuring that production capacities and availabilities are matched to demand requests. Finally, VN3 represents a completely different case, as it is, in fact, a project where MaaS is only involved in assisting the shift from paper-based information exchange to digitally enabled information exchange among stakeholders. In this case, the platform primarily supports strategic planning through the exchange of highly detailed component and overall system information, where granularity is related to information rather than the production process itself. Figure 6 illustrates the positioning of the two value networks within the updated three-dimensional matrix.

The updated product–process matrix illustrates the mapping of the three value networks (VN1–VN3) in terms of granularity and FILe level. The horizontal and vertical axes represent product and process characteristics, respectively. Granularity is illustrated in the third dimension and value networks are labeled directly within their respective quadrants, including their granularity (G) and FILe levels. Together, these cases demonstrate how a MaaS framework can handle all cases in the product-process matrix by accommodating varying degrees of granularity and volume-variety characteristics, extending its applicability across a wide range of manufacturing scenarios.

The revised structure of the product–process matrix, is now enriched with the additional dimensions of granularity and Functional Integration Level. In this respect, it offers a more complete representation of the three value networks. Instead of being arranged solely along a single process axis, the networks are positioned according to the complexity they exhibit (shaped by their product and process variety), the level of detail at which operations are defined, and the extent of coordination and information flow they support. VN1 is situated in a production setting with moderate product variety, a medium degree of granularity, and relatively strong integration of processes and information (Medium–High FILe). VN2 and VN3, while both linked to job-shop configurations and unique products, differ notably in the way they handle information and coordination: VN2 follows a structured yet adaptable approach (Medium FILe), whereas VN3 functions with minimal formalization (Low FILe), even though both operate at a high level of granularity.

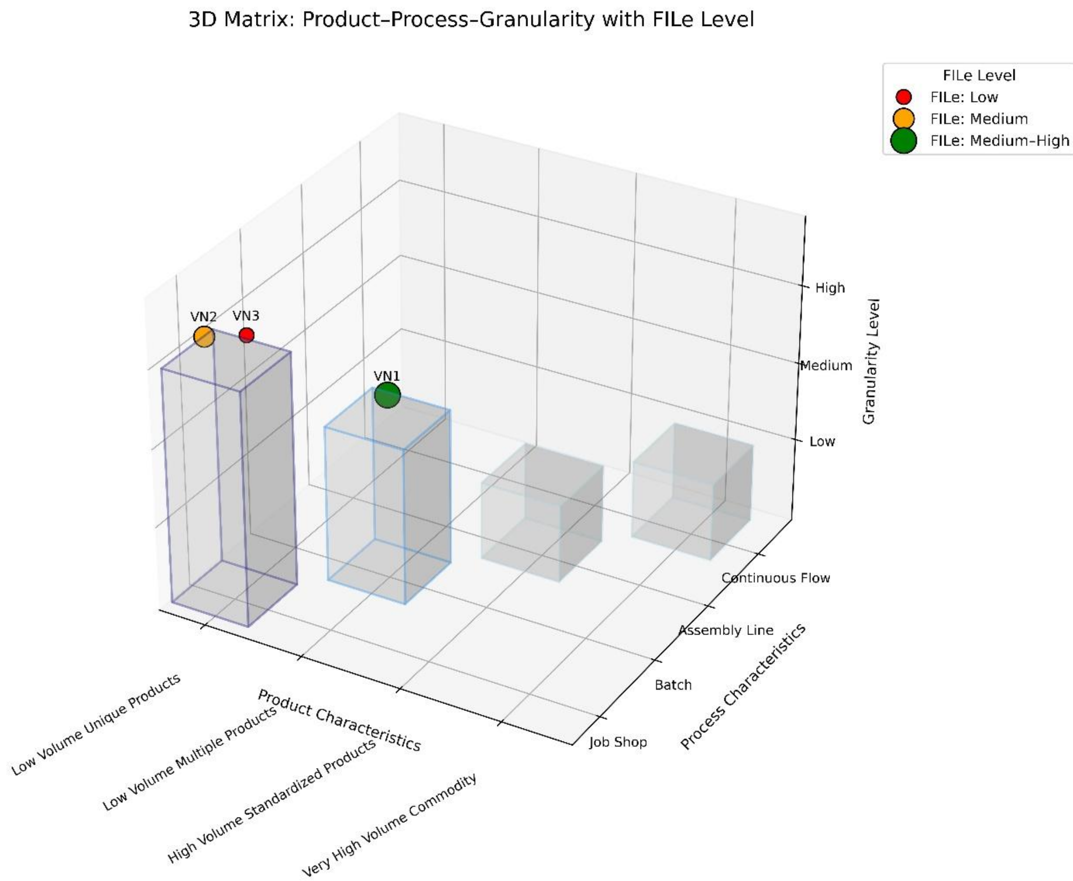

Figure 6 Classification on the 3D Process-Product-Granularity matrix (FILe is color-coded and granularity is represented in the third dimension)

This three-dimensional mapping reveals important structural and organizational distinctions that are not captured in traditional two-dimensional models. By incorporating both granularity and FILe into the matrix, we expose underlying differences that influence how each network should be supported, whether in terms of decision making and planning tools, digital infrastructure, or coordination practices between the actual structural and the DT properties of each network.

6. Validation Roadmap and Quantitative Performance Metrics

The benefits discussed thus far in the context of the paper represent conceptual expectations derived from the conceptual methodological framework rather than empirically verified outcomes. Subsequent actions of both platform and pilots will validate and determine the extent to which these expected advantages materialize in practice. The validation of the T4M methodological approach will follow a three-stage roadmap designed to progressively assess both technical functionality and organizational impact across the pilot implementations. This structured process ensures that the proposed framework can be empirically evaluated in terms of interoperability, efficiency, and resilience outcomes. These aspects are operationalized and quantitatively assessed through indicative KPIs for each stage of verification and validation.

Stage I – Platform-Level Verification

This initial phase focuses on verifying the functional adequacy, interoperability, and internal consistency of the T4M prototype. It will assess whether the platform's modules and data exchange mechanisms operate as intended.

Indicative metrics: Service registration accuracy (% of correctly formatted and interoperable entries), semantic matching precision and recall, and mean service composition time (s)

Stage II – Operational Validation through Pilots

This phase will leverage the three value networks (VN1–VN3) to evaluate the platform's operational performance under realistic manufacturing and coordination scenarios. The emphasis will be on adaptability, coordination efficiency, and resilience under variable demand or disruption.

Indicative metrics: Order fulfillment rate (%), resource utilization ratio (%), lead-time reduction compared to baseline processes, and supplier redundancy index (number of available alternative providers per part/service).

Stage III – Strategic Validation and Ecosystem Impact

The final stage will examine long-term and systemic effects, assessing how T4M supports broader ecosystem resilience, scalability, and sustainability goals. This evaluation will use both quantitative and perception-based metrics.

Indicative metrics: Platform adoption growth (# of active users/providers over time), transaction success ratio (%), stakeholder satisfaction and trust index (survey-based), and reduction in energy consumption or carbon footprint per manufactured unit.

Collectively, these three stages provide a clear and measurable pathway for validating the T4M platform's methodological and operational effectiveness. The proposed metrics establish a foundation for future empirical studies that will trace tangible improvements in flexibility, transparency, and resilience across distributed manufacturing networks.

7. Concluding remarks

7.1 Research contribution

This paper examines the transition from conventional manufacturing to a Manufacturing-as-a-Service (MaaS) paradigm through the development of the Tec4MaaSEs (T4M) platform. T4M aims to enable resilient and flexible production networks by combining Digital Twins (DTs), semantic interoperability, and distributed coordination mechanisms. By supporting dynamic matchmaking between providers and consumers, the platform facilitates negotiation, contract management, and improved utilization of underused resources. The approach is implemented and tested in three representative value networks (VN1: electronic boards, VN2: additive/subtractive manufacturing for mold parts, VN3: hydrogen facility construction), involving eight industrial partners. These pilots were selected to capture diverse challenges in manufacturing composition, coordination intensity, and decision complexity. The analysis of these networks helped identify key requirements, while also revealing the limitations of existing MaaS implementations in addressing granularity and integration heterogeneity. Our study introduced a three-dimensional framework that maps product–process variety, granularity, and Functional Integration Level (FILe), offering a structured basis for specifying platform services. This framework enables targeted analytics support and aligns digital functionality with the informational and operational structure of each network.

The work presented in the context of the current paper apart from practical application contributes to the scientific literature in three ways: Firstly, the Product-Process matrix is enhanced through the concepts of granularity and the Functional Integration Level to better capture the complexity of manufacturing environments. Secondly, a new methodological approach is proposed that operationalizes these concepts in a design for a MaaS platform. Finally, by mapping representative Value Networks across that space, insights emerge as to how this methodological approach could be implemented in practice.

The practical implementation of the T4M methodological approach will face inevitable challenges. Some of these challenges have already been mentioned in the previous sections of the paper and included (but are not limited to) the forthcoming EU Machinery Regulation or Data-Sharing and Privacy considerations. Regarding the EU Machinery Regulation specifically, in order for any MaaS platform to be compliant, it would require traceability, digital documentation and cyber risk assessments to be integral parts of it. Similarly, for data sharing agreements, or potential risk sharing agreements or even interoperability standards among providers and/or consumers of the platform, would require coordinated adaptation and adoption. The proposed T4M approach anticipates such challenges through its governance layer, however their actual (and effective) implementation remains a gradual and context specific process that will be one of the key elements of future iterations of the platform.

7.2 Limitations and further research

While the proposed approach demonstrates practical relevance and technical coherence, several limitations should be acknowledged. First, the pilots were designed as illustrative demonstrators and do not yet cover real-time runtime adaptation and resilience under disruption. Second, the integration of explainable analytics is currently limited to pre- and post-processing phases, and further research is needed to incorporate human-platform interaction mechanisms during live negotiations. Moreover, although the granularity and FILe concepts, are validated qualitatively, they indeed require further quantitative testing across a broader range of industrial domains. Therefore, future research should focus on expanding the scope of implementation across additional sectors (Standard, D., 2008), enhancing the automation of decision support in low-FILe environments, and evaluating long-term performance and sustainability outcomes. Specific extensions of the platform towards collaborative supply planning are also promising directions -for value creation (Li et al. 2024), especially when coupled with emerging semantic standards and regulatory frameworks. Finally, at this stage, the T4M platform is envisaged to incorporate negotiation between providers and consumers. However, additional business schemes such as cost-revenue structures, payment models or risk sharing arrangements are not explicitly in the architecture of the platform. These are essential dimensions that should be studied and added for the next iteration.

Overall, Tec4MaaSEs is an ongoing EU-funded project; the present work lays a solid foundation, towards well-structured user requirements elicitation and a robust MaaS architecture, adaptable to a variety of industrial settings enabling further exploration of collaborative supply planning, deeper automation of decision support, and broader validation across sectors, thus advancing the operationalization of resilient, data-driven value networks.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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