



# From manufacturing-as-a-service to company-as-a-service: a conceptual integration

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Received: 11 March 2026 / Accepted: 11 June 2026  
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## Abstract

Manufacturing-as-a-Service (MaaS) facilitates on-demand access to distributed manufacturing resources and services provided by third parties through platform-based ecosystems. It enables a distributed platform service-oriented production, but despite advances in AI-enabled planning, intelligent matchmaking, optimisation-driven orchestration and cyber-physical integration, the literature remains fragmented. Most studies report isolated decision layers (process planning, supplier selection, scheduling, pricing or trust) without proposing lifecycle-integrated architectures. A PRISMA 2020-compliant systematic review was conducted on 62 MaaS studies published between 2013 and 2026 to examine how intelligent manufacturing platforms are implemented and which decision functions they support. This paper analyses the literature identifying: (i) an archetype classification of MaaS solutions, from conceptual frameworks to trust infrastructures; (ii) a granularity-based input–output taxonomy that maps information units to intelligent decisions; and (iii) a limitation analysis highlighting barriers in data readiness, interoperability, governance and real-time orchestration under uncertainty. Findings show persistent silos across engineering intelligence, marketplace design, operational optimisation and governance mechanisms. Building on this evidence, the Company-as-a-Service concept is proposed as an extension that integrates MaaS modules into lifecycle-consistent organisational capabilities, coordinated through a “Digital Thread and Governance Kernel”. This paper designs principles for scalable, governance-aware, AI-enabled manufacturing ecosystems. Implications are discussed for platform developers and manufacturers seeking resilient, compliant deployment across SMEs, multi-site networks, and heterogeneous equipment fleets worldwide.

**Keywords** Intelligent Manufacturing Platforms · Distributed Production Systems · Artificial Intelligence in Manufacturing

## Introduction

Manufacturing companies increasingly compete not only on product performance, but also on rapid delivery, customisation, quality, cost efficiency, and the sustainability of products and processes. Achieving these objectives simultaneously often requires specialised capabilities and advanced technologies (Ivkić et al., 2024, 2025) (like additive manufacturing, specialist processes, digital systems) that many companies, especially Small and Medium Enterprises (SMEs), cannot economically develop in-house. In parallel, the digitalisation of manufacturing has enabled

“service-oriented business models” that externalise production capabilities and decision support through platform-based ecosystems.

Within this context, Manufacturing-as-a-Service (MaaS) refers to the on-demand access to manufacturing resources, skills, and production services through digital platforms that connect supply and demand. Rather than vertically integrating all resources, companies can source specific capabilities (processes, equipment, expertise) as modular services, potentially reducing investment barriers and increasing operational flexibility (Corti et al., 2021). The MaaS literature has expanded rapidly in recent years, spanning platform architectures, service discovery and matchmaking models, orchestration and scheduling methods, market mechanisms (pricing, auctions, and contracts), and solutions addressing trust, data governance, and sustainability (Tedaldi & Miragliotta, 2021). However, this wide range also makes a systematic comparison difficult. Proposed solutions frequently differ in abstraction level

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(conceptual frameworks vs. operational implementations), technological assumptions, required inputs (data, constraints, capability models), and delivered outputs (matchmaking, plans/schedules, market outcomes, sustainability indicators). Moreover, many contributions are developed and validated in sector-specific contexts (such as additive manufacturing, precision machining, or digital supply chains), making their transferability to other industrial domains unclear.

To address this gap, this paper presents a systematic literature review aimed at characterising how MaaS platforms and frameworks are implemented and which functions they support; clarifying the input information required by MaaS solutions and the outputs they generate; and synthesising the main limitations reported in the literature, highlighting sectoral differences. Accordingly, the review is guided by the following research questions:

- RQ1. How are MaaS platforms or frameworks described in the literature (types, abstraction levels, supported functions)?
- RQ2. What inputs do they require and what outputs do they provide (e.g., matchmaking, planning, scheduling, pricing, contract decisions, sustainability/resilience indicators, KPIs)?
- RQ3. What limitations are reported for MaaS solutions, and how do these vary by sector (e.g., data availability, interoperability, trust, process complexity, real-time requirements, standards/certifications)?

Building on the evidence emerging from the three research questions, the paper further discusses an implication that becomes visible in the reviewed landscape: MaaS research already covers many functions typically performed within a manufacturing firm (engineering enablement, sourcing/contracting, orchestration, and cyber-physical assurance), but these functions appear fragmented across different MaaS solution families. This motivates Company-as-a-Service (CaaS) as a conceptual extension: a firm-level operating model that composes external, platform-mediated services across the lifecycle rather than owning and vertically integrating the full production system. In this framing, the contribution of the paper is twofold: it provides a structured synthesis of MaaS research through archetypes, input–output mappings, and a limitation taxonomy; and it uses these findings to position CaaS as an explanatory lens and design hypothesis for lifecycle-integrated, governance-aware service-based manufacturing enterprises.

## Background

A systematic literature review was conducted following the PRISMA 2020 guidelines to synthesise heterogeneous MaaS research and to address RQ1–RQ3. In February 2026,

a search was performed in Scopus using the query: ‘manufacturing as a service’ AND (“platform” OR ‘servitisation’) applied in search fields “TITLE-ABS-KEY” considering only the paper wrote in English. The search was restricted to Scopus using a query focused on service-oriented manufacturing keywords, which may have excluded relevant contributions indexed in other databases (e.g., Web of Science) or available as preprints and industry white papers. Broader search terms such as cloud manufacturing, distributed production, or shared manufacturing were partially captured through indexed keywords but were not explicitly included in the query string. These choices prioritise precision over recall and represent a methodological limitation that future reviews should address through multi-database searches and systematic inclusion of grey literature.

Titles and abstracts were screened, and full texts were then assessed: studies were included if they described a MaaS platform/framework or an operational MaaS component and reported sufficient information to identify inputs and/or outputs (decision results). All 62 studies met the criteria and were included in the synthesis. The results cover the period from 2013 to 2026, with relative peaks in 2019 (~10% of documents), 2021 (~15.7% of documents) and 2025 (~23% of documents) and it covers also various sectors, including Engineering (34.1%), Computer Science (24.8%), Decision Science and Business and Management (14.0% and 10.9% respectively). These aspects highlight how this area of research is an emerging topic that has grown exponentially over the last seven years, thanks in part to new emerging technologies such as digitalisation, Industry 4.0 and 5.0 paradigms, as well as machine learning and artificial intelligence.

In addition, this research shows us that interest is not only linked to the manufacturing sector but that, starting from that sector, it is developing in an interdisciplinary manner, also involving less obvious areas such as Decision Science and Business/Management, which account for a total of 1/4 of scientific production. The selected contributions highlight a marked heterogeneity in the use, application and purpose of MaaS platforms, confirming that the paradigm does not converge towards a single standard implementation, but rather takes the form of solutions covering different parts of the “design-sourcing-execution-governance” chain which characterises Product Life-cycle Management (PLM) and generally involves a traditional manufacturing company.

### RQ1: Platforms and frameworks for MaaS

The MaaS literature exhibits substantial heterogeneity in how the paradigm is implemented. Platforms and frameworks differ in abstraction level, functional objectives, enabling technologies, and supported decision functions. To organise this diversity and to answer RQ1, a keyword

frequency was extracted from Scopus author keywords and indexed keywords. Keywords were manually normalised (merging variants, acronyms, synonyms), and then grouped to reflect recurring MaaS functions: conceptual framing, capability and process planning, marketplace/discovery and market design, operational orchestration and trust-data-sustainability.

Archetypes (A0-A4) are thematic groupings derived from normalised Scopus keywords, representing recurring functional categories that classify MaaS platforms/frameworks by dominant contribution. Aligned with keyword co-occurrence patterns, they span from conceptual framing to operational orchestration and trust/sustainability infrastructure. A sub-archetype A2.1 captures marketplace solutions explicitly modelled as economic systems governed by pricing, auctions, contracts, or game-theoretic mechanisms. To assess the robustness of the archetype classification, the archetype classification process was distributed among co-authors, each independently analysing a different dimension of the corpus: keyword normalisation, input identification, and input–output correlation mapping. The resulting classifications were then compared and discussed collectively, and disagreements were resolved through structured consensus. This multi-perspective procedure confirms that the five-category structure (A0-A4) reflects systematic patterns emerging from the literature rather than arbitrary grouping choices, as the independent analyses converged consistently toward the same dominant archetypes reported in Table 1.

In particular, A0 archetype brings together works that define conceptual models, theoretical frameworks or maturity analyses of MaaS. The most recent literature, e.g. (Andersen et al., 2025), proposes systematic methodologies for the servitisation of processes divided into phases (mapping, matching, collaboration). Other works (Tao & Qi, 2019) build the architectural basis of the service-oriented paradigm, defining the relationships between physical resources, digital capabilities and cloud services. Reviews on shared manufacturing consolidate the vision of MaaS as an “umbrella concept” for collaborative paradigms (cloud, distributed, social), highlighting the lack of end-to-end orchestration models. Overall, archetype A0 identifies works that frame MaaS as an enabling organisational and technological model rather than as an implemented platform.

A1 includes work that links MaaS to the digitalisation of process design and planning. In particular the set of works classified with A1 includes MaaS platforms as an engineering-oriented infrastructure, where the focus is on transforming project information into process knowledge and executable capabilities. Key examples are (J. Wang et al., 2017) models, which integrate resources and knowledge in a cloud environment, and data-driven approaches that learn precedence relationships between operations using Convolutional Recurrent Neural Networks (ConvRNN) (Yan

et al., 2025), removing the need for manual rules. In these cases, the dominant information unit that must be provided as input to these platforms is a *part* or *step* file (described as “PART”) representing a prototyped piece or CAD, and the typical output is a plan, routing or sequence of operations (“PLAN” Sect. 2.2.2.) that can potentially be integrated with subsequent allocation decisions. The common goal is to make the design and planning phases an integral part of the service, creating a continuous flow from CAD to production capabilities accessible on the platform. The A1 archetype therefore represents the level at which MaaS becomes a technical tool for configuring and production capabilities.

A2 includes works related to the economic and operational application of MaaS as a digital marketplace. It is a numerically significant group that interprets MaaS as a multi-sided ecosystem and as a “meeting point” between industrial players, in which the platform enables the discovery and selection of suppliers/services and the sharing of production capacity. Contributions in this category describe platforms that facilitate the search, evaluation and selection of suppliers or resources (e.g. Bettoni et al., 2018; Tedaldi & Miragliotta, 2023)). Multi-sided platforms allow the publication and booking of production capacity, often with crowdsourced manufacturing or capacity sharing functions. Recent solutions adopt Artificial Intelligence (AI) and Federated Learning (FL) for automatic matchmaking, preserving the ownership of supplier data. A2 represents MaaS as an ecosystem of discovery and connection, in which the platform mediates between supply and demand. Considering this archetype, it is possible to distinguish a specific second sub-archetype, A2.1, that involves mainly the Additive Manufacturing as a Service (AMaaS) sector that is related to the market design (pricing, auctions, contracts, games). It concerns works that treat MaaS as a market regulated by economic mechanisms. The proposed sub-archetype includes reverse auction mechanisms for the purchase of prototyping services (3D printing); game theory models (Hotelling, Stackelberg) for optimal pricing in MaaS marketplaces (Chen et al., 2024; Gong et al., 2024); simulations to assess the impact of different pricing policies and incentives (Chaudhuri et al., 2021). These frameworks consider the platform as a strategic actor that mediates economic interaction between customers and suppliers, optimising profits and market equilibrium. This area includes proposals for architectures for the exchange of unused capacity (Landolfi et al., 2019) and the co-creation of value (e.g. MANU-SQUARE and its conceptual/architectural extensions) (Bettoni et al., 2018), as well as empirical studies analysing real platforms and their deployment models (open vs closed) to characterise how MaaS is implemented today (Tedaldi & Miragliotta, 2023). At the same time, literature on crowdsourced manufacturing further extends this vision by showing cyber platforms that orchestrate distributed supply and demand and introduce decision

**Table 1** Literature results classification – archetypes, input, output

| Archetype                                                                                                                                                           | Archetype keywords                                                                                                                                                                                                                                                                                      | N#                               | Paper keywords                                                                                                                        | Input             | Output  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|-------------------|---------|
| A0 Conceptual/framework/review/<br>maturity-conceptual/methodological<br>level: definitions, taxonomies, refer-<br>ence frameworks, maturity analysis<br>and review | Manufacturing-as-a-Service (MaaS);<br>Cloud manufacturing; Supply Chains;<br>Industry 4.0; Servitization; Smart<br>manufacturing; Business Models;<br>Ecosystems; Industrial Research;<br>Ontology; Manufacturing Sector;<br>Network Architecture; Platform<br>Economy; Manufacturing Is; Case<br>study | (Duran et al., 2025)             | manufacturing as a service; Manufac-<br>turing systems; planning; scheduling;<br>shared manufacturing                                 | Literature review | FW/EVAL |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Mourtzis et al., 2020)          | B2B; e-marketplaces; IPSS; Supply<br>chain management                                                                                 | MKT/PLAT          | FW      |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Torrecilla-García et al., 2023) | Business model innovation; Case study;<br>IoT; MaaS; Servitization                                                                    | ORG               | FW/EVAL |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Eslami et al., 2025)            | Changeability; Flexibility; Manufactur-<br>ing as a Service; Production Systems;<br>Servitisation                                     |                   | FW      |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Naldi et al., 2026)             | maas; manufacturing-as-a-service;<br>platform economy; service-oriented<br>architecture; Servitization                                | ORG/PLAT          |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Pezzotta et al., 2026)          | Industry 4.0; Manufacturing-as-a-<br>Service; Servitization; Survey                                                                   |                   |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Beducci et al., 2026)           | Cloud Manufacturing; Digitalization;<br>Manufacturing-as-a-Service (MaaS);<br>Servitization                                           |                   | EVAL    |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Assef et al., 2026)             | Bibliometric Assessment; Cloud<br>Computing; Cloud Manufacturing;<br>Manufacturing as a Service; Software<br>as a Service             | PLAT              | FW      |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Jiao et al., 2024)              | -                                                                                                                                     |                   |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Ivkić et al., 2024)             | 3D Printer; Additive Manufacturing;<br>Cloud Platform; Cost–Benefit Analy-<br>sis; Manufacturing as a Service                         |                   |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (G. Zhang et al., 2023)          | -                                                                                                                                     |                   |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Gong et al., 2021a)             | Crowdsourcing; Crowdsourcing con-<br>tracting; Industry 4.0; Manufacturing<br>as a service; Open manufacturing;<br>Platform economics |                   |         |
|                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         | (Gong et al., 2021b)             | Crowdsourced manufacturing; Crowd-<br>sourcing contracting; Industry 4.0;<br>Manufacturing as a service; Open<br>manufacturing        |                   |         |

Table 1 (continued)

| Archetype | Archetype keywords | N#                            | Paper keywords                                                                                                              | Input    | Output  |
|-----------|--------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------|----------|---------|
|           |                    | (Corti et al., 2021)          | B2B platform; Capacity sharing; Manufacturing as a Service; Platform design; Requirements analysis; Value definition        |          |         |
|           |                    | (Silva et al., 2019)          | Digital platform architecture; Digital platforms; Manufacturing as a service                                                |          |         |
|           |                    | (Tao & Qi, 2019)              | Big data; cloud computing; cyber-physical integration; Internet of Things (IoT); manufacturing service; smart manufacturing |          |         |
|           |                    | (Bettoni et al., 2018)        | digital platform; manufacturing as a service; multi-sided business models; resource-efficiency; servitisation               |          |         |
|           |                    | (Ivkić et al., 2025)          | Additive Manufacturing; Cloud Crafting Platform; Cost–Benefit Analysis; Manufacturing as a Service                          |          | EVAL/FW |
|           |                    | (Seródio et al., 2024)        | CPS; Industry 4.0; SOA; Supply Chain 4.0; TMS                                                                               |          |         |
|           |                    | (Tedaldi & Miragliotta, 2023) | Manufacturing-as-a-Service (MaaS), Platform economy, Cloud manufacturing, Industry 4.0                                      |          | EVAL    |
|           |                    | (Tedaldi & Miragliotta, 2021) | Cloud Manufacturing; Industry 4.0; Manufacturing-as-a-Service (MaaS); Platform Economy                                      |          |         |
|           |                    | (Lerch & Heimberger, 2022)    | Digital manufacturing platform; digital service business models; Industry 4.0; platform economy; platformisation            |          | TAX     |
|           |                    | (Kaparis et al., 2025)        | digital twins; explainable AI; functional integration; granularity; Manufacturing-as-a-service; resilient value networks    | PLAT/NET | FW      |
|           |                    | (G. Zhang et al., 2022)       | Cloud; Cloud manufacturing; Digital twins; Platforms; Supply chain                                                          | SC       | FW      |
|           |                    | (Ellwein et al., 2023)        | Cloud Manufacturing; Control; Enterprise Resource Planning; Peer-to-Peer-Manufacturing; Production Planning                 | SC/ORG   | EVAL    |

Table 1 (continued)

| Archetype                                                                                                                                                                                     | Archetype keywords                                                                                                                                                                                                                                      | N#                            | Paper keywords                                                                                                                                                                       | Input      | Output     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|
| A1 From CAD to capabilities/process planning/configurators –Engineering level: transformation of requirements and product/process models into manufacturing capabilities and executable plans | Manufacture; Computer Aided Manufacturing (CAM); Manufacturing Process; Manufacturing Capability; Manufacturing Resource; 3D printer(s)/ modelling; Design; Fabrication; Flexible Manufacturing Systems; Machine Design; Advanced/Analytical Technology | (Andersen et al., 2025)       | Manufacturing-as-a-service, Resilience, Circular Economy, Servitization, Manufacturing System, Value Chain, Manufacturing Network                                                    | SC/PLAT    | FW         |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Gong et al., 2025)           | crowdsourcing; manufacturing-as-a-service; open manufacturing; platform economics; smart manufacturing                                                                               |            |            |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Tessaro et al., 2021)        | Industrial robots; Manufacturing as a service; Model predictive control; Process technology; System identification                                                                   | EQP        | CTRL       |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (J. Wang et al., 2017)        | Cloud Manufacturing; Information integration; Information Modeling; Machining Process; Machining process planning; Process knowledge; Resource service; SaaS (software as a service) | PART       | PLAN       |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Yip et al., 2013)            | Cloud manufacturing; Manufacturing service; Product configuration                                                                                                                    |            | MLA /PLAN  |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Yan et al., 2025)            | Convolutional neural network; Manufacturing operations sequencing; Process planning; Recurrent neural network                                                                        |            |            |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Kladovasilakis et al., 2025) | Customized Blades; Finite Element Analysis; Machine learning; Manufacturing-as-a-Service                                                                                             |            | PLAN/MATCH |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Yip et al., 2014)            | Architecture; Customisation; Manufacturing capability; Manufacturing service; Service description                                                                                    |            |            |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         | (Babiceanu & Seker, 2020)     | Artificial intelligence and machine learning; Cloud services; Manufacturing as a service; Product design selection                                                                   | ORDER/PART | MLA/PLAN   |
|                                                                                                                                                                                               |                                                                                                                                                                                                                                                         |                               |                                                                                                                                                                                      |            |            |

Table 1 (continued)

| Archetype                                                                                                                                   | Archetype keywords                                                                                                                                                                      | N#                       | Paper keywords                                                                                                                                                                        | Input     | Output     |
|---------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------------|
| A2 Marketplace/discovery/matchmaking–Market level: discovery, selection and connection between supply and demand for manufacturing services | Manufacturing Service; Crowdsourcing; Commerce /Sales; Digital Platforms; Service Platforms; (Open) Platforms; On-demand; Manufacturing Companies; Open Manufacturing; Service Industry | (Lentes et al., 2025)    | MaaS; Manufacturing Network Planning; Manufacturing-as-a-Service; Ontology-Based Matchmaking; Ontology-Based Systems; Resilient Manufacturing Systems                                 | MKT/PLAT  | MATCH      |
|                                                                                                                                             |                                                                                                                                                                                         | (Vathoopan et al., 2025) | Automated assessment; Circularity and Sustainability; Manufacturing-as-a-Service; Ontology-driven Simulations                                                                         |           |            |
|                                                                                                                                             |                                                                                                                                                                                         | (Simon et al., 2025)     | Capabilities; Manufacturing as a Service; Services; Shared Manufacturing; Skills                                                                                                      | NET       |            |
|                                                                                                                                             |                                                                                                                                                                                         | (Chan et al., 2024)      | Capabilities for manufacturing; Current engineering; Digital business ecosystem; Manufacturing as a service                                                                           | PART/PLAT | MATCH/EVAL |
| A2.1 Market design: pricing, auctions, contracts, games, incentives, contracts, etc                                                         | Cost–benefit analysis; Costs; Investments; Mechanism Design; Profitability; Smart Contracts; Game Theory; Budget Control                                                                | (Gong et al., 2024)      | Bilevel optimization; Crowdsourcing; Game theory; Manufacturing-as-a-service; Production planning; Task decomposition                                                                 | ORDER/MKT | MECH/SCHED |
|                                                                                                                                             |                                                                                                                                                                                         | (Chen et al., 2024)      | Industrial internet platform; Manufacturing-as-a-service; Multi-objective optimization; Stackelberg game; Task-service matching                                                       | MKT       |            |
|                                                                                                                                             |                                                                                                                                                                                         | (Pahwa & Starly, 2021)   | Cloud based design and manufacturing (CBD); Cloud manufacturing; Cyber-enabled manufacturing; Dynamic and stochastic knapsack problem (DSKP); Resource allocation; Two-sided matching |           | MLA /MECH  |
|                                                                                                                                             |                                                                                                                                                                                         | (Pahwa et al., 2023)     | Cloud Manufacturing; Mathematical Programming; Mechanism Design; Sharing Economy Marketplaces; Stable Matching                                                                        |           | MECH/MATCH |
|                                                                                                                                             |                                                                                                                                                                                         | (Sparr et al., 2021)     | Auction-based production planning; Cloud manufacturing; Manufacturing-as-a-Service; Ontologies                                                                                        |           |            |
|                                                                                                                                             |                                                                                                                                                                                         | (Pahwa et al., 2018)     | Distributed manufacturing; Mechanism design; Name Your Own Price; Reverse auction                                                                                                     |           | MECH       |
|                                                                                                                                             |                                                                                                                                                                                         | (Chaudhuri et al., 2021) | Competition; Manufacturing as a service (MaaS); Optimal pricing; Platforms; Spatial market                                                                                            |           |            |

**Table 1** (continued)

| Archetype                                                                                                                                                                                                             | Archetype keywords                                                                                                                                                                                      | N#                            | Paper keywords                                                                                                                                                 | Input      | Output     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|
| A3 Orchestration/scheduling/operational optimisation – operational level: resource allocation, planning, scheduling and execution decisions                                                                           | Bilevel optimization; Decision Making; (Chaos) Capacity Balancing/ Sharing and Optimisation (Algorithms); (Auction-based) Production Planning; Scheduling and Scheduling Algorithms; Production Control | (Wu et al., 2019)             | -                                                                                                                                                              | MKT/PLAT   | SCHED      |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Hu et al., 2019)             | AHP; Chaos optimization algorithm; Cloud manufacturing; Manufacturer; Scheduling                                                                               | ORDER/MKT  |            |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Duran-Mateluna et al., 2025) | Manufacturing-as-a-Service; Scheduling Problem; Task-machine eligibility; Tripartite decision perspective                                                      |            |            |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Lagos et al., 2026)          | Constraint Programming; Flow shop scheduling; Manufacturing-as-a-Service; Mixed Integer Linear Programming                                                     | ORDER/NET  |            |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Liu et al., 2022)            | bilevel optimization; linear physical programming; low-carbon product family planning; manufacturer loading balancing; manufacturing as a service              | PART/ORDER |            |
| A4 Trust-Data-Sustainability – infrastructure and governance level: security, data sovereignty, interoperability, blockchain, Federated Learning (FL), digital twin, edge-cloud and sustainability/resilience metrics | Cloud computing; Internet of Things (IoT); Information; Systems/Use; Digital Storage; Machine Learning; Blockchain; Sustainable; Development; Platform as a Service (PaaS)                              | (Bardas et al., 2025)         | Disruption sensing; Edge intelligence; Explainable AI; Human-AI collaboration; Supply chain resilience; Trusted industrial data                                | SC         | CTRL/MLA   |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Yan et al., 2024)            | Cyber manufacturing as-a-service; Federated learning; Unsupervised deep learning                                                                               | MKT/TRUST  | MLA /MATCH |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (K. Wang et al., 2022)        | open-source; real-time analysis; sensor fusion; smart manufacturing                                                                                            | EQP        | CTRL       |
|                                                                                                                                                                                                                       |                                                                                                                                                                                                         | (Marra et al., 2024)          | Digital Twins-as-a-service (DTaaS); Equipment as a Service (EaaS); Informative Digital Twin; Leasing; Manufacturing as a Service (MaaS); Novel Business Models | EQP/PLAT   | CTRL/FW    |

Table 1 (continued)

| Archetype | Archetype keywords | N#                      | Paper keywords                                                                                                                  | Input | Output     |
|-----------|--------------------|-------------------------|---------------------------------------------------------------------------------------------------------------------------------|-------|------------|
|           |                    | (Hasan & Starly, 2020)  | Blockchain; Cloud manufacturing; Cybermanufacturing; Distributed digital thread; Smart contracts                                | PLAT  | TRUST      |
|           |                    | (Potluri et al., 2021)  | Cloud Computing; Cloud Manufacturing; Cloud Privacy; Cloud Security; Encryption; Internet of Things; Manufacturing as a Service |       |            |
|           |                    | (Hasan et al., 2021)    | Blockchain; Distributed database; Gas price prediction; Lstm; Regression; Smart contracts; Time series                          |       | TRUST/MLA  |
|           |                    | (Landolfi et al., 2019) | Industrial Data Space; Manufacturing as a service; Sustainable manufacturing                                                    |       | TRUST/EVAL |
|           |                    | (Sofia et al., 2023)    | Federated platform; IIoT; MaaS; Machine learning; SDK                                                                           |       | TRUST/FW   |

support components. An explicit example is the application case related to orthodontics and additive manufacturing, used to discuss the operational implications and delivery challenges of MaaS in crowd-based production networks (Gong et al., 2021a, 2021b).

In these solutions, the dominant unit is the platform (defined as “PLAT”) where users can upload their task orders (ORDER) to be executed by other service providers identified on the platform through a marketplace (MKT) where supply and demand meet, and the main output is a match between the parties (MATCH, discovery/matchmaking), possibly enriched by multi-criteria ranking.

A3 is related to scheduling and operational optimisation tasks. In fact, alongside these “market” variations, several studies shift the focus to the execution phase, proposing MaaS platforms as tools for orchestration and operational optimisation. Here, the platform is not limited to selecting the provider, but supports allocation and scheduling decisions (Gallo et al., 2026) in multi-actor, multi-objective and dynamic contexts. The papers related to this archetype focus on the execution phase of MaaS, like the allocation and planning of resources after matchmaking. Numerous contributions propose multi-objective or bilevel optimisation models (Chen et al., 2024), (Liu et al., 2022) and Deep Reinforcement Learning (DRL) approaches for dynamic matching (Pahwa et al., 2023) and adaptive scheduling. These platforms provide decision-making and operational outputs: production plans, optimal assignments, execution times and costs. The A3 archetype therefore, defines MaaS as an intelligent orchestration system that coordinates planning and control decisions in distributed environments.

Representative examples include models formulated as Stackelberg games or bilevel optimisations to coordinate the platform and servicer in task management, with validations on industrial cases (e.g. the “tank trailer” case in crowdsourced/shared manufacturing contexts) (Chen et al., 2024; Gong et al., 2024). Complementarily, some studies explicitly address matching as a dynamic problem and propose data-driven approaches to improve real-time decisions in two-sided marketplaces (Pahwa & Starly, 2021; Pahwa et al., 2023). These solutions take in input orders (ORDER in Sect. 2.2.1.) with constraints, priorities, times, and return schedules (SCHED in Sect. 2.2.2.) in outputs with plans, allocations, times/costs, sometimes applying Machine Learning (ML) components.

A4, the last archetype, includes platforms and architectures focused on trust, security, data management and sustainability. In fact, in the literature, there is a trend that sees MaaS platforms as enabling infrastructures for addressing systemic issues related to trust, data governance, sustainability and resilience (Sidorenko et al., 2026). From this perspective, some architectures integrate data sovereignty and environmental assessment mechanisms (e.g. through Life

Cycle Assessment engines and connectors for controlled data exchange management) (Landolfi et al., 2019), while others extend MaaS through Digital Twin (DT) towards Digital Twin as a Service (DTaaS) and Equipment-as-a-Service (EaaS) models, including ex-ante assessment, monitoring and control support in industrial applications (Marra et al., 2024). At the same time, the literature on shared manufacturing and supply chains highlights that MaaS platforms can act as hubs for coordinating and reconfiguring production networks, especially in the event of disruption, but also emphasises the persistence of gaps in end-to-end integration and holistic planning (Andersen et al., 2025; Duran et al., 2025).

Emblematic examples are blockchain-based architectures for traceability and data provenance; hybrid solutions, like Ethereum with BigchainDB, to improve scalability and transparency; data-sovereign platforms integrated with International Data Spaces to guarantee data ownership (Landolfi et al., 2019); Digital Twin-based systems to extend MaaS towards DTaaS/EaaS models; Artificial Intelligence and XAI frameworks for early detection of disruption and sustainable supply chain resilience. Archetype A4 highlights the evolution of MaaS towards a data-centric and sustainable paradigm, where interoperability, security and environmental responsibility become central dimensions of the service.

In the end, archetypes are not mutually exclusive (many studies span multiple functions), but the classification captures the dominant contribution of each work and enables systematic comparison along a continuum from conceptual frameworks to operational, data-driven decision models.

Each type (A0–A4) of MaaS corresponds to a progressive level of abstraction from the most to the least: A0 identifies definition/method, A1 capability engineering, A2 supply–demand matching platform and economic mechanisms (in sub-archetype A2.1), A3 operational orchestration, A4 trust and sustainability infrastructure. The detailed classification is provided in the Table 1, where the predominant or most frequently reported archetype is assigned for each paper analysed in the literature. Starting from these archetypes and the level of abstraction reported in the papers on MaaS, the literature review continues with a study of the most common inputs and outputs.

## RQ2: What inputs do MaaS solutions require and what outputs do they provide?

Following the archetype classification (A0–A4) in Table 1, the analysis conducted in response to RQ2 examines MaaS inputs/outputs, revealing variability linked to the level of granularity of the problem addressed. Granularity denotes the level of detail at which a MaaS system operates, spanning three logical scales: micro (fine: individual components), meso (intermediate: tasks/market interactions), macro (coarse: networks/organisations). This determines input

complexity and output operability: micro demands precise proprietary data for atomic actions; meso processes operational tasks for multi-actor decisions; macro aggregates strategic constraints for governance. This classification reflects a natural progression from the technical specification of a single production artefact to systemic network or organisational dynamics. This granularity determines both the complexity of the inputs required and the operational nature of the outputs generated: at the micro level, the focus is on atomic details such as geometry and tolerances, requiring proprietary and computationally intensive data for executive outputs; at the meso level, on operational tasks and marketplace interactions for dynamic multi-actor decisions; at the macro level, on systemic aggregates for strategic assessments and governance. As solutions evolve from conceptual approaches to fully operational platforms, inputs become progressively richer and more complex, requiring not only declarative data but also real-time operational information, while outputs shift from descriptive and enabling assessments to directly executable decisions; this progression, however, brings to light the limitations of end-to-end integration, which will be explored in the next chapter.

The inputs required by MaaS solutions vary systematically according to the unit of analysis adopted and the level of granularity, reflecting different infrastructure assumptions and functional objectives. At the micro level (fine granularity), technical descriptions from PART or CAD dominate and include 3D geometry, materials, tolerances, manufacturing features (e.g., holes, pockets), quality/surface requirements (Yan et al., 2025) and often *step* or *part* files, which are central to capability engineering and process planning (archetype A1), where the platform transforms product specifications into executable process knowledge (PLAN) (Kladovasilakis et al., 2025), often integrating data-driven extractions of rules such as operational precedence learned (Chen et al., 2024; Sparr et al., 2021) through models such as ConvRNN. Here, the platform acts as a digital extension of CAD, reducing dependence on manual experts, but requires proprietary and computationally intensive data.

Moving to the meso level (intermediate granularity), ORDERS or operational tasks prevail: quantities to be produced, deadlines, priorities, logistical constraints (like delivery times, setup, ...), multi-criteria objectives (cost, quality, CO<sub>2</sub> emission, reliability) and supplier profiles (capacity, lead time) (Wu et al., 2019), often combined with MKT/PLAT with auction/pricing (Chaudhuri et al., 2021) rules or access policies. This meso-scale, typical of A2–A3, assumes that the part or process is already defined or abstracted, primarily feeding marketplaces for discovery and matching, or for operational orchestration.

At the macro level (coarse granularity), inputs are amplified to NET/SC with aggregate capacities, sourcing alternatives (Simon et al., 2025), network nodes, constraints,

**Table 2** Input–output analysis

| Input Unit | Granularity | Category             | Output frequency*                          |
|------------|-------------|----------------------|--------------------------------------------|
| PART       | Micro       | Technical/production | PLAN (75%), MLA (37.5%), MATCH (12.5%)     |
| EQP        | Micro       | Technical/production | CTRL (100%)                                |
| ORDER      | Meso        | Operational          | SCHED (83.3%), MATCH (50%), MECH (25%)     |
| MKT        | Meso        | Economic/contractual | MECH (42.8%), MATCH (35.7%), SCHED (35.7%) |
| PLAT       | Meso        | Data/IT              | FW/TAX (66.7%), EVAL (18.2%), TRUST (15%)  |
| NET        | Macro       | Data/IT              | FW (50%), SCHED (25%), MATCH (25%)         |
| SC         | Macro       | Sustainability/Risk  | FW/TAX (60%), EVAL (20%), MLA (20%)        |
| ORG        | Macro       | Organisational       | EVAL (60%), FW (40%)                       |

\* (%n of paper with this output/all the paper classified with that input)

disruption risks (Bardas et al., 2025), external indicators and resilience or circularity objectives; another macro input is EQP, which includes IoT sensory data, machine status, control parameters (K. Wang et al., 2022), and Digital Twin models (Marra et al., 2024); the last macro input ORG involves non-technical factors such as digital maturity, business objectives, barriers, and strategic governance, driving adoption analysis for A0/A4.

Inputs can be further grouped into five interconnected logical categories, each associated with empirical correlations emerging from the literature (summarised in Table 2, organised by granularity and type): technical-production (PART/EQP: machine-material compatibility, features, process parameters for producibility checks); operational (ORDER: execution constraints such as quantity, timing, priority, resource availability for dynamic scheduling (Duran-Mateluna et al., 2025), and KPIs such as lateness or utilisation); economic-contractual (MKT/PLAT: costs, pricing rules, incentives, auctions, platform policies for market equilibrium (Wu et al., 2019)); data/IT (PLAT/NET: standards, APIs, ontologies, digital identities, sharing policies for interoperability and credible exchanges); sustainability/risk (SC/NET: emissions/LCA, green targets, disruption indicators for multi-objective optimisation and network governance (Potluri et al., 2021)). This mapping not only explains why many proposals are not directly comparable as they depend on the granularity, quality and availability of inputs, but also highlights a hierarchical dependency: operational archetypes, such as A3, require reliable constraints and real-time availability, while A4 (trust/sustainability) requires data governance infrastructures (Potluri et al., 2021), which are often absent in practice and limit scalability.

These analysed inputs produce different outputs: concrete results or post-processing artefacts, classified as actionable decisions (directly executable), enabling artefacts (structural prerequisites) and cross-cutting components (predictive support). The outputs most commonly identified in the literature are PLAN (Process Planning: operational sequences/routing from CAD), MATCH (Supplier Matching: supplier ranking), SCHED (Scheduling: allocations/balancing), CTRL

(real-time Control on DT), FW (reference FrameWorks/roadmaps), TAX (conceptual TAXonomies), EVAL (KPI EVALuations/benchmarks), TRUST (data governance via blockchain), MECH (market MECHANisms: pricing/auctions), MLA (Machine Learning Artefacts: learned rules/predictions).

They can be grouped into three main types, with specific examples taken from literature: *actionable decisions*, outputs that generate concrete actions, determining what, how and when to produce and are directly executable outputs; *enabling artefacts*, outputs that prepare the ground without making a direct decision and represent mainly the structural prerequisites; *cross-cutting components*, outputs that influence other decisions or learn from the system realising a predictive/decision support.

In the first group, the actionable decision, includes output like PLAN, the sequence of action obtained from the translation of a CAD, routing or alternative setup; MATCH, the selection of compatible suppliers according to a multi-criteria ranking (that could involve cost, quality, time, CO<sub>2</sub>); SCHED, the scheduling of the activities to allocate resources, balances the load and optimise the production; CTRL, real-time commands on machines, Digital Twin set-points or closed-loop adjustments derived from monitor of the system. All these actionable decisions go directly into production.

The second group, the enabling artefacts, includes reference architectures, maturity models, and servitisation roadmaps that can be defined under the framework (FW) or taxonomy (TAX) concepts. In the enabling artefacts, the KPI assessments, cost–benefit analysis, and platform benchmarks are also included as “EVAL”. TRUST is the last enabling output that preserves the integrity and sovereignty of data, privacy and digital identity using blockchain. In the Cross-cutting components, instead the outputs are MECH, the optimal prices (Hotelling), auction outcomes or stable contracts, or MLA that can be described as the learned rules or the models (for example ConvRNN for precedence, DRL predictions for dynamic matching) based on artificial intelligence/machine learning or other strategies. So, while

enabling artefacts define the rules of the game, cross-cutting components act as an “intelligent engine” that optimises or learns for all other levels.

Some inputs necessarily generate certain outputs, but in other cases the association is not so obvious: for example, a PART typically generates process paths, operational sequences PLAN (J. Wang et al., 2017), machining alternatives MATCH or MLA for learning rules, bridging the gap between design and manufacturing by reducing dependence on manual rules (Babiceanu & Seker, 2020); an ORDER leads to SCHED, with order-resource assignments, time sequences, load balancing and multi-objective trade-offs often modelled with two-level programming (Gong et al., 2024); MKT and PLAT inputs produce optimal prices (Hotelling, Stackelberg) (Gong et al., 2024), auction results, stable contracts or strategic equilibria, alongside TRUST via blockchain, data sovereignty or a ledger for provenance and auditability (Potluri et al., 2021).

At the macro level, EQP yields CTRL with near real-time monitoring (K. Wang et al., 2022), commands on Digital Twin, setpoints and closed-loop adaptations, while SC and ORG generate EVAL (KPIs, maturity assessment, benchmarks) (Ellwein et al., 2023) or FW (servitisation roadmaps, reference architectures, adoption methodologies) (Andersen et al., 2025).

Then, by grouping these outputs into functional clusters, a logical flow emerges that reflects granularity: outputs mirror input granularity and in particular, micro inputs (PART/EQP) spawn technical/atomic results (PLAN, CTRL); meso (ORDER/MKT) drive operational decisions (SCHED, MECH); macro (SC/ORG) yield strategic enablers (FW/EVAL).

The first cluster of outputs that can be identified is the *product realisation* cluster that represents the flow design-to-manufacturing: these solutions deliver results that transform product information into process knowledge and manufacturability. This cluster includes MaaS solutions in which the platform “enters” the engineering phase and transforms fine inputs into PLAN and MLA, supporting distributed engineering with time and cost (Yip et al., 2014).

In the *partner selection cluster* the objective is to identify the best provider (Yan et al., 2024) in relation to the stated requirements (order, technical requirements, time/cost/quality constraints, sometimes CO<sub>2</sub>). The main output is a match (a shortlist or the selection) between supply and demand (Simon et al., 2025), often with a multi-criteria ranking that combines technical compatibility, cost, lead time, reliability, capacity (Vathoopan et al., 2025) and sometimes sustainability criteria. In many solutions, the match is not a “binary” outcome, but an information package that includes explanations of compatibility (e.g. constraints met/not met), risk or reliability indicators and, in more advanced cases, a

quantification of the “viability” of the service through simulations or metrics derived from historical data. that includes both the discovery and supplier selection (Sparr et al., 2021), produces MATCH and MECH from ORDER/MKT, including rankings, stability simulations and TRUST guarantees.

*Supply chain orchestration and coordination* cluster generates SCHED from meso constraints, with executable plans, dynamic KPIs and economic mechanisms (Duran-Mateluna et al., 2025) influencing allocations; finally, *cyber-physical control and performance assurance* cluster: from EQP and SC provides CTRL, diagnostics, alarms and assessments to validate operations (K. Wang et al., 2022), often with audit trails and benchmarks. The aim is to govern the system in operation and validate the results and for this reason machine status, near real-time performance indicators, alarms, failure predictions, and commands/parameters for remote control or process adaptation (e.g. closed-loop) are considered.

This input–output map reveals three critical limitations of MaaS literature that Section **Dissects systematically**:

- Functional silos: Micro-level solutions excel at PLAN but integrate SCHED in few cases; macro-level dominates FW/EVAL while neglecting operational CTRL entirely.
- Input idealism: Archetypes A3 (orchestration) and A4 (trust/sustainability) presuppose real-time IoT/Digital Twin data and federated infrastructures rarely available due to technical immaturity and data privacy regulations.
- Systemic trade-offs: Granularity creates inherent tensions between micro-level precision (proprietary CAD data) and macro-level scalability (federated governance), fragmenting solutions across isolated layers without end-to-end pipelines.

These gaps explain MaaS fragmentation: micro solutions lack marketplace orchestration; macro frameworks lack executable precision.

### RQ3: Limitations of MaaS platforms and sector variability

Despite the rapid growth of the Manufacturing-as-a-Service (MaaS) literature, large-scale adoption remains constrained by technical, organisational and economic barriers. Importantly, these limitations are not uniform across contributions: they depend on (i) the granularity level and the type of decision/output targeted, and (ii) the dominant archetypal focus of the proposal (A0-A4, Table 1). In fact, MaaS systems that mainly produce enabling artefacts (such as frameworks, taxonomies, assessment models and governance mechanisms) face different constraints compared to solutions aiming at operational decisions (matching, scheduling, or cyber-physical control). Building on RQ2, this section organises limitations in a taxonomy aligned with the main MaaS functional

blocks (capability/data modelling, discovery/matching, orchestration, market mechanisms, and trust/sustainability), and then discusses how these constraints vary by industrial sector and application context.

After classifying the various MaaS solutions according to inputs, outputs, the correlation between them, archetypes and the most common applications, it was possible to identify limitations within the framework we had constructed. These limitations are mainly related to data, from the way in which it can be acquired to its ownership, quality, reliability and quantity. In particular considering the data availability and quality, it's important to consider also data freshness, completeness, reliability. Many MaaS proposals implicitly assume that key data (like capabilities, lead times, costs, quality levels, and resource status) are available, standardised and continuously updated. What happens in reality is that these data are often incomplete, noisy, not interoperable, or proprietary, which directly undermines ranking and selection quality (MATCH/EVAL) and compromises the feasibility of orchestration outputs (SCHED). Evidence of this gap is recurrent in studies assessing “up-and-running” platforms and deployment maturity, where real implementations show uneven digital readiness and partial data coverage (Tedaldi & Miragliotta, 2021, 2023). The issue becomes more critical for data-driven resilience or monitoring pipelines, where model outputs depend on the stability and quality of sensing and indicators (K. Wang et al., 2022). As a result, platforms may revert to manual inputs, simplified proxies, or static profiles, limiting robustness and transferability. In addition, MaaS ecosystems are inherently heterogeneous: they must connect engineering tools (CAD/PLM), business systems (ERP, enterprise resource planning and MES, manager execution system), marketplace layers, and shop-floor equipment. Lack of shared data models, APIs, and semantic interoperability forces ad hoc integration, increases onboarding cost, and reduces cross-sector portability. These aspects reveal the limitation related to interoperability and standards that involves semantic alignment and integration technology and operational technology integration. Ontology-based discovery approaches address part of the problem but require maintenance, governance, and alignment across actors (Wu et al., 2019). Network/federation settings exacerbate this limitation because interoperability is no longer internal to one platform but distributed across organisations (for example, semantic interoperability and feedback loops at ecosystem level (Eslami et al., 2025), negotiation across networked assets (Hu et al., 2019)). Reference architectures and edge-cloud “data spine” approaches provide integration patterns (Beducci et al., 2026; Pahwa et al., 2023), but the literature still highlights integration as a scalability bottleneck, especially when moving from conceptual frameworks (FW/TAX) to operational decisions (MATCH/SCHED/CTRL).

In addition, the edge-cloud and cloud architectures open the problems/limitations about the trust, data sovereignty, intellectual property, secure exchange and governance overhead. In fact, a structural barrier to MaaS is that providers are reluctant to disclose sensitive information (true capabilities, process parameters, costs, performance records), while customers need credible data to reduce selection risk. Trust solutions (secure communication, data sovereignty connectors, blockchain provenance, decentralised assets) mitigate this barrier but introduce overhead and governance complexity. Data sovereignty integrated with sustainability assessment (e.g., LCA) shows the importance of controlled data exchange as a prerequisite for credible evaluation and supplier ranking (J. Wang et al., 2017). Secure communications are necessary but do not solve the governance problem alone (Potluri et al., 2021). Blockchain-based provenance and decentralised approaches improve traceability and non-repudiation but can raise scalability and cost issues (e.g., hybrid blockchain architectures (Hasan et al., 2021), decentralised CMaaS and digital assets (Hasan & Starly, 2020)). Federated learning approaches resolve the trade-off between training accuracy and data ownership but require substantial infrastructure and coordination (Yan et al., 2024; F. Zhang et al., 2026). Consequently, TRUST outputs often remain enabling artefacts rather than a fully integrated end-to-end solution like in applications MaaS for the aerospace, medical, automotive sectors or process industries: in regulated or high-liability sectors quality and traceability are not optional metrics but compliance processes involving qualification, audit trails and responsibility allocation. MaaS proposals often treat quality as a KPI (EVAL) or as a constraint in scheduling, but fewer contributions incorporate certification workflows and legal accountability as first-class system components. Digital Twin-enabled MaaS and control-as-a-service show how monitoring and control can improve assurance and operational visibility (Marra et al., 2024), yet certification integration remains underdeveloped. Crowd-based and case-based MaaS discussions illustrate why these gaps can restrict MaaS adoption to low-risk tasks, prototyping, or trusted/closed provider networks when formal assurance is missing (Gong et al., 2021a, 2021b, 2025). As a result, it frequently dictates whether MaaS can scale from opportunistic capacity sharing to mission-critical production.

Secure data sharing, data sovereignty and the guarantee of maintaining intellectual property rights encourage data sharing and use for training much more accurate models, enabling modelling and verifiability capabilities in complex processes (product–process–resource dependence).

In many industrial sectors (precision machining, qualified processes, specialised materials), capability cannot be reliably expressed via static keywords or simplified profiles, it is necessary to use real information and data. Capability is

contextual: it depends on feature–process–machine interactions, tolerances, tooling, and quality assurance practices. This limitation is particularly acute for partner selection (MATCH) and for CAD-to-plan pipelines (PLAN), where insufficient capability detail leads to downstream failures. Data-driven approaches that learn precedence or operational relationships from manufacturing data highlight both the opportunity and the dependency on rich contextual inputs (Yan et al., 2025). Capability modelling and footprint/Pareto-based evaluations aim to make capability descriptions more operational (Lagos et al., 2026), while simulation-backed discovery attempts to quantify “viability” beyond a binary match (Vathoopan et al., 2025). Nonetheless, the literature shows that true verifiability often requires additional artefacts (audits, certification, historical performance) that many MaaS platforms do not natively integrate.

Another critical limitation, identified in the literature and related with the data availability and model training, is the real-time orchestration under uncertainty (dynamic scheduling, multi-constraint optimisation). Orchestration and scheduling outputs (SCHED) are among the most operational MaaS functions, but they face major challenges in real settings: stochastic demand, dynamic capacity changes, uncertain processing times, and frequent disruptions. Optimisation-based contributions (CP/MILP, bilevel scheduling, etc.) demonstrate strong decision quality under defined assumptions but expose sensitivity to problem size, uncertainty and real-time requirements (Del Gallo et al., 2023; Duran et al., 2025; Mourtzis et al., 2020). Data-driven approaches (e.g., DRL-based accept/reject or dynamic decision logic) address adaptivity but introduce new issues, such as explainability, stability and the risk of policy misalignment when environments change (Pahwa & Starly, 2021). When sustainability constraints are embedded (e.g., low-carbon planning), complexity increases further and the gap between simulation and industrial feasibility can widen (Chaudhuri et al., 2021). Therefore, this limitation often becomes the key blocker preventing MaaS systems from progressing from “planning prototypes” to continuously updated, executable orchestration.

In the end, the last limitation identified is related to Market-design outputs (MECH). Pricing, auctions, contracts are widely studied and yet many models rely on simplified assumptions (information symmetry, rational behaviour, stable participation). Pricing strategies in MaaS marketplaces (MKT/PLAT) show how platform profit and participation depend on policy choices but do not fully capture adoption friction and heterogeneous actor behaviour (Liu et al., 2022). Reverse auctions and mechanism design models highlight fairness and efficiency trade-offs but remain sensitive to assumptions about bidding and information (Wu et al., 2019). Contract-based stability mechanisms address allocation robustness and match stability, yet their deployment requires governance and enforceability conditions that are

rarely guaranteed in open ecosystems (Pahwa et al., 2023). Empirical studies on deployment models (open vs closed) suggest that incentives, trust and critical mass strongly influence real outcomes, often leading to closed or semi-closed networks rather than fully open marketplaces (Tedaldi & Miragliotta, 2023).

## How MaaS platforms and frameworks are described: toward a Company-as-a-Service view

The literature on Manufacturing-as-a-Service (MaaS) does not converge toward a single platform blueprint. Instead, it depicts a heterogeneous landscape of frameworks, architectures and decision-support solutions that address different parts of the “design–sourcing–execution–governance” chain. Building directly on the input–output granularity taxonomy from RQ2 (Table 2), this section dissects why MaaS remains fragmented despite conceptual maturity. The three critical limitations identified (functional silos, input idealism, and systemic trade-offs between granularity levels) manifest differently across archetypes (A0–A4, Table 1) and decision outputs, creating sector-specific adoption barriers that prevent end-to-end platforms from scaling beyond prototypes.

The input idealism revealed in RQ2, where A3 orchestration and A4 trust presuppose real-time IoT/Digital Twin data, directly undermines operational outputs. Literature assumes perfect data availability (capabilities, lead times, machine status, quality metrics), yet real implementations reveal incomplete, noisy, proprietary datasets that in most of the case companies don’t want share. This data quality and availability gap disproportionately hits meso-level decisions: MATCH rankings degrade without standardised supplier profiles; SCHED fails under stochastic disruptions; CTRL becomes impossible without reliable sensor streams (EQP → CTRL: 100% dependency). Micro-level PLAN survives on CAD but in most of the cases cannot chain to downstream orchestration, creating the first silo: precision engineering disconnected from marketplace execution.

Interoperability compounds this fragility: heterogeneous MaaS ecosystems spanning ERP, MES, marketplaces, and shop-floor IoT lack semantic alignment and API standards. Ontology-based discovery mitigates but demands continuous governance across federated networks. Edge-cloud “data spines” pattern integration, yet ad-hoc connectors inflate onboarding costs, confining most A2 platforms to closed ecosystems rather than open marketplaces.

From RQ2 emerges that macro-level enabling artefacts expose the second silo: strategic governance without operational executability. Providers resist sharing contextual

capabilities (feature-process-machine interactions, true costs, quality records) due to intellectual property fears, while customers demand verifiable assurance for high-liability sectors. Blockchain solutions enable TRUST but introduce governance overhead, hybrid ledgers scale poorly, federated learning preserves privacy but requires coordination. Regulated sectors (aerospace, medical, automotive) amplify this: quality becomes compliance infrastructure, not optimisable KPI. Digital Twin CTRL improves visibility but rarely integrates certification workflows, restricting MaaS to low-risk prototyping or trusted networks.

This heterogeneity is systematic: MaaS contributions target different decision problems, operate at different abstraction levels, and assume different information units (e.g., part/CAD, order/task, market rules, platform architecture, network/supply chain, equipment/organisation). As a consequence, many MaaS “platforms” are function-specific, implementing discovery without orchestration, optimisation without cyber-physical assurance, or governance without decision automation.

Market design (A2.1) reveals similar brittleness: Hoteling/Stackelberg equilibria and reverse auctions assume rational actors and information symmetry, ignoring adoption friction and heterogeneous behaviours documented in empirical deployments. Contracts stabilise MATCH but demand unenforceable governance in open platforms.

These limitations map systematically to RQ1 archetypes, confirming RQ2 granularity patterns:

- A0 and A1, which represent conceptual and capability layers, struggle with transferability: frameworks and taxonomies proposed in the literature require interoperability that is absent or not standardised in fragmented information technology and landscapes.
- A2, for the supplier matching, discovery founders on data credibility: ontology-matching works theoretically but fails without trust.
- A2.1 market design ignores behavioural realism and critical mass requirements.
- A3 orchestration cannot handle production-scale uncertainty without real-time data pipelines.
- A4 trust/sustainability trades scalability for assurance, remaining enabling rather than operational.

These granularity-driven limitations explain why MaaS literature excels at individual functions but fails to deliver integrated platforms: RQ1 archetypes (A0–A4) provide modular capabilities; RQ2 confirms systematic input–output patterns; RQ3 reveals the missing organisational glue. The literature contains all necessary building blocks—PLAN engineering, MATCH discovery, SCHED orchestration, TRUST governance—but scatters them across silos without lifecycle continuity or accountability.

This paper resolves this fragmentation through Company-as-a-Service (CaaS), a conceptual synthesis that recomposes MaaS modules into a virtual enterprise spanning design to sourcing to execution to assurance. Grounded empirically in Tables 1 and 2, CaaS demonstrates how existing outputs form coherent company capabilities when orchestrated through a “Digital Thread and Governance Kernel” (DTGK), the persistent layer ensuring data continuity, policy enforcement, semantic alignment, and auditability across granularities. The next section derives CaaS structure directly from RQ2 clusters, transforming observed silos into staged organisational logic.

## From MaaS modules to company capabilities: the CaaS framing

Based on this evidence, this work proposes Company-as-a-Service (CaaS) as a conceptual framing that generalises MaaS from “manufacturing capacity on demand” to “company capabilities on demand.” CaaS denotes a virtual, modular enterprise that can be instantiated from a product idea and operate without owning a fully integrated physical plant, by composing specialised MaaS services across the company lifecycle from engineering to sourcing and contracting to execution and assurance. The rationale for introducing CaaS is directly grounded in RQ2 and RQ3. RQ2 shows that MaaS outputs cover complementary “company functions” but remain fragmented; RQ3 highlights recurrent barriers, especially those related to data readiness and trustworthy exchange, that prevent a simple sequence of services from becoming an operational organisation. CaaS is therefore not presented as another MaaS platform implementation (Fig. 1), but as a higher-level conceptualisation that explains how multiple MaaS archetypes may jointly reproduce organisational functions traditionally internalised within one firm (Fig. 2).

This synthesis clarifies why the state of the art appears fragmented: MaaS research covers “company functions” but distributes them across multiple platform types, decision scopes and abstraction levels. Based on this evidence, this work proposes CaaS as a conceptual framing that generalises MaaS from “manufacturing capacity on demand” to “company capabilities on demand”. CaaS denotes a virtual, modular enterprise that can be instantiated from an idea and operate without owning a fully integrated physical plant, by composing specialised MaaS services across the company lifecycle. To justify the structure of CaaS, it derived its functional core from the output clusters observed in RQ2. Specifically, the reviewed contributions can be synthesised into four macro-domains that approximate the core capabilities traditionally embedded in a manufacturing firm:

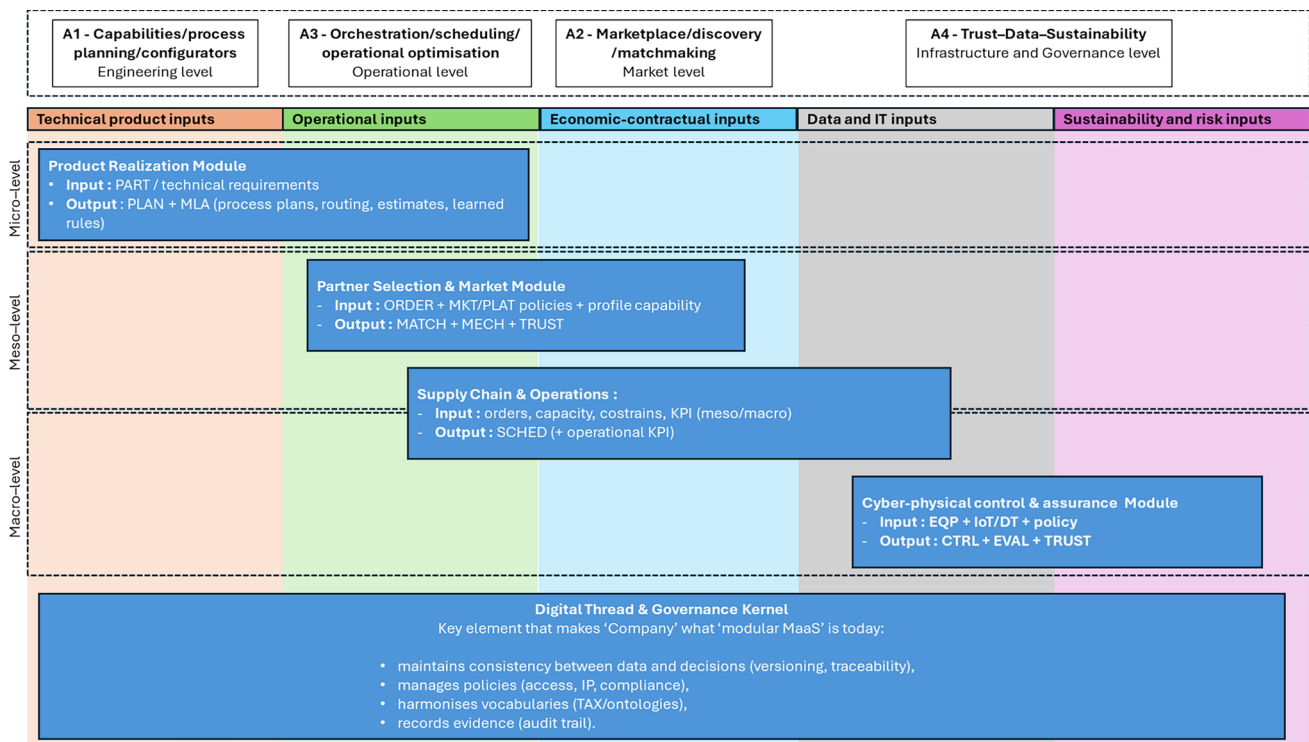


Fig. 1 MaaS schema

1. Product realisation and engineering enablement: outputs that translate product intent into manufacturable process knowledge: process plans, routings, feasibility and engineering estimates, often supported by learning components that extract rules or predict key indicators. This domain corresponds mainly to PLAN and MLA outputs typically associated with part/CAD and technical-production inputs.
2. Partner selection and market interaction: outputs that identify suitable suppliers/services through discovery and ranking, often coupled with contracting, pricing and incentive mechanisms. Trust, provenance and data sovereignty artefacts frequently emerge as prerequisites for credible selection. This domain aggregates MATCH, MECH and TRUST outputs typically associated with marketplace/platform inputs.
3. Operations and supply network coordination: outputs that generate executable allocation and scheduling decisions under capacity, eligibility and multi-objective constraints, sometimes extended with sustainability-aware objectives. This domain is primarily represented by SCHED outputs associated with order/task and network-level inputs.
4. Cyber-physical control and performance assurance: outputs that support monitoring, diagnostics and control in equipment-centric settings, often through data pipelines and digital twins, producing assurance evidence

and performance evaluation outputs. This domain maps to CTRL and EVAL outputs associated with equipment and sustainability/risk inputs.

This synthesis clarifies why the state of the art appears fragmented: MaaS literature does not lack “company functions,” but it distributes them across different units of analysis, granularity levels, and technology assumptions.

While the four domains capture the functional scope of CaaS, a company-level interpretation requires staging these capabilities into a lifecycle. The conceptual diagram, therefore, reorganises MaaS building blocks into sequential phases, in which the output of one phase becomes the structured input to the next.

- Step 0-Onboarding and governance (enabling condition): establishes digital identity, roles, minimum policies for access, IP, compliance, and shared vocabularies (taxonomy or ontologies). This phase operationalises enabling artefacts (TRUST, TAX/FW) as prerequisites for scalable collaboration.
- Step 1-From the idea to structured product specification (micro-to-meso): formalises the product intent into a machine-readable specification (functions, target cost/lead time, compliance constraints, expected volumes). This step is conceptually necessary because much MaaS literature starts from CAD or orders; CaaS explicitly

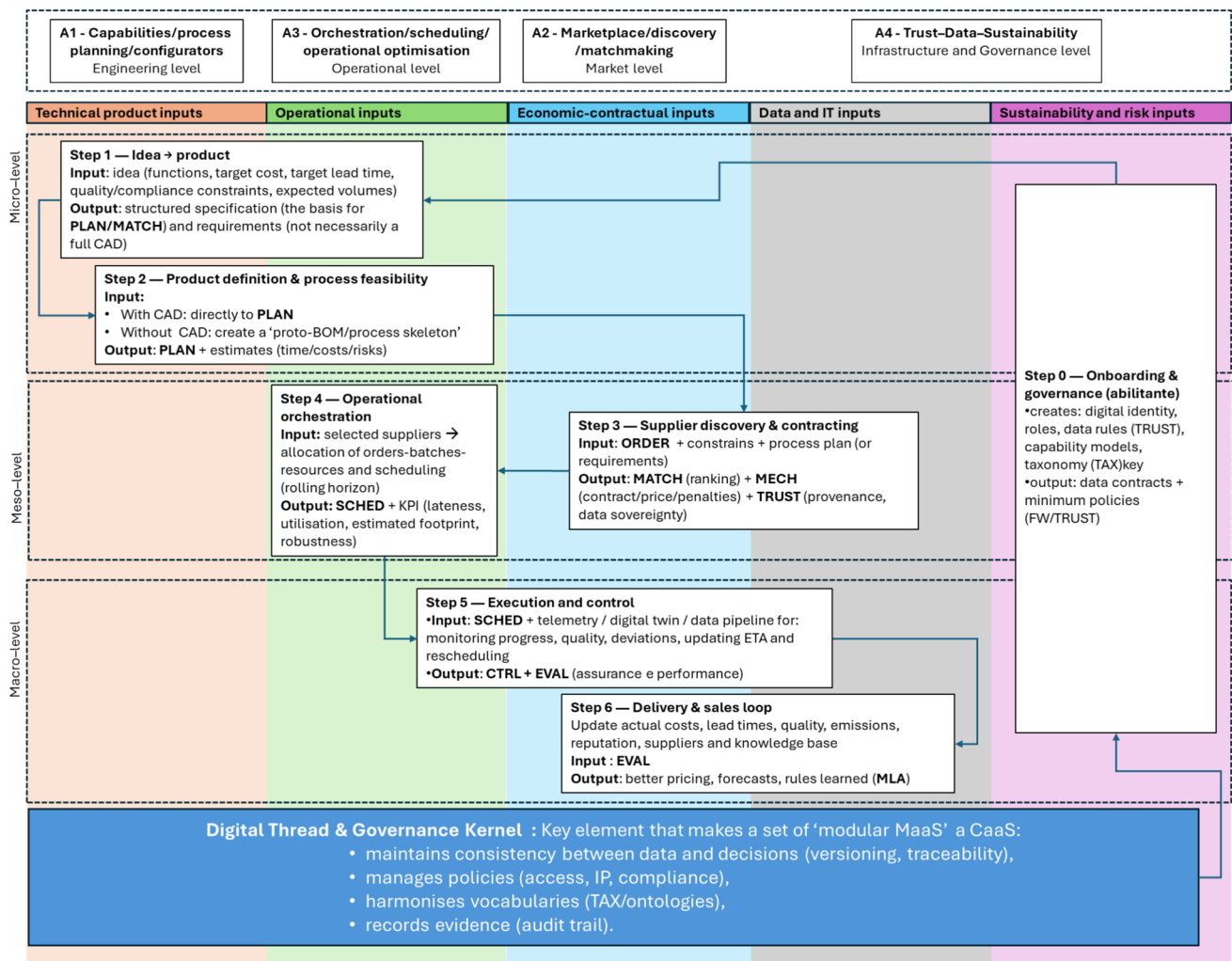


Fig. 2 CaaS derived structure

accounts for the pre-engineering “translation” that allows downstream MaaS services to operate coherently.

- Step 2-Product definition and process feasibility (micro-level engineering): converts CAD/features (when available) or a proto-process skeleton into process plans and feasibility estimates (**PLAN**), potentially enriched with learned rules/predictions (**MLA**). This step corresponds to engineering-oriented MaaS contributions and reduces downstream failure risk by grounding sourcing and orchestration in producibility evidence.
- Step 3-Supplier discovery and contracting (market and trust): uses the order/requirements together with planning outputs and marketplace rules to return ranked matches (**MATCH**), contractual/price conditions (**MECH**), and trustable exchange artefacts (**TRUST**). This phase integrates what the literature often treats separately (discovery, market design, governance) into a single decision

stage that determines “who does what, under which conditions, and with which guarantees.”

- Step 4-Operational orchestration (execution plan): transforms selected suppliers and their availability into allocation and scheduling plans (**SCHED**) and operational KPIs (lateness, utilisation, robustness, footprint), supporting rolling-horizon updates when demand/capacity changes.
- Step 5-Execution and control (closing the loop): connects orchestration outputs to cyber-physical monitoring/control (**CTRL**) via telemetry, data pipelines and/or digital twins (Abanda et al., 2024), producing performance evidence and evaluation outputs (**EVAL**) and enabling rescheduling when deviations occur. This phase addresses a common gap in marketplace-only MaaS solutions, where plans are not coupled to execution evidence.
- Step 6-Delivery and learning loop (adaptive improvement): consolidates actual costs, lead times, quality and sustainability indicators to update knowledge bases, fore-

casts, and decision policies (MLA/EVAL), improving subsequent planning, matching and orchestration cycles.

The lifecycle is not strictly sequential: different feedback loops link “downstream” stages back to “upstream” decisions, reflecting the dynamic nature of MaaS ecosystems. In particular, deviations detected during execution (Step 5) can trigger rescheduling updates in Step 4 (CTRL → SCHED), while performance evidence consolidated in Step 6 can update supplier rankings and contract conditions in Step 3 (EVAL → MATCH), and refines process plans and capability models in Step 2 (MLA → PLAN). These feedback mechanisms are essential to capture the iterative, adaptive behaviour of distributed production networks, where outputs from one cycle become inputs to the next, progressively improving decision quality across planning, matching and orchestration layers. In addition, the lifecycle structure is therefore not an arbitrary “process model”, but a reconstruction of what MaaS contributions already do in a fragmented way, aligned with the input/output granularity evidence: micro-level inputs dominate engineering planning, meso-level inputs dominate matching/scheduling, and macro-level inputs dominate governance, resilience and assurance.

Although the six-steps lifecycle may superficially resemble generic Product Lifecycle Management (PLM) models (Grieves, 2006; *ISO/IEC/IEEE 15288:2023*) it differs from them in two key respects. Firstly, PLM models describe a product’s lifecycle within a single vertically integrated organisation, whereas the CaaS lifecycle describes the instantiation of the entire business capability starting from external services mediated by a platform: each phase is not an internal process, but a composition of specialised MaaS modules originating from beyond organisational boundaries. Secondly, PLM frameworks do not address the governance of data exchange between companies, the protection of intellectual property or service-level accountability; these are, however, key concerns in the CaaS lifecycle, operationalised through the DTGK at every stage. The CaaS lifecycle is therefore not a reformulation of PLM logic, but an organisational reframing of existing MaaS building blocks, elevated from isolated platform functions to staged company capabilities governed across organisational boundaries. Composition at company level is not achievable through mere juxtaposition of MaaS modules. RQ3 highlights recurrent limitations related to data availability/quality, interoperability, trust/data sovereignty, and accountability (especially in cross-organisational settings). Moreover, many MaaS outputs are enabling artefacts (FW/TAX/TRUST) that remain non-persistent and weakly connected to operational decisions.

For this reason, the proposed CaaS framing introduces a “Digital Thread and Governance Kernel” as the coordinating

element that turns modular MaaS capabilities into an organisationally coherent system. Conceptually, the DTGK is a persistent layer that:

1. Maintains continuity and consistency across requirements, plans, contracts, schedules and execution evidence (versioning, traceability).
2. Governs policies for access, IP, compliance and data-sharing across actors and services.
3. Harmonises semantics through shared vocabularies (taxonomy/ontologies) to reduce interoperability friction (as described in (Meyers et al., 2024)).
4. Records provenance and audit trails to enable accountability and performance assurance.

A critical design challenge for the DTGK concerns real-world manufacturing occurrences (e.g. machine failures, quality deviations, late deliveries, etc.) that must be reliably mapped onto the governance layer. Drawing on oracle design principles (Caldarelli & Ellul, 2021), the DTGK conceptually incorporates a multi-party attestation mechanism in which threshold-based sensors or human-in-the-loop confirmations serve as trusted data feeds, triggering on-chain policy updates or contract amendments only when consensus across independent sources is reached. Dispute resolution is handled through a tiered escalation protocol: minor Service-Level Agreement deviations are managed automatically via pre-defined penalty clauses encoded in smart contracts, while unresolvable conflicts are escalated to a designated arbitration layer involving platform governance actors. Although this design remains to be validated empirically, it provides a concrete architectural rationale for trust claims that extend beyond “on-chain” transactions. In this sense, the DTGK represents the missing “company glue” that transforms a set of MaaS building blocks into a composable company capability. The conceptual diagrams thus capture a transition from a module-based view of MaaS (valid but loosely coupled) to a company-level view where functions are staged and synchronised through digital continuity and governance.

## Discussion and conclusion

The concept of a “distributed enterprise” composed of external capabilities and resources is not new. Earlier frameworks, including Virtual Enterprise (VE) (Camarinha-Matos & Afsarmanesh, 1999; Davidow & Malone, 1992), Extended Enterprise (Browne et al., 1995) and advanced Supply Chain Management models (Christopher & Towill, 2001; Ptak & Smith, 2016), proposed that firms could operate through networks of specialised partners rather than vertically integrated structures. CaaS builds on this intellectual foundation

but extends it to the specific context of Manufacturing-as-a-Service. Three key differences distinguish CaaS from previous approaches. First, the framework is empirically grounded in a systematic review of 62 MaaS studies. Its lifecycle phases and functional domains are derived from evidence emerging from the literature rather than from organisational theory alone. Secondly, CaaS introduces the DTGK as a core architectural component. It provides data continuity, interoperability, governance, and traceability across the entire lifecycle, addressing critical MaaS challenges such as data confidentiality, semantic integration, and accountability among distributed partners. Third, CaaS reflects the technological reality of modern MaaS ecosystems, where manufacturing capabilities are exposed as digital services, matched through AI-enabled platforms, coordinated through optimisation mechanisms, and monitored through DT and cyber-physical infrastructures. Consequently, CaaS should be viewed not as a rebranding of virtual enterprise concepts, but as an updated framework that adapts distributed enterprise principles to the digital, platform-based, and service-oriented nature of MaaS.

Having positioned CaaS with respect to earlier distributed enterprise paradigms, it is important to explain how the findings of this review motivate the proposed framework. The results of RQ1–RQ3 reveal not only the diversity of MaaS approaches but also the structural factors that prevent their integration into end-to-end industrial ecosystems. In particular, RQ1 highlighted that MaaS is better described as a set of archetypal layers (A0–A4) rather than a single platform blueprint. RQ2 demonstrated that inputs and outputs are systematically coupled considering also their level of granularity: micro-level inputs (PART and EQP) tend to yield engineering or control outputs (PLAN and CTRL), meso-level inputs (ORDER and MKT) drive discovery and orchestration (MATCH, SCHED and MECH), while macro-level inputs (NET, SC and ORG) mostly produce enabling artefacts (FW/TAX/EVAL). RQ3 further clarified why end-to-end MaaS implementations remain limited: the dominant barriers are socio-technical and revolve around data, especially data availability, reliability, interoperability, and, crucially, data confidentiality, sovereignty, and ownership.

These results motivate the proposed framework of Company-as-a-Service. CaaS does not claim that there is a single “complete MaaS platform” in the literature. Rather, it formalises the observation that MaaS research already provides most of the relevant functions for businesses, but as separate modules. CaaS, therefore, serves as an interpretative and design lens that explains how a virtual enterprise could be realised by composing specialised MaaS services throughout the entire lifecycle, from product definition to procurement, orchestration, and assurance. In this conceptualisation, the transition from “modular MaaS” to “business capability” is not driven solely by the addition of more optimisation

modules, but by the introduction of continuity and accountability across the phases.

A central implication is that data governance is not an accessory requirement but the core enabler of composability. The literature repeatedly shows that the same information that enables distributed product realisation (capabilities, costs, lead times, process parameters, performance evidence) is also the information that actors are least willing (or legally able) to disclose. This tension explains why many MaaS proposals remain confined to closed networks, simplified profiles, or one-shot decisions. The “Digital Thread and Governance Kernel” is introduced precisely to address this gap: it operationalises trust and continuity as first-class system properties by maintaining consistency across requirements, plans, contracts, schedules and execution evidence; enforcing access, IP, compliance policies; harmonising semantics; and recording provenance and auditability. Conceptually, DTGK is the “company glue” that transforms MaaS modules into an organisationally coherent enterprise logic.

From a practical perspective, the CaaS view suggests that future industrial adoption may be less about building one universal MaaS platform and more about orchestrating an ecosystem of interoperable services under shared governance. This is particularly relevant for SMEs and sectors with high investment barriers, where CaaS could enable rapid product realisation by leveraging external capabilities. At the same time, the framework makes clear that feasibility is sector-dependent: highly regulated domains and high-precision processes will require stronger assurance, certification workflows, and controlled data-sharing regimes, reinforcing the role of DTGK-like governance mechanisms.

In addition, this paper contributes a structured interpretation of MaaS research and proposes Company-as-a-Service (CaaS) as a higher-level conceptualisation grounded in the empirical heterogeneity of MaaS literature. The review indicates that MaaS does not converge to a monolithic implementation; instead, it offers a catalogue of building blocks whose inputs, outputs and limitations are systematically shaped by the unit of analysis and granularity of the decision problem. By synthesising archetypes, input/output clusters and recurrent barriers, we show that the main blocker to end-to-end composability is not the absence of algorithms, but the lack of persistent governance and digital continuity across stages, especially under confidentiality, sovereignty and intellectual property constraints.

CaaS reframes MaaS from “capacity on demand” to “company capabilities on demand”, describing how modular services can reproduce core firm functions across engineering, market interaction, orchestration, and cyber-physical assurance. The DTGK is positioned as the enabling mechanism that makes such composition credible by ensuring traceability, policy enforcement, semantic alignment and auditability. As a result, the proposed framework provides

both an explanatory lens for the current fragmentation of MaaS and a foundation for future design principles toward lifecycle-integrated, governance-aware industrial service ecosystems.

This study is subject to an important limitation in the conceptual nature of the proposed framework: CaaS is not empirically validated here, and sectoral differences are inferred from the literature rather than tested through longitudinal deployments. Future research should (i) operationalise DTGK requirements into measurable design principles and governance patterns; (ii) evaluate CaaS through real or simulated multi-actor case studies that span the full lifecycle; (iii) define metrics for “composability” (data readiness, interoperability cost, assurance completeness, and decision traceability); and (iv) investigate incentive-compatible governance schemes that balance value creation with data confidentiality and IP protection. Advancing along these directions would clarify when CaaS is economically and organisationally viable, and how MaaS ecosystems can evolve from partial solutions to coherent virtual enterprises.

The following propositions are the initial basis for future investigation of CaaS feasibility and performance:

- (1) **Composability threshold:** a MaaS ecosystem achieves CaaS-level composability when at least three of the four functional domains (engineering enablement, partner selection, orchestration, cyber-physical assurance) are interconnected through a shared governance layer that enforces common data standards and access policies. Below this threshold, lifecycle continuity cannot be maintained and the system degenerates into isolated platform transactions. Thus, future developments could concern the creation of concrete diagnostic tools: (a) developing a “composability scorecard” to measure the degree of interconnection between the four functional domains in real-world ecosystems, identifying which domain represents the most frequent bottleneck; (b) studying cases in which the threshold is reached progressively, to understand whether the order of integration of the domains affects the stability of the system; (c) defining a ‘shared governance layer’ in operational terms in terms of minimum technical requirements (API standards, metadata schemas, policy enforcement points, etc.).
- (2) **Governance overhead trade-off:** the adoption of a DTGK-like coordination mechanism increases onboarding cost and governance overhead in the short term but reduces total coordination cost across the lifecycle as the number of actors and transactions scales, due to semantic alignment and provenance reuse. This trade-off is expected to reach break-even earlier in ecosystems with high actor heterogeneity and repeated interactions. Further developments could

consider (a) an econometric model of lifecycle costs that incorporates onboarding variables and the economies of scale associated with semantic alignment, using empirical data from existing MaaS ecosystems; (b) measurable proxies for ‘actor heterogeneity’ and ‘repeated interactions’, to be able to predict the break-even point in new ecosystems in advance; (c) ‘DTGK-lite’ architectures that reduce the initial cost of adoption without compromising the ability to scale up to full governance, which is particularly relevant for SMEs with limited resources.

- (3) **Sector-specific feasibility:** the feasibility of CaaS is positively influenced by digital maturity at sector level and negatively influenced by the burden of regulatory compliance. In sectors with high digital readiness and low certification overhead (e.g. prototyping, non-critical components), CaaS instantiation is feasible with lightweight governance; in regulated sectors (aerospace, medical devices), full CaaS requires DTGK mechanisms that integrate certification workflows as first-class lifecycle components. It could be useful in this sense develop (a) sector-specific CaaS Feasibility Matrix that combines the digital maturity index and regulatory obligation, using existing data; (b) define certification workflow templates that can be integrated as native components of the DTGK for regulated sectors, avoiding the treatment of compliance as a constraint external to the lifecycle; (c) conduct pilot studies in low-barrier sectors (rapid prototyping, non-critical components) to gather empirical evidence before extending the framework to high-stakes contexts.

In addition to these future areas of research, it is important to acknowledge the methodological limitations of this review and the need for further studies to consolidate and expand the CaaS framework (as discussed in Sect. 2).

Although the literature already provides many of the functional building blocks needed to “assemble” a virtual company, key enablers are still missing (most notably governance and digital continuity) to make these blocks accountable, secure, and lifecycle consistent. The main challenge is therefore shifting from developing ever-new planning algorithms to engineering a governance substrate that renders cross-firm decisions executable and auditable. Once such a foundation is in place, CaaS suggests that competitiveness will depend less on owning factories and more on orchestrating trusted external capabilities through governed digital threads. In this sense, CaaS reframes MaaS from a service-marketplace narrative to an organisational capability narrative, where governance and continuity become the primary mechanisms for scalability.

**Authors contribution** All authors contributed to the study conception and design. Material preparation and analysis were performed by Ilaria Pietrangeli and Giovanni Mazzuto. The first draft of the manuscript was written by Ilaria Pietrangeli, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** Open access funding provided by Università Politecnica delle Marche within the CRUI-CARE Agreement. The research that led to these findings received funding from the Horizon Europe Framework Programme (HORIZON) with Grant Agreement No. 101177368 “Agile Manufacturing as a Service through AI Autonomous Agents” (MaaSai).

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