A Total Cost of Ownership Analysis of Additive Manufacturing as a Service

Burkhard List[1], Tobias Buhmann[2], and Igor Ivkić[2,3]

[1] b&mi, Wiesmath, AT
[2] University of Applied Sciences Burgenland, Eisenstadt, AT
[3] Lancaster University, Lancaster, UK

Abstract. Global manufacturing is experiencing a profound transformation as industries move away from resource-intensive mass production towards models that emphasise sustainability, localisation, and flexibility. Within this context, Manufacturing as a Service (MaaS) has emerged as a promising paradigm that leverages cloud technologies and additive manufacturing to enable on-demand, distributed production.

This paper applies a Total Cost of Ownership (TCO) perspective to evaluate the economic viability of MaaS in a holistic ecosystem setting. Our analysis considers multiple dimensions of additive manufacturing, including energy consumption, material usage, and production times, in order to identify the cost drivers that shape the feasibility of the MaaS approach. Building on these insights, we propose a profit-sharing framework that translates TCO outcomes into a distributive model, ensuring transparent and equitable value allocation among key stakeholders such as platform operators, service providers, and customers.

The results demonstrate that TCO analysis provides a powerful lens for assessing both efficiency and sustainability in MaaS, while the profit-sharing model offers a practical mechanism for balancing incentives and responsibilities across the ecosystem. By integrating cost transparency with fair value distribution, this work advances the discussion on how MaaS can contribute to resilient, economically viable, and socially sustainable manufacturing networks.

Keywords: Total Cost of Ownership (TCO) · Additive Manufacturing · Manufacturing as a Service · Profit Sharing Models.

1 Introduction

For decades, global manufacturing has been dominated by resource-intensive processes, long and vulnerable supply chains, and the inefficiencies of mass production [49]. Such practices not only generate significant ecological burdens, but also create dependencies that are highly sensitive to global disruptions, as illustrated by events such as the COVID-19 pandemic [29] and the blockage of the Suez Canal [9,25]. At the same time, market demand is increasingly shaped by consumers seeking fair, regional, and sustainable products [38], which conventional production models often fail to deliver.

The combination of cloud technologies [53] and additive manufacturing [51] has opened new pathways for rethinking industrial production. Together, these technologies form the foundation of Manufacturing as a Service (MaaS), an emerging paradigm that offers the potential to reconfigure production processes, supply chains, and customer interaction models. By enabling distributed, on demand production close to the point of need, MaaS can enhance supply chain resilience while simultaneously reducing the environmental footprint [26,30]. Beyond the technological shift, MaaS requires new approaches to business modelling, sustainability, and customer engagement [5,4,1].

Despite substantial progress in these areas, important research gaps remain. Most notably, there is still limited knowledge on how to systematically assess and fairly allocate costs and benefits within MaaS ecosystems. Total Cost of Ownership (TCO) has been established as a key framework in purchasing and supply chain management [14,36,12], offering transparency and a structured basis for decision making. Previous studies have demonstrated its relevance in evaluating efficiency and cost structures [28,50], but its application to MaaS has not been investigated in depth. Furthermore, the link between TCO analysis and distributive mechanisms such as profit-sharing has not yet been explored, despite its importance for ensuring fairness and long-term sustainability in digital manufacturing ecosystems. Governance-oriented research also highlights that digital platforms require new organisational logics to support collaboration and equitable participation [10,36].

This paper aims to address these gaps by applying a TCO perspective to the analysis of MaaS in an ecosystem context. Building on this assessment, we introduce a profit sharing model that translates TCO insights into a distribution framework for stakeholders such as platform operators, service providers, and customers. In doing so, our work advances earlier studies on additive MaaS [21,22], moving beyond efficiency comparisons towards a broader consideration of economic, organisational, and social dimensions of value creation.

By integrating TCO frameworks with business model innovation and cloud-based manufacturing architectures, this research contributes to the ongoing debate on the future of production systems. We show how TCO can serve not only as a tool for cost transparency and managerial decision support, but also as the foundation for equitable value distribution across stakeholders. In this way, MaaS can evolve into a model that reconciles efficiency, sustainability, and fairness, with implications for industry, consumers, and policy makers alike.

The remainder of this paper is structured as follows: Section 2 reviews related work on cloud-based manufacturing, additive manufacturing, business models, sustainability, and decision support frameworks. Section 3 outlines the methodological approach used for the TCO analysis of MaaS ecosystems. Section 4 presents the results of the analysis and develops a profit-sharing model based on the findings, followed by a discussion. Finally, Section 5 concludes with a summary of contributions and directions for future research.

2 Related Work

This chapter provides a comprehensive overview of the current state of research in four interrelated areas that form the foundation of this study: (1) cloud-based manufacturing systems, (2) additive manufacturing, (3) business models, sustainability, and social aspects, and (4) decision support mechanisms with a particular focus on Total Cost of Ownership (TCO) frameworks. By systematically reviewing these domains, we aim to highlight the technological, organisational, and economic dimensions of MaaS. This overview not only establishes the context for our analysis but also identifies the existing research gaps that motivate our focus on TCO based evaluations and the development of a profit sharing model for MaaS ecosystems.

2.1 Cloud-based Manufacturing

Cloud-based manufacturing (CBM) has evolved as a transformative paradigm that integrates cloud computing, the Internet of Things (IoT), and artificial intelligence (AI) to enhance the adaptability and efficiency of production systems. Unlike conventional manufacturing, which is often constrained by local resources and rigid infrastructures, CBM enables dynamic allocation of resources, service-oriented access, and global scalability. Thames and Schaefer [45] provide an early conceptualisation of the technological foundations of CBM, outlining the interplay between cloud technologies and manufacturing practices, while also emphasising the opportunities for innovation and the challenges related to implementation. Caiazzo et al. [7] expand on this by demonstrating how AI-assisted monitoring and risk classification can substantially improve process control and operational safety, thereby addressing one of the key limitations of conventional monitoring approaches.

A considerable body of research has focused on developing and testing CBM architectures. Zhang et al. [54] explored the feasibility of a comprehensive prototype platform, which integrated multiple manufacturing functions into a unified cloud based environment. This work provided a proof of concept that has since influenced subsequent CBM frameworks. Extending this idea, Cui et al. [11] proposed a specific application in the context of additive manufacturing, where they identified four distinct roles (1)loud operators, (2) service providers, (3) demanders, and (4) logistics providers, highlighting the necessity of multi stakeholder collaboration for efficient service delivery.

The architectural diversity of CBM systems has also been addressed through distributed and hybrid approaches. Škulj et al. [41] introduced a distributed network model supported by compute and knowledge clouds, emphasising its potential to overcome the rigidity of centralised infrastructures and to provide more scalable solutions. Similarly, Lu et al. [27] discussed hybrid cloud models that combine conventional production systems with cloud technologies, enabling seamless integration, resource optimisation, and interoperability between physical and virtual assets.

Another central strand of research concerns the integration and optimisation of manufacturing resources across different environments. Wang et al. [48] and Rudolph and Emmelmann [37] analyse how cloud computing can support interoperable and globally optimised resource sharing strategies. Their findings underline the contribution of CBM to collaborative manufacturing ecosystems, where virtualisation and service orientation are key enablers for efficiency gains and cost reductions.

Despite these advances, challenges remain in fully realising the potential of CBM. Adamson et al. [2] and Wu et al. [52] highlight the persistent concerns related to cybersecurity, data integrity, and the need for advanced monitoring and control mechanisms. These studies emphasise that without robust safeguards and intelligent control frameworks, the trustworthiness and scalability of CBM systems may be compromised, limiting their industrial adoption.

More recent work has increasingly focused on forward looking applications and the potential for CBM to support personalised, flexible, and service driven manufacturing. Giunta et al. [18], Vedeshin et al. [47], and Simeone et al. [40] present novel use cases that illustrate how cloud-based technologies can enable new business models, mass customisation, and the provision of manufacturing as a service. These contributions show that CBM is not only a technological shift, but also a driver of organisational and economic transformation in the manufacturing sector.

Taken together, the literature illustrates a clear trajectory: from the early conceptualisation of cloud enabled manufacturing, through the development of prototype systems and hybrid models, to recent explorations of practical applications and emerging business opportunities. This evolution highlights both the maturity of CBM as a research field and the remaining challenges that require further investigation, particularly in relation to security, interoperability, and large-scale adoption.

2.2 Additive Manufacturing Systems

Additive manufacturing (AM), commonly referred to as 3D printing, has developed into one of the most prominent technological innovations in recent decades. The disruptive potential of this technology lies in the ability to challenge and complement traditional subtractive and formative manufacturing methods by enabling novel approaches to design, prototyping, and production. AM technologies support the creation of highly complex geometries, promote material efficiency, and shorten product development cycles, which positions them as a cornerstone of the emerging paradigm of digital and distributed manufacturing.

A broad range of studies has examined the transformative impact of AM across industrial sectors. Shahrubudin et al. [39] and Rauch et al. [35] provide comprehensive overviews of its application in industries such as automotive, aerospace, and mechanical engineering. They emphasise that AM enables the fabrication of components with intricate geometries that are infeasible with conventional methods, while also reducing material waste and accelerating design iterations. These contributions highlight the role of AM in fostering shorter innovation cycles and increasing responsiveness in competitive industrial environments.

Beyond civilian industries, AM has been explored in military and defence related contexts as a means to address supply chain vulnerabilities and improve operational efficiency. Jagoda et al. [23] report on the deployment of 3D printing for rapid, on-site production of spare parts, which is particularly advantageous in conflict or crisis areas where traditional supply chains are disrupted. Fiske et al. [16] extend this perspective by discussing the feasibility of using AM for constructing buildings in remote or resource constrained locations. Similarly, Rankin et al. [34] demonstrate the potential of low cost, 3D-printed surgical instruments, which can enhance the availability and functionality of medical equipment in battlefield settings.

The medical sector has become a particularly active domain for AM applications, with significant progress in personalised treatment solutions. Url et al. [46] describe the integration of 3D printing services into hospitals, enabling the production of customised implants and surgical instruments tailored to individual patients. This represents a shift towards patient- pecific treatment strategies and demonstrates the potential of AM to reshape healthcare delivery. Ghilan et al. [17] extend this perspective by addressing the rise of 4D printing and the incorporation of machine learning methods, which are increasingly applied to optimise device functionality and improve design efficiency in the medical domain.

Despite these advances, important challenges remain that limit the widespread adoption of AM. Panda et al. [32] identify critical issues in quality assurance, repeatability, and material selection, underlining the technical and organisational barriers to scaling up AM processes. They argue that integration into existing manufacturing ecosystems requires careful strategic planning, particularly with regard to standardisation, certification, and interoperability with established production workflows.

Taken together, these contributions illustrate how AM has progressed from experimental applications towards industrial, military, and medical adoption, while simultaneously revealing the technical and organisational challenges that must be addressed to realise its full transformative potential.

2.3 Business Models, Sustainability and Social Aspects

The rapid development of digital technologies and their integration into the manufacturing industry has triggered a fundamental transformation of traditional business models. In this context, MaaS exemplifies a shift towards platform based and highly flexible production environments. Goldhar and Jelinek [19] already highlighted the potential of Computer Integrated Manufacturing (CIM) to improve product variety and customisation through the integration of information technologies into production processes.

Such approaches paved the way for more adaptive systems that allow companies to respond quickly and cost effectively to individual requirements. Building on this foundation, Rauch et al. [35] and Smith et al. [42] analyse the introduction of mass customisation and adaptive manufacturing systems, demonstrating that these innovations not only affect production efficiency but also fundamentally reshape customer interaction and the value chain itself.

Recent work has extended these insights to digital platforms and monopolistic market contexts. Nie et al. [30] show how the flexibility of additive manufacturing in monopolistic environments impacts customer loyalty and market dominance, while Ivanov et al. [20] emphasise that cloud supply chain models can enable seamless integration of physical and digital assets, thereby increasing operational flexibility and responsiveness to volatile market conditions. In addition, decision support mechanisms and strategic tools are increasingly embedded into platform architectures. Pahwa and Starly [31] demonstrate that deep reinforcement learning can enhance adaptability and decision making on MaaS platforms, whereas Chaudhuri et al. [8] analyse differentiated pricing strategies as a lever to improve profitability and market penetration. At the same time, Akbari et al. [1] underline the importance of integrating business and customer perspectives in B2B2C service environments, showing that customer experience is a critical success factor in digital manufacturing ecosystems. A related dimension is scalability: Sun et al. [43] show that, under certain conditions, additive manufacturing processes can outperform conventional methods in terms of cost and speed, while classical analyses such as Economies of Scale carried out by Junius [28] provide a theoretical foundation for understanding how efficiency gains emerge as production volumes increase.

Sustainability and social aspects have emerged as equally important in the design of next generation business models. Boons and Lüdeke-Freund [5] identify three core elements that must be aligned in sustainable business models (1) value proposition, (2) value creation and delivery, and (3) value capture. Their framework illustrates how sustainability cannot be treated as an add-on but must be integrated into the logic of the business model itself. Complementing this perspective, Bocken et al. [4] highlight the potential of pay per use models to stimulate behavioural change by shifting consumer focus from ownership to usage, thereby fostering more sustainable consumption practices.

At the operational level, Tao et al. [44] and Fisher et al. [15] show that cloud manufacturing can enhance resource efficiency, reduce waste, and increase energy efficiency through optimised processes and improved material usage. Dhir et al. [13] and Bulut et al. [6] further examine the challenges and opportunities of MaaS adoption in small and medium sized enterprises (SMEs), emphasising regional disparities in infrastructure and digital readiness. From an organisational perspective, Coskun-Senkan et al. [10] analyse governance challenges in digital business ecosystems, while Baldwin [?] explores how innovation dynamics in ecosystems require new approaches to organisational design that go beyond corporate level strategies.

A third area of research addresses management tools and decision support mechanisms that are critical for the adoption of new business models. Panda et al. [32] stress that scaling up additive manufacturing requires systematic approaches to quality assurance, material selection, and process integration, highlighting the organisational dimension of technological adoption. The Total Cost of Ownership (TCO) framework has been widely recognised as an essential instrument in this regard. Woldt et al. [50] propose TCO as a decision-making framework to support global supply chain decisions, also demonstrating how cognitive biases may affect managerial judgement. Earlier studies by Ronchi et al. [36] and Ellram [14] established the relevance of TCO in supply chain management and strategic cost management, illustrating its function in providing transparency across the entire value chain.

Taken together, the literature shows that business models in manufacturing are undergoing profound change along three dimensions: the transformation of production and interaction logics through digital platforms and MaaS, the integration of sustainability and social responsibility into the core of business models and the increasing reliance on decision support tools such as TCO and AI-driven systems. These strands of research underline the multifaceted challenges and opportunities facing manufacturing companies as they adapt to the digital and sustainable economy.

2.4 Summary

The reviewed literature demonstrates substantial progress in the areas of cloud based manufacturing, additive manufacturing, and the development of innovative business models with sustainability considerations (see Table 1). Collectively, these studies provide valuable insights into the technological foundations, industrial applications, and strategic implications of MaaS. Nevertheless, significant research gaps remain regarding the holistic integration of these perspectives within a unified MaaS ecosystem.

While prior work has addressed architectural designs, platform mechanisms, sustainability considerations, and decision support frameworks such as TCO, few studies explicitly analyse how TCO can be applied to evaluate the performance of MaaS ecosystems as a whole. In particular, the question of how costs and benefits are distributed across multiple stakeholders including (1) platform operators, (2) service providers, (3) customers, and (4) supporting entities, remains largely unexplored. This lack of research limits our understanding of the economic viability of MaaS, especially in relation to fair and sustainable value distribution.

The contribution of this paper is to close this gap by conducting a TCO analysis of MaaS in the context of an integrated manufacturing ecosystem. Building on this analysis, we develop a profit sharing model that translates TCO findings into a distributive framework for stakeholders. In doing so, this work contributes to the field by (1) applying TCO as a methodological lens for evaluating additive MaaS, (2) identifying the implications of TCO for cost efficiency, sustainability, and scalability, and (3) proposing a structured profit sharing model that ensures equitable distribution of value among ecosystem participants. This approach advances the discussion on how MaaS can be both economically viable and socially sustainable in real world industrial contexts.

Table 1. Summary of Related Work on MaaS Ecosystems.

Cloud-based Manufacturing Systems	**Sources**
Technological Foundations and Advanced Technologies	[45,7]
Feasibility and Integrated Platforms in the Context of Cloud Manufacturing	[54,11]
Decentralised and Hybrid Cloud Network Architectures to increase Flexibility	[41,27]
Interoperability and Service-Oriented Cloud Manufacturing Systems	[48,37]
Cyber-Security Challenges and Monitoring Systems	[2,52]
Innovative Applications and Future-Oriented Technologies	[18,47,40]
Additive Manufacturing	**Sources**
Transformative Impact on Industrial Applications	[39,35]
Military Applications and Field Logistics	[23,16,34]
Medical Applications and Personalised Treatments	[46,17]
Challenges in Implementation and Material Selection	[32]
Business Models, Sustainability and Social Aspects	**Sources**
Business Model Innovations and Market Transformation	[19,30,20]
Mass Customisation, Adaptive Systems and Customer Integration	[35,42,31]
Platform Optimisation, Pricing and Scalability	[31,8,43]
Economies of Scale and Efficiency Models	[28,43]
Sustainable Business Models and Consumption Patterns	[5,4]
Sustainability and Regional Adaptations of MaaS	[44,15,13,6]
Governance and Ecosystem Innovation	[10,36]
Decision Support and Management Tools	**Sources**
Total Cost of Ownership (TCO) Frameworks in Manufacturing and Supply Chains	[50,36,14]
Technical and Organisational Limitations of AM Integration	[32]

3 Cloud Crafting Platform as Business Ecosystem

In recent years, manufacturing has been reshaped by shifting consumer expectations and new technological capabilities. Customers increasingly demand insight into production processes and prefer regional, transparent and sustainable solutions. Additive manufacturing has become a key enabler in this regard, providing flexible and cost effective ways to produce diverse products directly where they are needed [51,39,28]. This development is embodied in the Cloud Crafting Platform, which connects distributed 3D printers and enables them to be offered as MaaS [22].

The platform allows individual printer operators to act as local production nodes that can deliver customised outputs while remaining integrated into a broader network. This approach reduces reliance on global supply chains, shortens transport distances, and creates direct environmental benefits [22]. Beyond the immediate economic and ecological advantages, the concept also supports stronger regional value creation by embedding production into local contexts.

However, understanding the Cloud Crafting Platform solely as a technical solution would be insufficient. Earlier studies focused on its native cloud architecture and the economic logic of distributed manufacturing, but its role is more expansive. The platform has the potential to increasingly function as the organizing core of a distributed business ecosystem. In this capacity, governance mechanisms, organisational structures, and coordinated stakeholder interactions are as critical as the underlying technology. The following sections therefore extend the analysis, examining the Cloud Crafting Platform through four perspectives: (a) economies of scale, (b) sustainable business innovation, (c) stakeholder mapping in a business to business to consumer (B2B2C) context, and its (d) architecture and governance.

3.1 Business Ecosystem Innovation

Economies of scale (EOS) have historically shaped industrial competitiveness, with internal EOS (InEOS) deriving from fixed-cost degression, specialisation, and learning, and external EOS (ExEOS) emerging from clustering, shared infrastructure, and spillovers [28]. In conventional large scale manufacturing, static InEOS dominate by lowering unit costs as production volume rises. Additive manufacturing, however, operates under different conditions. As emphasised in our previous papers [21,22], modularity and lower capital requirements reduce reliance on InEOS, enabling smaller decentralised hubs. Rather than mass production, the Cloud Crafting Platform creates efficiency by aggregating and sharing data streams across locations. Knowledge generated in one hub becomes immediately available to others, turning distributed learning into a collective advantage and fostering ExEOS through artificial clusters and shared standards.

This re-framing of scale, shifts competitiveness from “growth through volume” towards “growth through connectivity.” Here, business innovation becomes critical. Embedding sustainability into its governance model, the platform aligns ecological and social objectives together with economic performance [5]. Reduced transport distances, lower CO_2 emissions, and improved access to advanced production capacities highlight the sustainability potential of distributed manufacturing as possible through MaaS. Moreover, innovative models such as pay per use (PPU) [4] reduce overproduction, match supply more closely to demand, and open participation to a wider range of stakeholders. Transparent revenue or profit sharing and smart contracts increase the potential for reinforced trust and fairness, ensuring equitable value distribution within the ecosystem.

In this way, sustainable business innovation complements the structural limits of economies of scale in additive manufacturing. While traditional industry depends on volume driven cost reduction, the MaaS approach as proposed in our previous publication [21] demonstrates how governance, digital integration, and innovative value capture mechanisms can generate competitive advantage in decentralised ecosystems. The empirical findings from our previous publication [22] confirm the economical competitiveness of 3D printing in manufacturing. Integrating hidden and external costs, towards a TCO calculation, reveals the systemic benefits of this ecosystem model. Therefore, further innovation in the business ecosystem represents both a response to the limits of EOS and a pathway to sustainable competitiveness in distributed manufacturing networks, taking into account the involved stakeholders.

3.2 Stakeholder Mapping

The MaaS Use Case functions within a hybrid B2B2C system, where different stakeholders are interconnected. Positive customer experience in such ecosystems depends on multiple dimensions, including shared vision, interaction quality, end-user orientation, relationship experience, service quality, and outcome orientation [33]. Trust, transparency, and fairness are therefore critical elements that go beyond transactional efficiency.

Building on the stakeholder framework outlined in our previous publication [21], the Cloud Crafting Platform further needs to incorporate governance mechanisms to strengthen ecosystem cohesion. Transparent revenue sharing or profit sharing reduce opportunism, establish accountability, and ensure equitable distribution of created value [22]. This orientation extends to supporting stakeholders such as policymakers, technology providers, and funding institutions, ensuring legitimacy and regulatory alignment.

A practical illustration of this interplay of stakeholders in the business and consumer environment can be seen in the overall use case of the Cloud Crafting Platform [22]. The platform acts as a bridge between the point of sale (web shops) and the point of manufacture (3D printer operators). CAD model designers provide digital blueprints that form a product catalogue, which web shop operators integrate into their online stores. When a customer purchases a product, the Cloud Crafting Platform identifies the nearest qualified SME and transmits the production specifications. This ensures localised manufacturing, shorter transport distances, and regional value creation.

Within this ecosystem, five key stakeholders interact seamlessly: (1) the customer, who initiates the process, (2) the web shop operator, (3) the Cloud Crafting Platform operator, (4) the CAD model designer, and (5) the 3D printer operator. In this context the customer is understood as a private individual who interacts with the remaining stakeholders, who represent different business units, throughout the process. In parallel, all the business untis related stakeholders constantly need to interact to perform a MaaS. Thus, the ecosystem can be understood as a B2B2C system. Next to the operational system, the economic system is designed as a profit sharing system which ensures, that revenues and the related profits are equitably distributed among the four business service providers (web shop, platform operator, designer, manufacturer) [21], all together forming the ecosystem. Accordingly, the Cloud Crafting Platform acts not only as a technical enabler but also as a governance system, where its dual role ensures that architecture and stakeholder alignment jointly create transparency, trust, and sustainability within a distributed manufacturing ecosystem.

The following figure shows the mapping of the identified stakeholders onto the overall use case initiated by the buying customer, processed by the Cloud Crafting Platform and additively manufactured by the 3D-printing SME [21,22]:

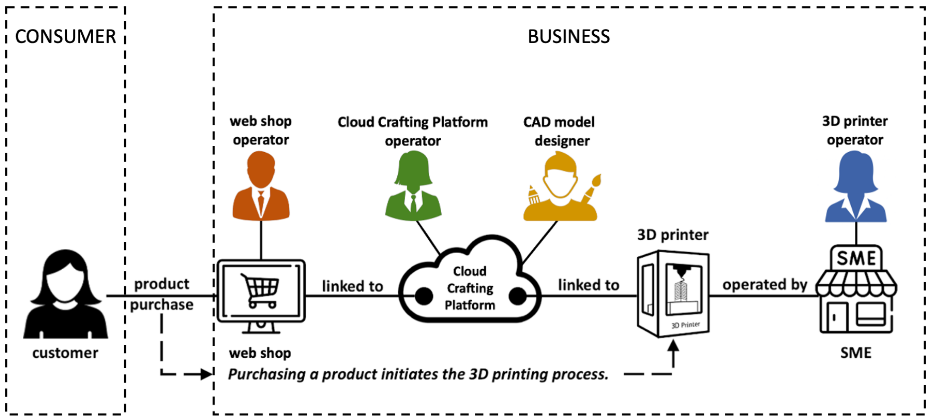

Fig. 1. Overall Use Case where a buying customer acts as consumer and initiates the on-demand MaaS process in a business environment (adapted from [21,22]).

The technical architecture of the Cloud Crafting Platform reinforces this mapping. As described in our previous publication [22], the system is organised into a layered structure: (1) data streaming, (2) service management, (3) security and trust, (4) integration, and (5) user interfaces. These layers enable scalability, interoperability, and transparency. Yet architecture alone is insufficient. Literature on digital ecosystems highlights that governance and architecture must evolve in parallel [10]. Decisions on modularity, standardisation, and interfaces directly affect how effectively access rules, incentives, and licensing schemes can be implemented. Baldwin [36] similarly emphasises that organisation design in ecosystems requires aligning modular structures with governance rules to manage distributed innovation.

3.3 Prototype Architecture

The Cloud Crafting Platform has been implemented using a service oriented architecture (SOA) that ensures scalability, security, and seamless integration between web shops and distributed 3D print shops. As described in our previous publication [22], the architecture is designed to provide the necessary endpoints for processing online purchases and automatically routing them to the nearest qualified MaaS site. Two gateways form the entry points: the API Gateway handles secure requests from web shops, while the Cloud Gateway manages real-time communication with production sites. A load balancer, in combination with a discovery service, distributes traffic and enables dynamic registration of services, ensuring reliability and flexibility. The following figure shows the core components of the Cloud Crafting Platform [21,22]:

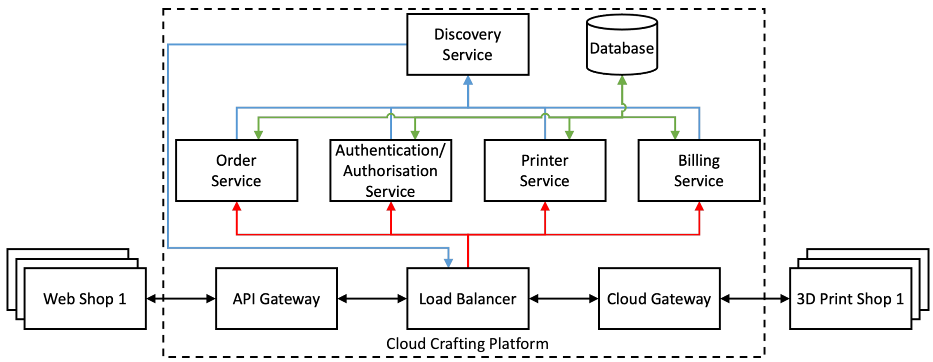

Fig. 2. Service-Oriented Cloud Crafting Platform Architecture (adapted from [21,22]).

As shown in Figure 2, the core services coordinate the full workflow of the MaaS ecosystem. The Order Service manages order lifecycles and tracks progress from initiation to completion. The Authentication and Authorisation Service provides the security backbone, implementing role based access and token validation. The Printer Service controls job scheduling, monitoring, and quality assurance across connected machines, while the Billing Service manages financial transactions, including the profit sharing model between web shops, platform operators, CAD designers, and 3D printer operators [22]. A central database underpins these services, storing order data, printer configurations, user credentials, and transaction records.

The architecture was validated through a cloud based testbed setup [22]. The platform was deployed in Microsoft Azure, hosting the core services and integrating a dedicated web shop as the point of sale. On the manufacturing side, a laboratory point of manufacture was established with three 3D printers (Ultimaker 2+ Connect, Creality K1 Max, and Prusa MK4), each connected to Raspberry Pi controllers running OctoPi OS. This configuration enabled secure, real-time printer communication through the Cloud Gateway and automated execution of jobs. The end to end test confirmed that customer orders could be placed online, routed through the platform, and produced locally, demonstrating both the technical feasibility and the economic potential of the MaaS approach.

The following figure shows the deployment of the experimental testbed including the integration of a web shop to the Cloud Crafting Platform running in the Azure cloud and the local SME production environment consisting of three different 3D-printers[22]:

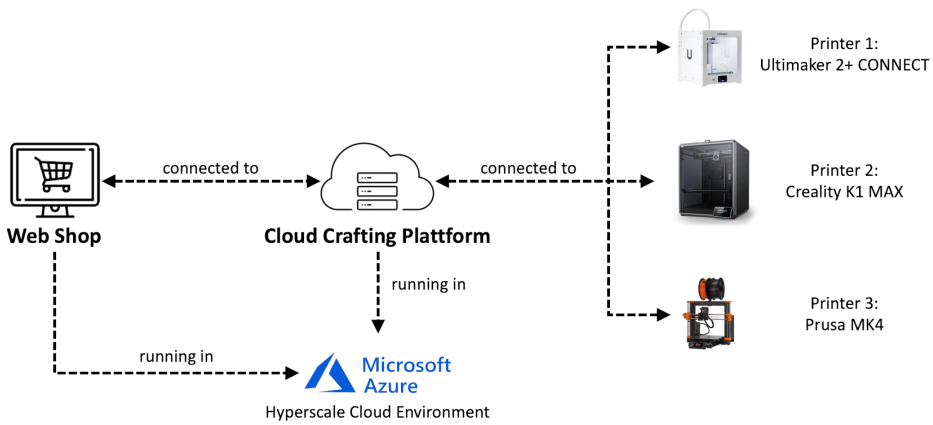

Fig. 3. Testbed Setup for End-to-End Validation of the MaaS Approach [22].

The following figure shows the local setup of a 3D printer connected to a Raspberry Pi that runs OctoPi OS interacting with the Cloud Crafting Platform [22]:

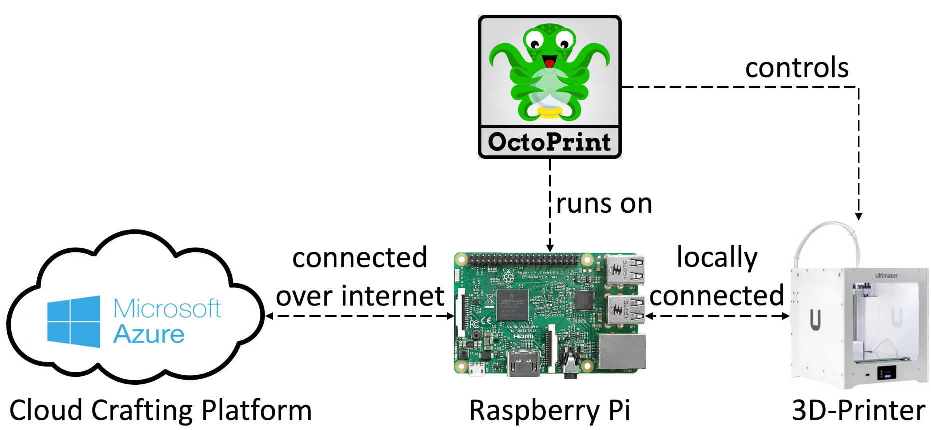

Fig. 4. Testbed Laboratory Setup Simulating a Local SME Production Site [22].

4 Total Cost of Ownership Analysis

The TCO framework is a well established concept in supply chain management and provides a comprehensive framework for evaluating the full cost implications of sourcing and production decisions, extending beyond purchase price to include operating, transaction, and end of life costs [14]. In the context of MaaS, TCO serves as an analytical lens to assess the economic feasibility of the Cloud Crafting Platform for all stakeholders within its profit sharing ecosystem. Rather than comparing decentralised and centralised production, the focus lies on understanding how lifecycle costs and hidden expenditures are distributed across platform participants. This perspective enables a transparent evaluation of value creation and value capture, ensuring that web shop operators, CAD designers, 3D printer operators, and the platform provider all participate fairly in the revenues generated. By making the full cost structure visible, TCO supports informed decision making, equitable profit sharing, and long term sustainability of the distributed manufacturing network.

The TCO analysis builds on the dataset generated in our previous study [22], in which the efficiency of the MaaS architecture was evaluated using three different 3D printers. For this purpose, data on energy consumption, production time, and material usage was collected across multiple production runs. These manufacturing cycles were conducted using specially designed rings, as illustrated by the CAD model rendering shown below [22]:

Fig. 5. Designed Ring as a Test Product for the Cost-Benefit Analysis [22].

4.1 TCO Framework in MaaS

The TCO framework has been widely applied to emphasise the importance of lifecycle oriented cost assessment in industrial decision making [12]. This methodology extends the evaluation of cost structures beyond the purchase price to include multiple categories [14]:

- investment costs (machinery, infrastructure and setup)
- operating costs (energy, labor, maintenance, consumables)
- transaction costs (coordination, quality assurance, logistics)
- stakeholder costs (compliance, licensing, environmental and social obligations)
- end-of-life costs (recycling, disposal, reuse)

In a distributed Business Ecosystem context, TCO provides a structured approach to assess the economic feasibility of MaaS. Rather than focusing solely on production costs, the framework integrates hidden and externalised costs that shape long term competitiveness. The findings of our previous publication [22] show that when transportation savings, improved utilisation of production assets, and transparent licensing mechanisms are included, the MaaS model achieves not only cost efficiency but also equitable distribution of value within the ecosystem. This supports the transition from a volume driven model to a connectivity and sustainability driven approach.

Traditional cost accounting relies on self cost calculations as the basis for pricing decisions. Within the TCO framework, however, self costs are extended to cover categories such as digital integration, compliance, and continuous quality assurance. For decentralised manufacturing hubs, this implies that economic competitiveness depends as much on digital infrastructure and service quality as on direct production expenses.

Moreover, TCO acts as a foundation for transparent profit sharing between stakeholders, as proposed by our previous publication [22]. This ensures that economic value is allocated fairly across web shop operators, CAD designers, 3D printer operators, and the platform provider. By embedding sustainability metrics such as CO_2 emissions and resource efficiency [5] into the assessment, TCO further strengthens the platform's ability to align ecological, social, and economic objectives. In this way, the TCO framework functions not only as a cost evaluation tool but as a governance instrument for equitable and sustainable value creation in distributed manufacturing ecosystems.

4.2 Evaluation

To evaluate the economic viability of the Cloud Crafting Platform, in our previous publication [22] we applied a comprehensive cost-benefit analysis using a custom designed ring as a test product. This approach focused on capturing the operational self costs across three dimensions: (1) web shop operation, (2) cloud platform infrastructure, and (3) local production costs. Together, these dimensions form the foundation for a TCO perspective across 4 stakeholders tailored to the MaaS model.

Webshop Operational Costs covered expenses related to maintaining an online retail presence, including Shopify subscription fees, transaction costs, and integration expenses. These recurring costs were distributed over the assumed sales volume of 100 rings per month to derive per-unit expenses.

Microsoft Azure Cloud Infrastructure Costs represented the expenses to run the service oriented platform architecture, covering compute, storage, bandwidth, and monitoring services. These included the API Gateway, Load Balancer, Discovery Service, and core services such as Order, Authentication, Printer, and Billing. Distributed over the same sales volumes, these cloud costs became a critical component of unit self costs.

Production Costs were determined through systematic test runs (n=50) with three different 3D printers, (1) Ultimaker 2+ Connect, (2) Creality K1 Max, and (3) Prusa MK4. Measurements included material usage, energy consumption, and production times. The Creality K1 Max proved to be the most cost effective in terms of material costs, while the other printers offered comparable performance. Energy consumption was analyzed across three phases (pre-print, print, and post-print) to capture the complete operational footprint.

By combining these three cost dimensions, the total unit manufacturing costs per ring were calculated between EUR 2.121 and EUR 2.237, depending on the printer model. With an anticipated market price of EUR 10 to 15 per unit, this resulted in contribution margins of approximately 400 to 600%. These findings validate the economic feasibility of the Cloud Crafting Platform through Additive Manufacturing and demonstrate that the self costs framework provides a reliable baseline for TCO calculations.

InEOS and Maximum Production Runs further refine the self cost baseline. The maximum number of production runs per year technically achievable gives the maximum amount for internal economies of scale (InEOS) and is critical for distributing fixed and operational costs across the total output. A TCO framework for a printer hub based on a central European SME cost structure set up in the rural area of Burgenland, Austria, was chosen as a suitable role model. Therefore, the assumptions applied were 253 operational days per year and 18 operational hours per day, assuming that the printer hub operates on 3 shifts per operational day. Each printer hub was assumed to be running a different printer, with 10 printers within each hub. According to the printer manufacturer's specification and the feedback from relevant user groups, a printer specific uptime was identified as a measure for it's faultless performance. Based on the measured average print times as per our previous publication [22] of each machine, the potential maximum number of runs per year was calculated as follows:

– The Ultimaker 2+ CONNECT (Hub 1), with an average print time of 38.05 minutes per ring, the number of runs per operational day is given by the floor of the daily 18 operational hours divided by the average print time, resulting in 28 runs per printer daily. With 10 printers operating at 90% uptime, this equals **63 756 runs per year**.

– The Creality K1 MAX (Hub 2), with an average print time of 13.25 minutes per ring, the number of runs per operational day is given by the floor of the daily 18 operational hours divided by the average print time, resulting in 81 runs per printer daily. With 10 printers at 70% uptime, this corresponds to **143 451 runs per year**.

– The Prusa MK4 (Hub 3), with an average print time of 15.5 minutes per ring, the number of runs per operational day is given by the floor of the daily 18 operational hours divided by the average print time, resulting in 69 runs per printer daily. With 10 printers at 95% uptime, this yields **165 841 runs per year**.

The number of production runs can be calculated as follows:

$$N_{hub} = \lfloor \frac{18 * 60}{t_{printer}} \rfloor * 253 * 10 * u_{printer}, \text{ where} \tag{1}$$

u_{printer}	is the average uptime factor per each printer
t_{printer}	is the average print duration per each printer
N_{hub}	is the number of production runs per year per each printer hub

These values set the maximum production capacity per each hub and equals the maximum number of rings that can be sold per each distributor in cooperation with the specific hub, via the Cloud Crafting Platform. Using a conservative market price of EUR 10 per ring a potential Consumer would pay, as investigated in our previous publication [22], the potential annual sales value per ecosystem was calculated:

$$R_{ecosystem} = N_{hub} * 10, \text{ where} \tag{2}$$

N_{hub}	is the number of production runs per year per each printer hub
$R_{\text{ecosystem}}$	is the revenue per year per each ecosystem consisting of Consumer, Web Shop Operator, Platform and Hub

Resulting in the potential annual sales value per web shop as:

Ecosystem 1 (Hub 1):	EUR	637 560
Ecosystem 2 (Hub 2):	EUR	1 434 510
Ecosystem 3 (Hub 3):	EUR	1 658 410

While all three Ecosystems can generate significant revenue under these assumptions, differences in efficiency and uptime of the associated Hub translate into varying profitability, once stakeholder costs according to the TCO framework are considered.

These maximum revenue figures contribute to covering such stakeholder costs, such as platform operation, web shop hosting, marketing, rent, depreciation, energy, materials and others. Higher utilisation or greater efficiency directly reduces unit self costs and strengthens the TCO framework as a method for assessing long term profitability and ecosystem feasibility.

The stakeholder cost allocations applied were as follows:

- **Stakeholder 1 (Platform Operator):** EUR 282 100 annually (platform operation, support, development, marketing, administration).
- **Stakeholder 2 (Printshop Operator/SME):** ranging from EUR 131 539 to EUR 227 651 depending on printer model used in the associated Hub (labor, energy, material, depreciation, rent).
- **Stakeholder 3 (Distributor/Web Shop):** ranging from EUR 219 369 to EUR 367 393 depending on the sales numbers limited by the associated Hub (sales, commission, marketing, warehousing, IT).
- **Stakeholder 4 (CAD Designer):** EUR 80 000 for design and engineering expenditure (labor, software, prototyping.

From these cost allocations, the Earnings Before Interest and Taxes (EBIT) for each Ecosystem can be expressed as:

$$EBIT_{Ecosystem} = R_{Ecosystem} - (C_{S1} + C_{S2_{Ecosystem}} + C_{S3_{Ecosystem}} + C_{S4}), \text{ where} \tag{3}$$

$C_{\text{S1}}, C_{\text{S2 \& Ecosystem}}, C_{\text{S3 \& Ecosystem}}, C_{\text{S4}}$	represent the costs per each stakeholder
$R_{\text{Ecosystem}}$	represents the value of sold goods
$EBIT_{\text{Ecosystem}}$	represents the earnings before interests and taxes per printer hub

Next to the calculation of the absolute value of the EBIT per Ecosystem it is essential to evaluate the performance of each Ecosystem in relation to its revenue and the related cost structure. Therefore, the ratio between the Revenue and EBIT per Ecosystem, resulting in the EBIT Margin was calculted as follows:

$$EBITMargin_{Ecosystem} = \frac{R_{Ecosystem}}{EBIT_{Ecosystem}} * 100, \text{ where} \tag{4}$$

$R_{\text{Ecosystem}}$	represent the value of sold goods per Ecosystem
$EBIT_{\text{Ecosystem}}$	represents the earnings per Ecosystem
$EBITMargin_{\text{Ecosystem}}$	represents the percentage of EBIT from Revenue

The following EBIT and EBIT margins results were obtained:

	Ecosystem 1	Ecosystem 2	Ecosystem 3
Revenue	637 560	1 434 510	1 658 415
Stakeholder 1	−282 100	−282 100	−282 100
Stakeholder 2	−165 137	−131 539	−227 651
Stakeholder 3	−219 369	−334 927	−367 393
Stakeholder 4	−80 000	−80 000	−80 000
EBIT	−109 046	605 944	701 271
EBIT margin (%)	−17.1	42.2	42.3

While the Ecosystem 2 and Ecosystem 3 deliver strong EBIT and EBIT margins under the assumed conditions, the Ecosystem 1 fails to cover stakeholder costs, operating at a loss. These findings underscore that profitability in the MaaS ecosystem is strongly shaped by printer efficiency, utilisation rates, and stakeholder cost allocations.

To evaluate the profit distribution, the achieved EBIT was further allocated to the stakeholders in a way that the relative distribution equaling the stakeholder's share of cost to the total cost of all shareholders per each Ecosystem. The allocation of EBIT according to the stakeholder's cost share calculate as:

$$EBIT_{Stakeholder} = \frac{C_{Stakeholder}}{C_{Ecosystem}} * EBIT, \text{ where} \quad (5)$$

$C_{\text{Ecosystem}}$	represents the total costs per Ecosystem
$C_{\text{Stakeholder}}$	represents the Stakeholder's share of costs
$EBIT_{\text{Stakeholder}}$	represents the Stakeholder's share of EBIT

Resulting in an allocation of EBIT for each Ecosystem as follows:

Ecosystem 1 (Printer 1): EBIT EUR −109 046 distributed as:

Stakeholder 1:	EUR	−41 202
Stakeholder 2:	EUR	−24 119
Stakeholder 3:	EUR	−32 040
Stakeholder 4:	EUR	−11 684

Allocated EBIT margin = −17% across all stakeholders.

Ecosystem 2 (Printer 2): EBIT EUR 605 944 distributed as:

Stakeholder 1:	EUR	206 305
Stakeholder 2:	EUR	96 197
Stakeholder 3:	EUR	244 938
Stakeholder 4:	EUR	58 505

Allocated EBIT margin = 42% across all stakeholders.

Ecosystem 3 (Printer 3): EBIT EUR 701 271 distributed as:

Stakeholder 1:	EUR	206 686
Stakeholder 2:	EUR	166 793
Stakeholder 3:	EUR	269 178
Stakeholder 4:	EUR	58 614

Allocated EBIT margin = 42% across all stakeholders.

This profit sharing perspective illustrates that while the Ecosystem 2 and Ecosystem 3 generate substantial positive returns for all stakeholders, the Ecosystem 1 leads to uniformly negative allocations, highlighting the critical role of printer selection in ensuring ecosystem wide profitability.

4.3 Discussion

In our previous publication [22], a weighted distribution model was proposed to allocate profits among stakeholders based on infrastructure investment, operational responsibility, and ongoing commitment. The suggested allocation assigned 40% of profits to the Cloud Crafting Platform Operator, 30% to the Printshop Operator, 20% to the Web Shop Operator, and 10% to the CAD Designer. This model was designed to reflect the relative impact and ongoing contributions of each stakeholder to the ecosystem.

To investigate this approach, the proposed distribution was applied to the EBIT results obtained from the TCO analysis for each Ecosystem. The allocations followed the proposed 40/30/20/10 split, with EBIT shares distributed accordingly among the four stakeholders and are calculated as such:

$$EBIT_{Stakeholder} = EBIT_{Ecosystem} * Split_{Stakeholder}, \text{ where} \tag{6}$$

$EBIT_{\text{Ecosystem}}$	represents the total EBIT of the Ecosystem
$Split_{\text{Stakeholder}}$	represents the Stakeholder's share according to the weight distribution model
$EBIT_{\text{Stakeholder}}$	represents the Stakeholder's share of EBIT

Resulting in an allocation of EBIT for each Ecosystem as follows:

Ecosystem 1 (Printer 1): EBIT EUR −109 046 distributed as:

Stakeholder 1:	EUR	−41 202	EBIT margin: −18%
Stakeholder 2:	EUR	−24 119	EBIT margin: −25%
Stakeholder 3:	EUR	−32 040	EBIT margin: −11%
Stakeholder 4:	EUR	−11 684	EBIT margin: −16%

Ecosystem 2 (Printer 2): EBIT EUR 605 944 distributed as:

Stakeholder 1:	EUR	206 305	EBIT margin: 46%
Stakeholder 2:	EUR	96 197	EBIT margin: 58%
Stakeholder 3:	EUR	244 938	EBIT margin: 27%
Stakeholder 4:	EUR	58 505	EBIT margin: 43%

Ecosystem 3 (Printer 3): EBIT EUR 701 271 distributed as:

Stakeholder 1:	EUR	206 686	EBIT margin: 50%
Stakeholder 2:	EUR	166 793	EBIT margin: 48%
Stakeholder 3:	EUR	269 178	EBIT margin: 28%
Stakeholder 4:	EUR	58 614	EBIT margin: 47%

The comparison revealed that the proposed distribution model and the calculated EBIT results lead to the same overall outcome: profitable Ecosystems remain profitable, and unprofitable remain unprofitable. For instance, while both Ecosystem 2 and Ecosystem 3 demonstrated strong positive EBIT values for all Stakeholders under the applied distribution, Ecosystem 1 continued to show a negative EBIT, even when profits were allocated according to the proposed scheme. This consistency indicates that while distribution models may alter the magnitude of stakeholder allocations, they do not fundamentally change the profitability status of a given Ecosystem using a given printer hub. Importantly, applying the weighted distribution ensures that stakeholders are compensated in proportion to their role in maintaining the ecosystem. The Platform Operator receives the highest share for maintaining infrastructure and ensuring system reliability, the Printshop Operator is rewarded for physical production and quality assurance, the Web Shop Operator is compensated for managing customer interaction and sales, and the CAD Designer is rewarded for the product design.

In conclusion, the analysis supports the conclusion that the proposed profit sharing model can be considered a fair approach. Furthermore, it balances the relative impact of each stakeholder on the ecosystem and ensures transparent, rule based allocation of profits without distorting the underlying economic feasibility of the different printer hubs.

5 Conclusions

This paper concentrated on the evolving technology of distributed manufacturing, where additive manufacturing and digital platforms merge to enable new forms of production and value creation. Against the backdrop of shifting consumer expectations toward transparency, sustainability, and regional value generation, the Cloud Crafting Platform was introduced as a means to operationalise MaaS. In this regard, the problem addressed in this work was twofold: first, to demonstrate how decentralised 3D printing networks can be technically and organisationally coordinated via a cloud based platform; second, to evaluate whether such an ecosystem can be both economically viable and equitable for its diverse stakeholders.

Our approach combined a multi perspective analysis including the business ecosystem perspective and the economic perspective. From the business ecosystem perspective, we examined the role of economies of scale, sustainable innovation, and governance structures within a B2B2C context. From the economic perspective, we conducted a TCO analysis to capture not only direct production costs but also hidden, externalised, and stakeholder specific costs. This was evaluated using a cloud-based prototype architecture and a series of testbed experiments with three different 3D printer models. Among our key findings was that the Cloud Crafting Platform is technically feasible, as demonstrated by the prototype architecture that successfully integrates online purchase, secure data streaming, and localised production. Another finding was that the TCO analysis confirmed the economic competitiveness of decentralised MaaS, provided utilisation rates and printer efficiencies are leveraged effectively. In this regard, the profitability depends strongly on printer hub performance: while high efficiency ecosystems achieve EBIT margins of over 40%, less efficient setups remain structurally unprofitable. Finally, it could be demonstrated that the profit sharing models, whether cost based or weighted by stakeholder responsibility, do not alter the profitability status of ecosystems but ensure fairness and transparency in distributing value.

Our research showed how to model, implement, and evaluate distributed manufacturing ecosystems in terms of their profitability. The combination of cloud native architecture and lifecycle oriented cost analysis provides a governance instrument that aligns economic, ecological, and social objectives. This paves the way for extending the model beyond additive manufacturing toward CNC, robotics, and hybrid production systems.

In future work, we plan to expand the platform to to accommodate additional manufacturing technologies and advanced quality control mechanisms. In addition, the goal is to integrate the platform into broader regulatory and industrial frameworks, ensuring interoperability, trust, and sustainable competitiveness in global markets. Finally, we will optimise the presented evenue and profit sharing schemes using empirical data from real world pilots. In conclusion, our work demonstrated that distributed, platform based manufacturing is not only a technological possibility but also an economically and socially robust pathway toward the next generation of industrial value creation based on MaaS.

References

1. Akbari, M., Foroudi, P., Nasiri, M., and Seyyedamiri, N. (2020). How customer experience drives word-of-mouth in B2B2C platforms? *Journal of Business & Industrial Marketing*, 35(9):1539–1555.
2. Adamson, G., Wang, L., Holm, M., and Moore, P. (2017). Cloud manufacturing–a critical review of recent development and future trends. *International Journal of Computer Integrated Manufacturing*, 30(4-5).
3. Baldwin, C. Y. (2012). Organization design for business ecosystems. *Journal of Organization Design*, 1(1):20–23.
4. Bocken, N. M. P., Short, S. W., Rana, P., and Evans, S. (2018). Consumption reduction through collaborative consumption: a systematic review of sharing and pay-per-use business models. *Journal of Cleaner Production*, 195: 1068–1081.
5. Boons, F. and Lüdeke-Freund, F. (2013). Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. *Journal of Cleaner Production*, 45:9–19.
6. Bulut, S., Wende, M., Wagner, C., and Anderl, R. (2021). Impact of manufacturing-as-a-service: business model adaption for enterprises. *Procedia CIRP*, 104:1286–1291.
7. Caiazzo, B., Murino, T., Petrillo, A., Piccirillo, G., and Santini, S. (2023). An iot-based and cloud-assisted ai-driven monitoring platform for smart manufacturing: design architecture and experimental validation. *Journal of Manufacturing Technology Management*, 34(4):507–534.
8. Chaudhuri, A., Datta, P. P., Fernandes, K. J., and Xiong, Y. (2021). Optimal pricing strategies for manufacturing-as-a service platforms to ensure business sustainability. *International Journal of Production Economics*.
9. Chopra, S. and Meindl, P. (2007). *Supply chain management. Strategy, planning & operation*. Springer.
10. Coskun-Senkan, O., Pesch, R., and Thiesse, F. (2024). Governance challenges in digital business ecosystems. *Electronic Markets*, 34:123–140.
11. Cui, J., Ren, L., Mai, J., Zheng, P., and Zhang, L. (2022). 3d printing in the context of cloud manufacturing. *Robotics and Computer-Integrated Manufacturing*, 74:102256.
12. Degraeve, Z., Labro, E., and Roodhooft, F. (2000). An evaluation of vendor selection models from a total cost of ownership perspective. *European Journal of Operational Research*, 125(1):34–58. doi: `https://doi.org/10.1016/S0377-2217(99)00199-X`.
13. Dhir, A., Talwar, S., Islam, N., Alghafes, R., and Badghish, S. (2023). Different strokes for different folks: Comparative analysis of 3d printing in large, medium and small firms. *Technovation*, 125:102792.
14. Ellram, L. M. (1993). Total cost of ownership: elements and implementation. *International Journal of Purchasing and Materials Management*, 29(3):2–11.
15. Fisher, O., Watson, N., Porcu, L., Bacon, D., Rigley, M., and Gomes, R. L. (2018). Cloud manufacturing as a sustainable process manufacturing route. *Journal of manufacturing systems*, 47:53–68.
16. Fiske, M., Edmunson, J., Fikes, J., Johnston, M., and Case, M. (2018). 3d printing in space: A new paradigm for america's military. *The Military Engineer*, 110(715):74–77.
17. Ghilan, A., Chiriac, A. P., Nita, L. E., Rusu, A. G., Neamtu, I., and Chiriac, V. M. (2020). Trends in 3d printing processes for biomedical field: opportunities and challenges. *Journal of Polymers and the Environment*, 28:1345–1367.

18. Giunta, L., Hicks, B., Snider, C., and Gopsill, J. (2023). A living lab platform for testing additive manufacturing agent-based manufacturing strategies. *Procedia CIRP*, 119:656–661.
19. Goldhar, J. D. and Jelinek, M. (1990). Manufacturing as a service business: Cim in the 21st century. *Computers in Industry*, 14(1-3):225–245.
20. Ivanov, D., Dolgui, A., and Sokolov, B. (2022). Cloud supply chain: Integrating industry 4.0 and digital platforms in the "supply chain-as-a-service". *Transportation Research Part E: Logistics and Transportation Review*, 160:102676.
21. Ivkić, I., Buhmann, T., List, B., and Gnauer, C. (2024). Towards a cost-benefit analysis of additive manufacturing as a service. In *Proceedings of the 14th International Conference on Cloud Computing and Services Science - CLOSER*, pages 338–345. INSTICC, SciTePress.
22. Ivkić, I., Buhmann, T., and List, B. (2025). A Cost-Benefit Analysis of Additive Manufacturing as a Service. *arXiv preprint arXiv:2502.05586*.
23. Jagoda, J., Diggs-McGee, B., Kreiger, M., and Schuldt, S. (2020). The viability and simplicity of 3d-printed construction: A military case study. *Infrastructures*, 5(4):35.
24. Junius, K. (1997). Economies of Scale: A Survey of the Empirical Literature. *Kiel Working Paper No. 813*, Kiel Institute of World Economics (IfW), Kiel, Germany. Available at: https://hdl.handle.net/10419/46809.
25. Lee, J. M.-y. and Wong, E. Y.-c. (2021). Suez canal blockage: an analysis of legal impact, risks and liabilities to the global supply chain. In *MATEC web of conferences*, volume 339, page 01019. EDP Sciences.
26. Lu, Y. and Xu, X. (2019). Cloud-based manufacturing equipment and big data analytics to enable on-demand manufacturing services. *Robotics and Computer-Integrated Manufacturing*, 57:92–102.
27. Lu, Y., Xu, X., and Xu, J. (2014). Development of a hybrid manufacturing cloud. *Journal of manufacturing systems*, 33(4):551–566.
28. Mai, J., Zhang, L., Tao, F., and Ren, L. (2016). Customized production based on distributed 3d printing services in cloud manufacturing. *The International Journal of Advanced Manufacturing Technology*, 84:71–83.
29. Mugurusi, G. and de Boer, L. (2013). What follows after the decision to offshore production? a systematic review of the literature. *Strategic Outsourcing: An International Journal*, 6(3):213–257.
30. Nie, J., Xu, X., Yue, X., Guo, Q., and Zhou, Y. (2023). Less is more: A strategic analysis of 3d printing with limited capacity. *International Journal of Production Economics*, 258:108816.
31. Pahwa, D. and Starly, B. (2021). Dynamic matching with deep reinforcement learning for a two-sided manufacturing-as-a-service (maas) marketplace. *Manufacturing Letters*, 29:11–14.
32. Panda, S. K., Rath, K. C., Mishra, S., and Khang, A. (2023). Revolutionizing product development: The growing importance of 3d printing technology. *Materials Today: Proceedings*.
33. Rejikumar, G. and Asokan-Ajitha, A. (2022). Business Customer Experience in B2B2C Service Settings: A Scale Development. *Journal of Business & Industrial Marketing*, 38(4):886–904. doi: https://doi.org/10.1108/JBIM-07-2021-0342.
34. Rankin, T. M., Giovinco, N. A., Cucher, D. J., Watts, G., Hurwitz, B., and Armstrong, D. G. (2014). Three-dimensional printing surgical instruments: are we there yet? *Journal of Surgical Research*, 189(2).

35. Rauch, E., Unterhofer, M., and Dallasega, P. (2018). Industry sector analysis for the application of additive manufacturing in smart and distributed manufacturing systems. *Manufacturing Letters*, 15:126–131.
36. Ronchi, S., Brun, A., Golini, R., and Fan, X. (2000). Total cost of ownership along the supply chain: A management framework. *International Journal of Production Economics*, 68(2): 111–122.
37. Rudolph, J.-P. and Emmelmann, C. (2017). A cloud-based platform for automated order processing in additive manufacturing. *Procedia Cirp*, 63:412–417.
38. Schwilling, T., Schulze, I., Wilts, H., and Du Bois, P. (2021). Circular economy 2021. secondhand in deutschland.
39. Shahrubudin, N., Lee, T. C., and Ramlan, R. (2019). An overview on 3d printing technology: Technological, materials, and applications. *Procedia manufacturing*, 35:1286–1296.
40. Simeone, A., Caggiano, A., and Zeng, Y. (2020). Smart cloud manufacturing platform for resource efficiency improvement of additive manufacturing services. *Procedia Cirp*, 88:387–392.
41. Škulj, G., Vrabič, R., Butala, P., and Sluga, A. (2017). Decentralised network architecture for cloud manufacturing. *International Journal of Computer Integrated Manufacturing*, 30(4-5):395–408.
42. Smith, S., Smith, G. C., Jiao, R., and Chu, C.-H. (2013). Mass customization in the product life cycle. *Journal of Intelligent Manufacturing*, 24:877–885.
43. Sun, M., Ng, C. T., Yang, L., and Zhang, T. (2024). Optimal after-sales service offering strategy: Additive manufacturing, traditional manufacturing, or hybrid? *International Journal of Production Economics*, 268:109116.
44. Tao, F., Cheng, Y., Zhang, L., and Nee, A. Y. (2017). Advanced manufacturing systems: socialization characteristics and trends. *Journal of Intelligent Manufacturing*, 28:1079–1094.
45. Thames, L. and Schaefer, D. (2017). Industry 4.0: An overview of key benefits, technologies, and challenges. *Cybersecurity for Industry 4.0: Analysis for Design and Manufacturing*, pages 1–33.
46. Url, P., Stampfl, D., Tödtling, M., and Vorraber, W. (2022). Challenges of an additive manufacturing service platform for medical applications. *Procedia CIRP*, 112:400–405.
47. Vedeshin, A., Dogru, J. M. U., Liiv, I., Draheim, D., and Ben Yahia, S. (2019). A digital ecosystem for personal manufacturing: an architecture for cloud-based distributed manufacturing operating systems. In *Proceedings of the 11th International Conference on Management of Digital EcoSystems*, pages 224–228.
48. Wang, Y., Zheng, P., Xu, X., Yang, H., and Zou, J. (2019). Production planning for cloud-based additive manufacturing—a computer vision-based approach. *Robotics and Computer-Integrated Manufacturing*, 58:145–157.
49. Westkämper, E. and Löffler, C. (2016). Strategien der produktion-technologien. *Konzepte und Wege in die Praxis*, 1(2.1).
50. Woldt, R., Meyer, L., and Schubert, T. (2025). Total Cost of Ownership as a decision support tool in manufacturing ecosystems: biases and applications. *International Journal of Production Research*, 63(14):4120–4136.
51. Wong, K. V. and Hernandez, A. (2012). A review of additive manufacturing. *International scholarly research notices*, 2012(1):208760.
52. Wu, D., Greer, M. J., Rosen, D. W., and Schaefer, D. (2013). Cloud manufacturing: Strategic vision and state-of-the-art. *Journal of Manufacturing Systems*, 32(4):564–579.

53. Xu, X. (2012). From cloud computing to cloud manufacturing. *Robotics and computer-integrated manufacturing*, 28(1):75–86.
54. Zhang, L., Luo, Y., Tao, F., Li, B. H., Ren, L., Zhang, X., Guo, H., Cheng, Y., Hu, A., and Liu, Y. (2014). Cloud manufacturing: a new manufacturing paradigm. *Enterprise Information Systems*, 8(2):167–187.