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Blockchain and additive manufacturing: a taxonomy of business models

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Additive manufacturing processes such as 3D printing have seen significant progress in the industry in recent years and have become an integral part of Industry 4.0. This fourth industrial revolution is characterized by the increasing networking and automation of production systems and the use of large amounts of data. In this context, distributed ledger technologies (DLT), which include blockchain technology, offer promising opportunities to change production fundamentally. Production processes can be more secure and efficient by creating trust and transparency in data storage and eliminating dependence on centralized instances. However, the full potential of blockchain technology is often not realized due to the perceived complexity of its implementation. Overcoming this skepticism requires a better understanding of the application possibilities and, more importantly, successful practical examples demonstrating blockchain technology's transformative power in the industry. This study explores how blockchain can be effectively integrated into additive manufacturing processes and offers a structured overview of existing blockchain-based business models within this domain. Hence, a systematic literature interview, Crunchbase review, and Workshop are performed to examine specific use cases of blockchain in additive manufacturing and analyze how these technologies interact with existing business models. In order to provide an overview of existing blockchain-based business models in the context of additive manufacturing, a taxonomy is developed in the underlying paper to identify characteristic features. The taxonomy is further demonstrated along different existing business models.

KEYWORDS

blockchain, AM, additive manufacturing, 3D print, business models

Introduction

Additive manufacturing, widely recognized as 3D printing, has emerged as a transformative technology reshaping the production landscape. Enabling rapid prototyping, customization, and decentralized production has become a cornerstone of Industry 4.0—a paradigm shift characterized by the convergence of automation, data exchange, and interconnected systems in manufacturing (Stuckmann-Blumenstein et al., 2024a; Camarinha-Matos et al., 2017). This digital revolution introduces significant challenges and opportunities, especially in shared manufacturing models, where multiple stakeholders collaborate across a distributed network (Yu et al., 2020). Shared manufacturing involves pooling resources, capabilities, and expertise to achieve common production goals, but it also requires robust mechanisms to ensure trust, transparency, and equitable value distribution among participants (Jiang and Li, 2020; Yu et al., 2020). One of the primary barriers to adopting such models is the lack of trust among participants, which limits transparency, efficiency, and secure data sharing (Stuckmann-Blumenstein et al., 2024a; Jiang and Li, 2020).

Distributed ledger technologies (DLT), such as blockchain, hold promise as a solution to these challenges. Blockchain's inherent features—immutability, decentralization, and the ability to execute automated transactions via smart contracts—enable trust and transparency in data management (Zheng et al., 2017; Bashir, 2020). These characteristics are particularly relevant to shared manufacturing environments like 3D printing, where they can mitigate issues related to intellectual property protection, secure digital file sharing, and traceability in supply chains (Guo et al., 2022; Raj, 2021). In this context, developing decentralized Web3 marketplaces for 3D printing becomes crucial, as they provide a platform for transparent and trustless transactions while requiring a well-defined business model to ensure sustainability and practical adoption (Große et al., 2022; Stuckmann-Blumenstein et al., 2024b).

Despite its potential, the application of blockchain technology in additive and shared manufacturing remains underexplored, with limited research on how innovative business models can be developed around this intersection (Klöckner et al., 2020). Blockchain applications in additive manufacturing—particularly in 3D printing—are frequently discussed and are beginning to find their way into industrial practice. While current literature highlights blockchain's promise in enhancing production security and efficiency, skepticism about its complexity and implementation has hindered adoption. There is a growing need for practical frameworks and successful use cases to demonstrate blockchain's transformative potential, particularly in shared manufacturing (Krämer et al., 2024).

Thus, the following research questions (RQ) emerge:

RQ 1: Which business models exist in blockchain-based additive manufacturing for practical industrial applications?
RQ 2: What are the common characteristic features of these business models?
RQ 3: How can the characteristic features be categorized in a taxonomy?

This paper addresses this gap by developing a taxonomy of blockchain-based business models tailored to the context of shared manufacturing, with a focus on additive manufacturing. Hence, this paper offers a new structure for this emerging field. By systematically identifying and categorizing key features of these business models, this research provides practitioners with actionable insights and strategies for leveraging blockchain technology to foster secure, transparent, and efficient production processes. The study draws on a comprehensive review of existing literature, data from industrial blockchain use cases, and insights from expert workshops to validate the taxonomy.

The structure of the paper is as follows: First, we review related work on blockchain applications in additive manufacturing and blockchain-based business models. Next, we detail the research design and methodology employed in the study. We then present the developed taxonomy, highlighting its implications for shared manufacturing, and validate it with a survey. Finally, we discuss the contributions of this research and provide an outlook on future developments and potential avenues for further exploration.

Related work and theoretical foundations

Blockchain in additive manufacturing

Additive manufacturing has emerged as a transformative concept that reshapes resource utilization. In the context of blockchain, additive manufacturing is often used in sharing concepts like used in the sharing economy or for traceability reasons (Stuckmann-Blumenstein et al., 2024a). Sharing approaches enhance machine utilization, promote economies of scale, and strengthen resilience in manufacturing ecosystems (Yu et al., 2020). However, it faces challenges such as intellectual property protection, data security, and the need for equitable collaboration frameworks (Stuckmann-Blumenstein et al., 2024a).

Li et al. (2021) introduce the concept of social manufacturing, a novel paradigm that leverages networked manufacturing resources to meet personalized demands through crowd intelligence. Their blockchain-enabled digital twin collaboration platform addresses challenges related to decentralization and heterogeneity in social manufacturing resources (SMRs). This platform uses contracts to formalize collaboration within a 3D printing scenario, enhancing the efficiency of shared manufacturing systems. This approach aligns with the growing interest in the intersection of blockchain technology and additive manufacturing, aiming to foster collaborative ecosystems that improve both scalability and flexibility in production Li et al. (2021).

Similarly, Lu et al. (2021) explore the service-oriented transformation of manufacturing resources through a blockchain-enabled secure digital twin platform. This platform digitalizes physical resources into services and employs a rule-based off-chain mechanism to match customer orders with available manufacturing capabilities. Their architecture, developed using a private Ethereum blockchain and InterPlanetary File System (IPFS), highlights the potential for enhancing service-oriented manufacturing. Their experimental case in 3D printing demonstrates the practical benefits of secure and transparent resource-sharing in manufacturing networks Lu et al. (2021).

Li et al. (2021) propose a blockchain-based framework enabling fine-grained sharing of digital twins, addressing adoption challenges faced by small and medium-sized enterprises (SMEs) and individual resource owners. This framework, tested with multiple 3D printers, effectively enhances throughput and sustainability while promoting resource-sharing practices. This research is pivotal in advancing blockchain applications in additive manufacturing, particularly for SMEs that require scalable solutions for resource sharing Li et al. (2021).

In the aerospace industry, blockchain integration with additive manufacturing has been proposed to optimize the production of metal components. The system secures data throughout the production process by implementing a digital twin framework, ensuring compliance with stringent technical standards and traceability. This reduces time-to-market and optimizes cost efficiency, showcasing the potential of blockchain to enhance the reliability and efficiency of high-tech additive manufacturing processes (Klöckner et al., 2020). This approach is consistent with the growing emphasis on transparency and data security in the 3D printing business model (Klöckner et al., 2020).

Blockchain's role in intellectual property (IP) protection and data security is also evident in the development of secure design marketplaces and shared factories. By enabling secure, transparent transactions, blockchain facilitates the delivery of customized, cost-efficient products while mitigating the risks associated with unauthorized access and IP theft. This contributes to transforming value creation and delivery within 3D printing ecosystems, supporting new business models focused on local manufacturing and resource optimization (Klöckner et al., 2020).

Trust is crucial among parties involved in shared manufacturing, particularly concerning proprietary technologies and sensitive information. Principal-agent theory helps theorize these challenges by highlighting hidden characteristics, actions, and intentions (Jensen and Meckling, 1998; Krämer et al., 2024). The theory advocates for incentives that promote transparency and accountability. At the same time, blockchain technology provides a decentralized solution to mitigate these problems by ensuring all actions in a shared ecosystem are recorded (Treiblmaier, 2018).

Blockchain can (Treiblmaier, 2018):

- Mitigate Hidden Characteristics by storing verifiable credentials for agents.
- Address Hidden Actions through smart contracts that enforce agreement fulfillment.
- Counter Hidden Intentions with transparent, auditable transactions.

In industrial settings, both private and public blockchains are commonly used to fulfill corporate demands for transparency and data redundancy. In the manufacturing sector, blockchain integration provides end-to-end visibility across production processes and can serve as a verifiable digital receipt for customers. When combined with 3D printing, blockchain technology further strengthens intellectual property protection and enhances transparency throughout the design and production lifecycle. For instance, using non-fungible tokens (NFTs) with 3D printing files can secure designs against unauthorized access. Furthermore, blockchain can enable real-time monitoring of production processes, facilitating secure collaboration among stakeholders. Additional synergies between digital twins and blockchain enhance accountability and personalization in manufacturing. As industries focus on sustainability and efficiency, blockchain technology plays a crucial role in collaborative supply chain management, making it essential for the future of shared manufacturing.

Blockchain business models

Business model terminology emerged in the 1990s, and since then, business models have become increasingly important in research and industry practice (Veit et al., 2014). Business model analysis has established itself as a strategic management tool to support companies in evaluating their business logic and innovation management (Veit et al., 2014; Möller et al., 2020). Although the business model concept has already been extensively researched, there is no standardized definition. There are different approaches in the literature regarding what a business model is and what characterizes it, such as resource-oriented, activity-oriented, knowledge-oriented, economic, strategy-oriented and network-oriented approaches (Chao and Goli, 2024). However, a growing consensus is that business models should be understood as a comprehensive description and architecture of how an organization creates, delivers and captures value (Osterwalder et al., 2005; Shafer et al., 2005; Teece, 2010).

With the advent of information and communication technologies and the rise of digital businesses, the importance of the business model concept has further increased (DaSilva and Trkman, 2013). This focus stems from the understanding that the economic value of a technology depends on its commercialization through a business model (Chesbrough, 2010). Consequently, digitalization has challenged traditional methods of value creation and capture in business models (Teece, 2010) and opened new ways of creating value (Amit and Zott, 2001). In parallel, blockchain technology, which is known for its inherent characteristics, offers innovations for value creation and the development of new business models (Grünewald et al., 2024). Innovations in business models refer to changes in the way organizations create, deliver and capture value, including adjustments in activities, structures and governance (Chesbrough, 2010; Ramdani et al., 2019).

However, the application of traditional business models to new technologies such as blockchain presents unique challenges (Upadhyay, 2024). Despite the potential attributed to blockchain in academia, its integration into business models is still at an early stage (Treiblmaier and Špan, 2022; Grünewald et al., 2024). The need for a deeper understanding of how blockchain can revolutionize business processes is highlighted by Glaser (2017). It points to a gap in understanding blockchain's capabilities as a value creator. The study of the role of blockchain in business model innovation focuses on both technical aspects and architectural designs for value creation. Kavanagh and Dylan-Ennis (2020) and Pereira et al., (2019) address these technical discussions, while other research examines the broader business implications of blockchain (Nowiński and Kozma, 2017). The development of a taxonomy of blockchain-based business models by Weking et al. (2020), the derivation of blockchain business model archetypes in the domain supply chain management by Grünewald et al. (2024), and the investigation of value creation through blockchain by Schlecht et al. (2021) reflect the ongoing research into the transformative potential of blockchain for businesses. Adopting a business model perspective is essential to understanding how blockchain technology can foster innovative ways to generate and capture value (Chao and Goli, 2024).

Business models of industries and companies enabled by emerging technologies are often underdeveloped and fragmented (Upadhyay, 2024). Therefore, the underlying paper focuses on blockchain-based business models in additive manufacturing, particularly in 3D printing. The investigation of the role of blockchain in additive manufacturing and its influence on prevailing and future business models has been examined by

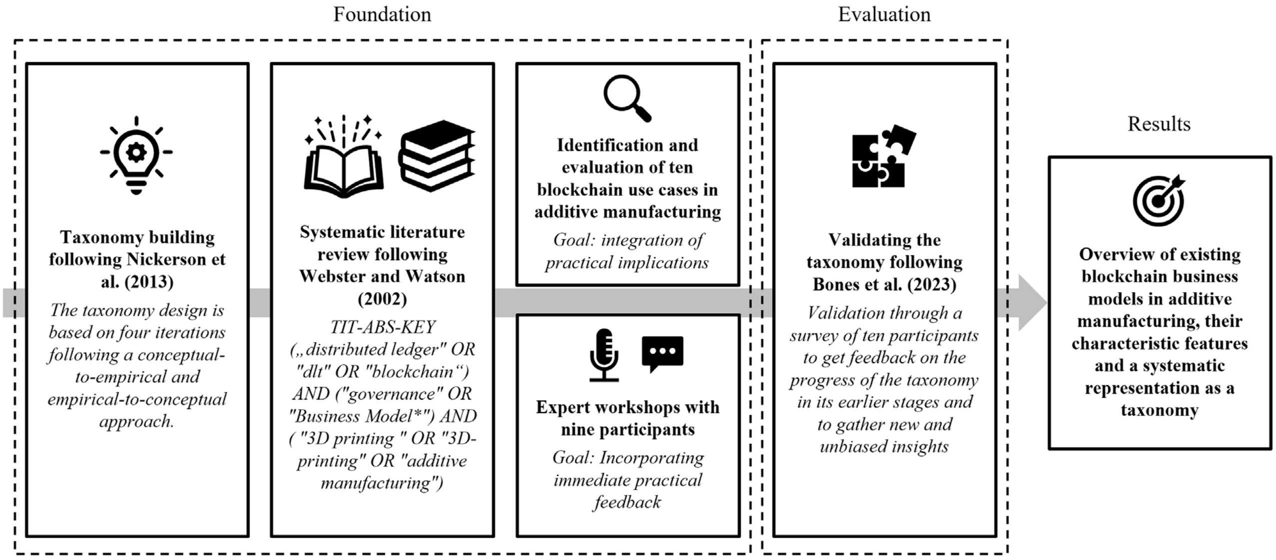


FIGURE 1
Overview of the research design.

Mayer et al., (2021) and Klöckner et al., (2020), among others. The research results show a consensus that blockchain can create new business models in additive manufacturing and change existing business processes (Mayer et al., 2021).

Research design

This study is based on a multi-level research design that draws on established scientific methods to answer the research questions stated above (see Figure 1).

An in-depth literature review, described in detail in the Related Work section, provides the theoretical foundation for the study in order to determine the current state of research. A systematic literature review (SLR) further refines the research process. It ensures a structured and reproducible methodology that serves as the foundation for the initial categorization and development of the taxonomy. To integrate practical implications into the taxonomy development process, empirical data on existing blockchain business models in additive manufacturing were collected and evaluated, and direct feedback from practitioners was incorporated in an expert workshop. The taxonomy was validated using a survey, thoroughly evaluating its practical applicability and theoretical soundness.

Taxonomy building

Taxonomies are a widely used approach in information systems (IS) research to classify, clarify, structure, and systematically examine complex phenomena (Nickerson et al., 2013). Their morphological representation allows for practical insights into the structure of a phenomenon, i.e., its morphological configuration (Álvarez and Ritchey, 2015). To identify the design elements of blockchain-based business models in additive manufacturing, we apply the renowned taxonomy methodology proposed by Nickerson et al., (2013), generating knowledge conceptually and empirically. To enhance the process, we integrate the framework of Szopinski et al., (2019), which incorporates an evaluation phase into our design iterations. Our research approach is divided into the iterative steps illustrated in Figure 2 and integrates inductive and deductive classification paradigms. This process continues until the taxonomy design reaches theoretical saturation (Nickerson et al., 2013; Gerber et al., 2017).

At first, we define a meta-characteristic, representing the purpose of the taxonomy and serving as the starting point for subordinate elements. The second phase determines the ending condition, defining the point at which taxonomy development is considered complete. Nickerson et al., (2013) identify eight objective and five subjective ending conditions that guide this phase. In the next phase, the user starts the conceptual construction of the taxonomy by deciding on an empirical-conceptual approach or its reverse. In the fourth phase, researchers may choose a conceptual-empirical approach, where dimensions are first derived conceptually and tested empirically on a subset of objects in the fifth phase. Alternatively, the empirical-conceptual approach may be applied, where dimensions are first identified inductively and then conceptually refined. This process is repeated iteratively until theoretical saturation is achieved, meaning no further adjustments to dimensions and features are required (Nickerson et al., 2013).

Ending conditions, meta-characteristic and meta-dimensions

The meta-characteristic defines the taxonomy's overarching goal and purpose. To address RQ3, we establish the meta-characteristic as "Characteristics of blockchain-based business models in additive manufacturing," which explores the impact of blockchain technology within this domain. This meta-characteristic provides the foundation for identifying subsequent dimensions and

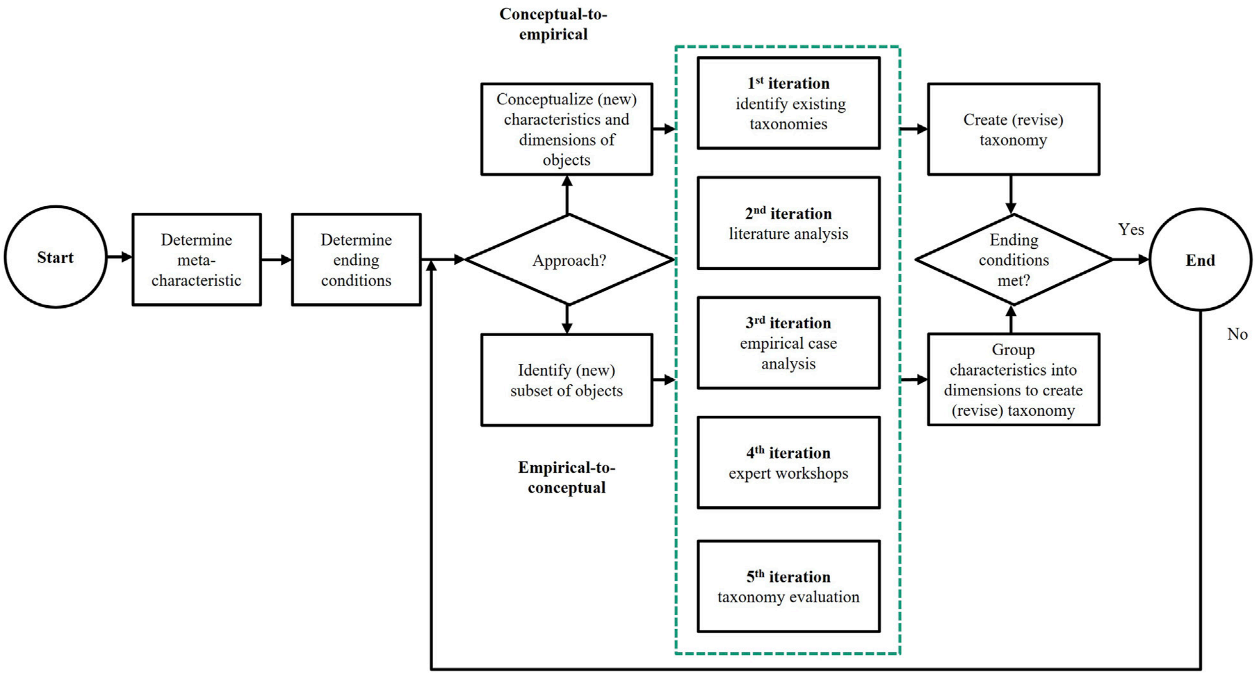


FIGURE 2
Procedural model for taxonomy development adapted from Nickerson et al., (2013).

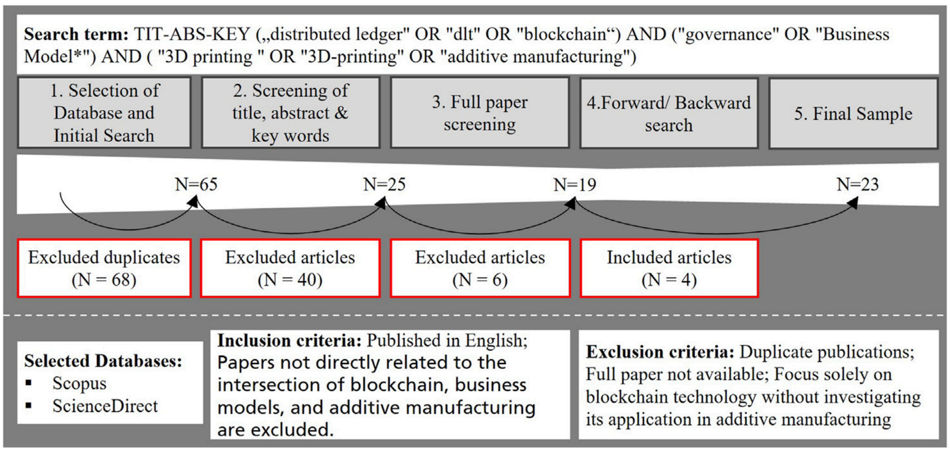


FIGURE 3
Visualization of literature search process.

characteristics and remains unchanged throughout the iterative development process.

A meta-dimension is used as a higher-level conceptual framework to derive dimensions and characteristics systematically. Following the approach of Remane et al. (2017), this method enables the targeted derivation of meaningful dimensions. Specifically, we adopt the V4 framework Al-Debei et al., (2008) developed, which offers an ontological high-level structure for business models and integrates economic (business models) and technical (architectures) aspects for classifying blockchain applications.

The V4 framework subdivides business models into four key components, making it particularly suited for analyzing blockchain-based business models (Grünewald et al., 2024):

- The Value Proposition encompasses the bundle of products and services that provide value to a specific customer segment (Chesbrough, 2010).
- The Value Architecture refers to the technological and organizational infrastructure required to deliver these products and services (Al-Debei and Avison, 2010).

TABLE 1 Abbreviated ending conditions adopted from Nickerson et al., (2013).

Ending Conditions		Design it.				Eval.
		#1	#2	#3	#4	#5
Objective	All objects or a representative amount of objects have been examined	-	-	-	✓	✓
	No object was merged with a similar object or split into multiple objects in the last Iteration	-	-	-	-	✓
	At least one object is classified under every characteristic of every dimension	✓	✓	✓	✓	✓
	No new dimensions or characteristics were added in the last iteration	-	-	-	-	✓
	No dimensions or characteristics were merged or split in the last iteration	-	-	-	-	✓
	Every dimension is unique and not repeated	✓	✓	✓	✓	✓
	Every characteristic is unique within its dimension	✓	✓	✓	✓	✓
	Each cell (combination of characteristics) is unique and is not repeated	✓	✓	✓	✓	✓
Subjective	Concise: Is the taxonomy meaningful without being overwhelming?	-	-	-	✓	✓
	Robust: Do the dimensions/characteristics provide for differentiation?	-	-	-	✓	✓
	Comprehensive: Can all objects or a random sample be classified?	-	-	-	-	✓
	Extendible: Can a new dimension/characteristic simply be added?	-	-	-	-	✓
	Explanatory: What do the dimensions/characteristics explain?	-	-	-	-	✓

- The Value Network includes the actors involved in creating the value proposition, the channels for value delivery, and the network's roles and modalities (Al-Debei and Avison, 2010).
- The Value Finance integrates revenue streams and cost structures, which are crucial for understanding the economic feasibility of blockchain applications (Al-Debei et al., 2008).

Taxonomies are considered complete when they reach a state that effectively represents the objects they aim to classify (Nickerson et al., 2013; Bock and Wiener, 2017). In line with standard taxonomy construction practices, the ending conditions defined by Nickerson et al. (2013) are satisfied in our work, ensuring the taxonomy's validity and utility. Through iterations, adjustments are made to the dimensions and characteristics until the fourth iteration, when the ending conditions are met. At this stage, each dimension and characteristic is uniquely associated with at least one object, ensuring no redundancy across dimensions or characteristics. After the fourth iteration, the eight dimensions of the taxonomy are confirmed to fulfill the subjective ending conditions. Table 1 summarizes the termination criteria. This visual representation avoids unnecessary complexity and aligns with similar taxonomies in its structure and detail (Oberländer et al., 2019; Kundisch et al., 2022). The resulting taxonomy is robust, extendable, and comprehensive while also differentiating between individual objects. The taxonomy also serves an explanatory function, illustrating the impact of blockchain technology in additive manufacturing.

Conceptual-to-empirical design iterations

In the first iteration, we develop an initial taxonomy by integrating existing taxonomies and typologies from prior research (see related work). During the second iteration, a systematic literature review (SLR) is conducted, a well-established approach for conceptualizing dimensions and characteristics (Kundisch et al., 2022). This process follows the guidelines proposed by vom Brocke et al. (2009) and Webster and Watson (2002). Scopus and ScienceDirect are the primary sources, encompassing the most relevant IS journals and proceedings. The scope of the review is confined to peer-reviewed, English-language publications contributing to the taxonomy's development. This includes conceptual studies on taxonomy development and articles addressing blockchain applications in additive manufacturing. The initial search yields 65 papers. A manual screening of titles, abstracts, and keywords, conducted to eliminate irrelevant or duplicate entries, narrows the selection to 19 papers. A full-text screening further refines the sample and serves as the basis for forward and backward search. Finally, 23 relevant papers are identified for the taxonomy development. The search process is summarized in Figure 3.

TABLE 2 Samples with name of the organization or project, maturity, and website.

#	Sample	Use case	Maturity	Link
1	OpenDXM/GlobalX	Secure deployment of 3D print data	Productive solution	https://www.prostep.com
2	Ambrace BV	Service platform for the 3D printing of spare parts	Productive solution	https://www.ambrace.com
3	dCentra GmbH	Secure deployment of 3D print data	Proof of concept	https://www.dcentra.io/
4	Chair of Microfluidics University Rostock	Quality management for a digital additive manufacturing part record	Research	https://www.uni-rostock.de/
5	C3BO	Capacity exchange for the 3D printing	Research	https://blockchain-europe.nrw/
6	Tecon	Service platform for the 3D printing of spare parts	Research	https://tecon.io/
7	SAMPL - Secure Additive Manufacturing Platform	Secure deployment of 3D print data	Research	https://sampl.fks.tuhh.de/en/home.html
8	3DOS	Service platform for the 3D printing	Productive solution	https://3dos.io/
9	ADDITIVE MARKING	Product Passport for additive manufacturing	Productive solution	https://additive-marking.de/
10	3DPlex	Service platform for the 3D printing	Productive solution	3dplex.io/

Empirical-to-conceptual design iterations

To integrate practical implications into the taxonomy development process, we gather and analyze additional empirical data on existing business models in additive manufacturing. This is a reasonable approach, as many organizations transparently share information about their business models—including their business approach and, in some cases, the corresponding charge (Teece, 2010). The data collection method follows the approach outlined by Grünewald et al., (2024). Given the novelty of blockchain technology, the underlying study focuses on a broad investigation of use cases from established companies, startups, and research projects that explore blockchain applications, emphasizing additive manufacturing.

For data collection, we conduct searches in databases such as Crunchbase and Google Search using keywords like "additive manufacturing" and synonyms such as "3D printing" combined with "blockchain." Crunchbase, one of the largest enterprise databases, serves over 70 million users and contains more than 2 million registered companies. It offers a comprehensive range of business-related information, including funding, investments, founding members, mergers and acquisitions, industry trends, and news. Companies in Crunchbase can be filtered based on various criteria, such as location, industry, and technology focus.

We apply five criteria to ensure the relevance of the included use cases:

- Only companies that have received funding are included to ensure data quality and viability (Krishna et al., 2016).
- We exclude companies that are no longer operational, such as those without a verifiable website or content in English or German (Möller et al., 2019).
- Companies unrelated to additive manufacturing are filtered out.
- We exclude use cases in which blockchain technology is not essential to the application (Weking et al., 2020).
- We exclude companies with insufficient publicly available information about their use cases (Täuscher and Laudien, 2018).

Following the approach of Tönnissen et al., (2020), to detail the use cases, we collect data using primary sources such as company websites and interviews and secondary sources, including publicly available articles, blog posts, and videos. In cases in which companies address multiple blockchain use cases, each use case is analyzed individually according to the aforementioned criteria, which results in some companies being listed multiple times. Ultimately, ten use cases are identified, as shown in Table 2.

We analyze these use cases by classifying them according to the dimensions and characteristics of our preliminary taxonomy. We aim to assign each use case to a single characteristic within each dimension during this process. Three scenarios emerge: (1) the use case can either be assigned to an existing characteristic in a dimension based on the available information, (2) it cannot be assigned to any characteristic due to insufficient accessible information, (3) or the use case provides information relevant to a dimension but does not match any of the existing characteristics, prompting adjustments or additions to the taxonomy design elements (e.g., the consideration of the TECON use case led to the addition of the characteristic product passport in the dimension use case). Throughout the third iteration, the frequency of the third scenario decreases progressively, leaving only the first two scenarios in our use case analyses. The empirical data collection is from the fall of 2024, with at least two authors independently performing the analysis. Despite promising developments in practice, blockchain applications remain highly dynamic, meaning some analyzed use cases may disappear while new ones are likely to emerge.

TABLE 3 Workshop participants.

Experts	Role	Relevant disciplines
#1: Academics	Research Associate	Knowledge in blockchain technology, additive manufacturing, and business models
#2: Applied Research	Research Associate	Knowledge in business model research and blockchain technology
#3: Industry	CEO	Expert in blockchain and E-Commerce
#4: Industry	CEO	Expert in additive manufacturing
#5: Academics	Research Associate	Knowledge in blockchain technology, additive manufacturing, and business models
#6: Applied Research	Research Associate	Knowledge in Software-Design, Blockchain and AI
#7: Applied Research	IT Dev	Knowledge in Software-Design, Blockchain and AI
#8: Industry	IT Dev	Knowledge in UI-Design
#9: Industry	IT Dev	Knowledge in Database-Design

TABLE 4 Final taxonomy of blockchain business models in additive manufacturing.

	Dimension	Characteristics						Ex
Value Proposition	Use case	Local manfacturing	Shared factories	Marketplaces	Product passport	Quality management		N
	Customer value	Cost/Sacrifice Value	Digital twin	Customization	Production on-demand	Flexible production capacities		N
	Customer segment	Business		Consumer		Both		Y
Value Network	Supply chain actor	OEM	Service provider	Supplier	Supervisory authority	Third parties	Customer	N
	Customer relationship	Automated operations		No direct relationship		Co-creation		Y
	Customer interface	App-based		Browser-based		On-premise		N
Value Architecture	Blockchain purpose	Monetization	IP and data protection		Traceability and authentication	Process automation		N
	Governance structure	Centralized		Hybrid		Distributed		Y
	Interoperability	Isolated system		Cross-chain communication		Standardized interfaces		Y
	Data Storage	On-chain		Off-chain		Hybrid		Y
Value Finance	Pricing mechanism	Price-based		Demand-based		Feature-based		Y
	Revenue model	Subscription	Freemium	Fee	Pay-per-use	Passive income		Y
	Currency acceptance	Fiat currency	Crypto currency	Hybrid		None		Y

Ex = Exclusivity, Y = Yes, and N = No.

In the fourth iteration, expert workshops are conducted to incorporate direct practical feedback into the taxonomy development process. These workshops are structured based on the method outlined by Szopinski et al., (2019) and revolve around three core questions: *Who* (i.e., the subject), *What* (i.e., the object), and *How* (i.e., the method). The workshops involve academics and practitioners who had not previously participated in the taxonomy development process (*Who* and *How*). The real-world problem is defined as "characterizing blockchain business models in additive manufacturing" (*What*).

Participants include researchers from universities and applied research institutes and practitioners with expertise in at least one of the following areas: blockchain technology, additive manufacturing, or business model development. The participants were divided into two groups to explore potential blockchain use cases in additive manufacturing. Discussions focus on key topics, including business models, governance structures, security and intellectual property (IP), and legal considerations. One author moderates each group, while two additional authors are responsible for documenting feedback and deriving implications to refine the taxonomy. Table 3 provides an overview of the workshops, including participant profiles.

Based on the workshop findings, the authors identified new design elements and refined existing ones. This included renaming certain elements, expanding features, consolidating aspects, and removing unnecessary components (e.g., adaptation and adjustment of the currency acceptance dimension). At this stage, the termination conditions were fulfilled, marking the conclusion of the taxonomy development process and the transition to the taxonomy evaluation phase.

Taxonomy of blockchain business models in additive manufacturing

Table 4 illustrates the final taxonomy, which comprises 13 dimensions (Dn) and 50 characteristics (Cn.m), structured across four meta-dimensions based on the framework by Al-Debei et al., (2008). While taxonomies are traditionally constructed with mutually exclusive characteristics (Nickerson et al., 2013), the specific nature of the identified attributes leads us to adopt non-exclusive characteristics consistent with a morphological approach. This methodology is particularly appropriate as it aligns with the taxonomy's role as a visualization tool (Möller et al., 2022). However, this choice introduces additional complexity, requiring a higher level of generalization for characteristic attributes and potentially complicating the explicit representation of exemplars.

Value proposition

A business model must deliver a compelling value proposition to its customers, addressing a significant problem or fulfilling a critical need for a specific target group through an appropriate product or service offering (Johnson et al., 2008). The value of a technology is ultimately determined by the customer's willingness to pay for the associated product or service (Chesbrough and Rosenbloom, 2002). Building on prior research and in alignment with the defined framework, the meta-dimension v*alue proposition* encompasses three dimensions: *use case*, c*ustomer value*, and c*ustomer segment*.

Both academic literature and industrial practice explore various blockchain applications in additive manufacturing. The dimension *use case* (D1) pertains to the diversity of use cases for blockchain solutions. The taxonomy differentiates between l*ocal manufacturing* (C1.1) (Klöckner et al., 2020), *shared factories* (C1.2) (Klöckner et al., 2020), *marketplaces* (C1.3) (Klöckner et al., 2020), *product passport* (C1.4), and *quality management* (C1.5) (Westphal et al., 2023). To create value, businesses must understand and meet customer needs effectively. The taxonomy addresses this aspect through the dimension of *customer value* (D2). In business model terminology, this typically involves resource optimization, process improvement, and the generation of new revenue streams. Specifically, blockchain integration in additive manufacturing enables outcomes such as *cost/sacrifice value* (C2.1) (Mayer et al., 2021), *digital twin* (C2.2) (Mayer et al., 2021), *customization* (C2.3) (Klöckner et al., 2020), *production on-demand* (C2.4) (Klöckner et al., 2020), and *flexible production capacities* (C2.5) (Klöckner et al., 2020). The dimension *customer segment* (D3) identifies the product or service's target group (Rückeshäuser and Ostern, 2017). A level of abstraction is required to ensure meaningful inclusion in the taxonomy. Consequently, a two-part classification is applied, distinguishing between the *business* (C3.1) and *consumer* (C3.2) segments, and *both* (C3.3).

Value network

The positioning of a company within its *value network* plays a crucial role in defining its business model. Through its interactions with suppliers, partners, and customers, the company can facilitate the delivery of complementary goods, enhance network effects, and contribute additional value to existing information systems (Rückeshäuser and Ostern, 2017). This positioning also highlights where customer value is generated within the value chain context (Chesbrough and Rosenbloom, 2002). In light of this, the taxonomy examines the dimensions of *supply chain actor*, *customer relationship*, and *customer interface*.

The dimension *supply chain actor* (D4) identifies the entities interacting within a blockchain network solution. The taxonomy distinguishes between several actor categories, including *OEMs* (C4.1), *service providers* (C4.2), *suppliers* (C4.3), *supervisory authorities* (C4.4), *third parties* (C4.5), and *customers* (C4.6). The dimension of *customer relationship* (D5) focuses on acquiring new customers and retaining existing ones (Osterwalder and Pigneur, 2013). Utilizing DLT enables automated customer interactions through *automated operations* (C5.1) (Mayer et al., 2021). Additionally, decentralizing business models may eliminate the need for direct customer relationships (C5.2), fostering transparency and trust in aspects like quality assurance and auditing (Mayer et al., 2021). Collaborative efforts between data-providing companies and service providers exemplify Customer Relationship *co-creation* (C5.3), where value is co-generated with customers (Mayer et al., 2021). The dimension *customer interface* (D6) refers to how users access the product or service, such as *app-based* interfaces (C6.1), *browser-based* solutions (C6.2), or *on-premise* software (C6.3) (Duparc et al., 2022).

Value architecture

The *value architecture* outlines the technological and organizational framework that underpins a business model (Al-Debei and Avison, 2010). This taxonomy encompasses the dimensions of *blockchain purpose*, *governance structure*, *interoperability*, and *data storage* within the business model.

The *blockchain purpose* dimension (D7) represents various characteristics and highlights how blockchain technology provides value for additive manufacturing. Following (Ghimire et al., 2022), the taxonomy distinguishes between *monetization* (C7.1), *intellectual property (IP) and data protection* (C7.2), *traceability and authentication* (C7.3), and *process automation* (C7.4). The *governance structure* dimension (D8) refers to the primary technical framework utilized by a data provider to facilitate information sharing within an ecosystem (Gelhaar et al., 2021a). The selected governance structure impacts several factors, including incentive mechanisms, data security, data control, and the trust level among ecosystem participants (Al-Zahrani, 2020). Data sharing can be implemented via a *centralized infrastructure* (C8.1), such as proprietary cloud platforms (Azkan et al., 2020). Alternatively, ecosystems may adopt *distributed infrastructures* (C8.2), leveraging distributed ledger technologies or peer-to-peer networks (Gelhaar et al., 2021b). *Hybrid infrastructures* (C8.3), which integrate centralized and distributed technologies like cloud platforms and blockchain solutions, are also gaining traction (Große et al., 2020). The *interoperability* dimension (D9) addresses the ability of different blockchain systems within an ecosystem to interact seamlessly and exchange data, ensuring efficient functionality and integration. This dimension differentiates between i*solated systems* (C9.1), which do not allow external connectivity, *cross-chain communication* (C9.2), which facilitates data exchange across multiple blockchains, and *standardized interfaces* (C9.3), enabling compatibility with various protocols and platforms (Harris, 2023). The *data storage* dimension (D10) focuses on the methods used for storing data in a system, emphasizing a balance between security, scalability, and efficiency. *On-chain storage* (C10.1) (Krämer et al., 2022; Bhateja et al., 2023) involves storing data directly on the blockchain, ensuring high immutability, transparency, and security levels. However, this approach is limited by blockchain networks' storage capacity and can be costly due to its resource-intensive nature. In contrast, *off-chain storage* (C10.2) (Krämer et al., 2022; Bhateja et al., 2023) relies on external databases or cloud systems, offering greater scalability and cost efficiency. While suitable for managing large data volumes, this method may challenge trust and data integrity. *Hybrid storage* models (C10.3) (Krämer et al., 2022; Bhateja et al., 2023) combine the advantages of both approaches, storing critical or sensitive data on-chain for security purposes and less critical data off-chain to enhance performance and reduce costs.

Value finance

To ensure the profitability of a business model, it is essential to analyze its financial perspective. A successful business model must establish a coherent profit-generation mechanism (Morris et al., 2005). The meta-dimension of *value finance* encompasses various aspects related to costs, pricing strategies, and revenue distribution (Al-Debei and Avison, 2010). This includes addressing considerations such as "*Pricing mechanism*", "*Revenue model*", and "*Currency acceptance*".

The *pricing mechanism* dimension (D11) defines the method by which the final price paid by the customer is determined. According to Möller et al., (2019), a three-part classification is applied, distinguishing between *demand-based* (C11.1), *feature-based* (C11.2), and *price-based* (C11.3). In a demand-based model, pricing is influenced by usage frequency, the realized price, or a percentage commission. In contrast, feature-based pricing is determined by the specific functionalities or services the customer selects. The dimension *revenue model* (D12) refers to the specific pattern of revenue generation, i.e., it explains how the business makes money. Our sample reveals that five pricing mechanisms are dominant *subscription* (C12.1) (Grünewald et al., 2024), *freemium* (C12.2) (Möller et al., 2019), *fee* (C12.3) (Möller et al., 2019), *pay-per-use* (C12.4) (Grünewald et al., 2024) and *passive income* (C12.5) (Duparc et al., 2022). The *currency acceptance* dimension (D13) specifies the types of currencies the operator accepts for payment. An analysis of blockchain use cases reveals diverse payment methods, which can be categorized as *fiat currency* (C13.1) (Grünewald et al., 2024), *cryptocurrency* (C13.2) (Grünewald et al., 2024), and *hybrid* (C13.3) (Grünewald et al., 2024) models that combine fiat and cryptocurrencies, and free solutions, where users can access the service without payment (C13.4).

Case study: TECON

In order to ensure the internal validity of the taxonomy, its application is demonstrated using the example of the TECON Initiative depicted in Table 5. TECON is an innovative initiative revolutionizing product management by integrating non-fungible tokens (NFTs) into unique, verifiable product passports. This approach assigns each product—particularly spare parts—a distinctive NFT that digitally represents its identity and lifecycle.

The *use case* empowers companies to independently produce spare parts or other customizations for their products, including product passport features. Blueprints for these parts can be purchased through integration into webshops. The *customer value* lies in the interconnected and securely stored information on a decentralized solution, ensuring data security and authenticity. Using decentralized storage, TECON provides a reliable and secure repository for all product information, specifications, and associated data, including blueprints. The current customer segment focuses exclusively on the business domain, particularly users of machinery and its producers, identified as *supply chain actors*. The *customer interface* is browser-based and accessible through a webshop or QR codes on the physical parts. The *blockchain aims to protect blueprint providers' intellectual property* through individualized and licensed blueprints for each customer while ensuring the traceability of part interconnections. Since XIONI GmbH offers the initiative, the service distribution is managed by XIONI, with a centralized *governance structure* as the service provider. The systems are also *interoperable*, particularly regarding integration with diverse webshops or internal systems, thanks to standardized interfaces. *Data storage* is hybrid: large datasets are stored on IPFS and webshops, while smaller datasets are maintained on-chain. Customers pay based on requested features and a pay-per-use model. Both fiat and cryptocurrency are accepted as payment methods.

The appendix (see Table A1 shows the taxonomy with classified examples from the taxonomy application. Among these is the Tecon case study. In addition, further use cases are presented to illustrate the broader applicability of the taxonomy.

Discussion

In order to ensure the proposed taxonomy's external validity and identify its limitations, an online survey is conducted following the methodology outlined by (Bons et al., 2023). Participants were asked to respond to ten questions anonymously. Twenty experts were carefully selected and contacted via email based on their experience with blockchain projects, particularly in an industrial context.

The survey aimed to achieve two objectives: first, to gather feedback on the progression of the taxonomy from its earlier stages, and second, to collect new and unbiased insights. Of the twenty experts contacted, ten responded, resulting in a response rate of 50.0%. This response formed the basis for subsequent evaluation and

TABLE 5 Final taxonomy on the example of Tecon.

	Dimension	Characteristics						Ex
Value Proposition	Use case	Local manfacturing	Shared factories	Marketplaces	Product passport	Quality management		N
	Customer value	Cost/Sacrifice Value	Digital twin	Customization	Production on-demand	Flexible production capacities		N
	Customer segment	Business		Consumer		Both		Y
Value Network	Supply chain actor	OEM	Service provider	Supplier	Supervisory authority	Third parties	Customer	N
	Customer relationship	Automated operations		No direct relationship		Co-creation		Y
	Customer interface	App-based		Browser-based		On-premise		N
Value Architecture	Blockchain purpose	Monetization	IP and data protection		Traceability and authentication	Process automation		N
	Governance structure	Centralized		Hybrid		Distributed		Y
	Interoperability	Isolated system		Cross-chain communication		Standardized interfaces		Y
	Data Storage	On-chain		Off-chain		Hybrid		Y
Value Finance	Pricing mechanism	Price-based		Demand-based		Feature-based		Y
	Revenue model	Subscription	Freemium	Fee	Pay-per-use	Passive income		Y
	Currency acceptance	Fiat currency	Crypto currency	Hybrid		None		Y

discussion. The evaluation sought to determine whether the taxonomy comprehensively identifies relevant topics and whether these topics are organized into meaningful and practical clusters. To address these objectives, the first seven questions of the survey required participants to rate seven attributes (see Table 6) using a Likert scale. This scale, standard in survey questionnaires, ranged from 1 (lowest level of agreement) to 5 (highest level of agreement). The final three questions were open-ended, allowing participants to recommend further improvements. The applied Likert scale is ordinal, meaning the values have a defined order, but the intervals between them are not necessarily equal (Heumann and Schomaker, 2016). The survey results were analyzed using appropriate statistical methods and visualized using relevant diagrams.

The business model governance taxonomy received highly positive evaluations, with over 80% of participants rating it as "rather agree" or "strongly agree" across all dimensions. Clarity and comprehensibility (1) achieved 80% approval, while coverage of relevant aspects (2) was rated even higher at 90%. Logical structure and topics (3) received unanimously positive feedback, with 100% of responses rather than strongly agreeing. Usefulness (4) and clear structure (5) were both rated positively by 80% of participants, highlighting their practical value. Practical implementation (6) stood out with 90% approval and only 10% rather not agree, reflecting strong feasibility. Finally, the likelihood of recommendation (7) was high, with 80% of participants indicating they would recommend it. To get more ideas for improvement, we also integrated three open-text questions to get a better impression of the feedback.

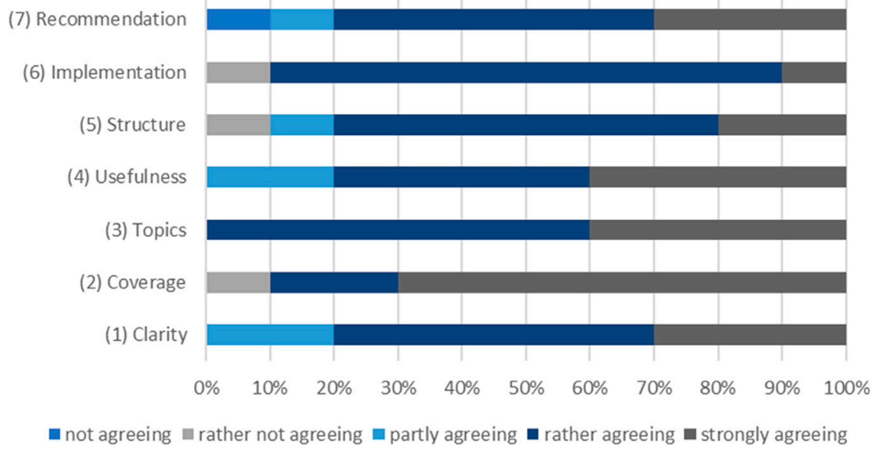
Several respondents suggested reducing the number of dimensions and categories for simplicity and enhancing clarity, particularly regarding categories' exclusivity and potential non-exclusive alternatives. Specific feedback includes calls for a more precise purpose and better explanation of dimensions like interoperability and data storage, especially for users unfamiliar with blockchain applications. Some respondents questioned the taxonomy's ability to derive business model archetypes due to non-exclusive characteristics. In contrast, others requested refinement of specific terms, such as *consumer* versus *customer* in the *customer segment* dimension, to avoid confusion. Practical questions about the interdependence of dimensions, like *customer relationships* and *supply chain actors*, were also raised. Additional suggestions include integrating the interaction of blockchain with emerging technologies like AI and big data and addressing the diverse needs and interests within a value network. Despite these suggestions, the taxonomy was praised for its comprehensiveness, holistic perspective, and coverage of blockchain's impact on business models.

The feedback from the participants underlines the taxonomy's high level of clarity, practical relevance, and comprehensive inclusion of design elements. The team of authors discussed the evaluation results regarding possible implications for the taxonomy. Based on the participants' input, the authors decided that no further adjustments are necessary, which means that the taxonomy has reached a sufficient saturation level to mark the end of the development process.

Conclusion, limitations and outlook

This study presents a taxonomy designed to categorize and better understand the emerging business models at the intersection of blockchain and additive manufacturing. To achieve this, three research questions (RQs) have been established and addressed

TABLE 6 Evaluation results, visualized as a stacked bar chart.



through this contribution. First, a comprehensive literature review and systematic market analysis explored the business models associated with blockchain-based additive manufacturing for practical industrial applications (RQ1). A market analysis utilizing data from Crunchbase examined ten real-world applications, offering insights into industry trends and existing business models. This analysis served as a foundation for identifying the practical applications of blockchain within additive manufacturing.

In addition, RQ2 investigated the common characteristics of these business models. A systematic literature review developed a concept matrix, capturing recurring patterns and features among the identified models. The market analysis strengthened these findings, ensuring a solid connection between academic insights and real-world observations.

Lastly, a rigorous iterative process was employed to categorize these characteristic features into a cohesive taxonomy. The taxonomy was created by synthesizing insights from existing frameworks, literature, and market analysis and then refined through expert workshops and feedback sessions. Studies have highlighted the ability of blockchain solutions to transform and disrupt existing business models in additive manufacturing while also enabling the creation of entirely new business models. Based on scientific literature, an empirical series of ten use cases, and expert workshops, a taxonomy of blockchain-based business models in additive manufacturing was developed, allowing for the classification of business models based on 13 dimensions and 50 characteristics. Although blockchain technology has been discussed in academic literature for several years, its implementation in industrial practice is still in its early stages. As a result, there is a gap between academia's promises and its current business value. The extent to which blockchain technology is adopted in additive manufacturing fosters the emergence of new business models or impacts existing ones, a key focus of the taxonomic analysis. The taxonomy's internal validity was demonstrated through its application to specific use cases, showcasing its utility in research and practice. To assess its external validity, a survey was conducted, revealing a high level of agreement among experts, with all questions receiving over 80% agreement. For practitioners, the taxonomy provides a structured overview of possible manifestations, aiding in clearer decision-making and analysis. As a theoretical contribution, it helps bridge the gap between practice and theory, offering a common framework that integrates insights from both domains.

Certain limitations exist in taxonomic analysis. The procedural approach to taxonomy development cannot eliminate the influence of the authors' subjective assumptions, particularly in defining meta-dimensions, suitable dimensions, and characteristics. Another limitation concerns the collection of company data. The data collection focuses on companies that develop and implement blockchain solutions in additive manufacturing. For this purpose, the startup database CrunchBase and an extended secondary research approach were selected. However, it cannot be ruled out that this method may have failed to identify further relevant companies essential for developing and validating the taxonomy. This study will be expanded by incorporating additional databases and companies to gain a more comprehensive understanding and to identify emerging business models. Another aspect relates to the data basis for the coding process, which relies on publicly available information such as company websites, existing technical or white papers, and CrunchBase data. This approach enhances the validity of the dataset. Although the empirical data collection was conducted collaboratively within the research team and differing assessments were discussed, the data remains susceptible to personal influences and preferences. For the development of the taxonomy a limited pool of available experts participating in the workshops may have constrained the methodological rigor, resulting in methodological ambiguity. Thus, the results must be interpreted with an awareness of these contextual limitations. Engaging more practitioners for iterative feedback will strengthen the taxonomy's practical applicability and reveal additional limitations in real-world contexts. Furthermore, incorporating a legal perspective as a new point of view could yield valuable insights, particularly regarding regulatory compliance and ethical considerations, which are increasingly crucial in evolving new business models.

Future research should expand upon this study by involving a broader and more diverse range of academic and industrial experts, including those from interdisciplinary fields, to enhance the taxonomy's robustness and generalizability. Additionally, we suggest that researchers revisit our work, as blockchain's emerging nature in additive manufacturing inherently restricts the research scope and the available findings. Further research is needed on how the transformation of additive manufacturing to holistic business models based on blockchain technology can be realized. As progress continues and the technology is adopted in business practice, the sample size can be expanded, allowing archetypal business model patterns to be derived. In a more mature field, more academic research and experts will be available to refine the taxonomy and adapt it to the continuous and dynamic changes in this field. As progress continues and the technology is adopted in business practice, the sample size can be expanded, allowing archetypal business model patterns to be derived. A particular focus is expanding the business model perspective to include blockchain-based value creation. In this context, further research is also needed regarding the contribution of blockchain technology to increasing resilient value creation and promoting sustainability. The question of how blockchain technology and token concepts can be used to enable sustainable economic activity and how such concepts can be designed must be answered. This understanding helps implement sustainable business models and evaluate new forms of value creation, e.g., through tokenization, in economic terms.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. PS-B: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. PK: Writing – original draft, Writing – review and editing. LK: Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE A1 Taxonomy of blockchain business models in additive manufacturing.

<table>
<tr><th></th><th>Dimension</th><th colspan="6">Characteristics</th><th>Ex</th></tr>
<tr><td rowspan="3">Value proposition</td><td>Use case</td><td>🟡 Local 🔴 manfacturing</td><td>Shared factories 🔵</td><td>Marketplaces 🔴 🔵 🟡</td><td>Product passport 🔴</td><td colspan="2">Quality management</td><td>N</td></tr>
<tr><td>Customer value</td><td>Cost/Sacrifice Value 🔵</td><td>Digital twin 🔴</td><td>Customization 🔴</td><td>Production on-demand 🔴 🔵</td><td colspan="2">🔵 Flexible production capacities</td><td>N</td></tr>
<tr><td>Customer segment</td><td colspan="2">Business 🔴 🔵</td><td colspan="2">Consumer</td><td colspan="2">Both 🟡</td><td>Y</td></tr>
<tr><td rowspan="3">Value network</td><td>Supply chain actor</td><td>OEM 🔴 🔵 🟡</td><td>🟡Service provider</td><td>Supplier 🔴 🔵</td><td>Supervisory authority</td><td>Third parties</td><td>Customer 🟡</td><td>N</td></tr>
<tr><td>Customer relationship</td><td colspan="2">Automated operations 🔴 🔵</td><td colspan="2">No direct relationship</td><td colspan="2">Co-creation 🟡</td><td>Y</td></tr>
<tr><td>Customer interface</td><td colspan="2">App-based</td><td colspan="2">Browser-based 🔴 🔵 🟡</td><td colspan="2">On-premise</td><td>N</td></tr>
<tr><td rowspan="4">Value architecture</td><td>Blockchain purpose</td><td>Monetization 🟡</td><td colspan="2">🔴IP and 🟡 data protection</td><td>Traceability and 🔴 authentication</td><td colspan="2">Process automation 🔵</td><td>N</td></tr>
<tr><td>Governance structure</td><td colspan="2">Centralized 🔴 🟡</td><td colspan="2">Hybrid</td><td colspan="2">Distributed 🔵</td><td>Y</td></tr>
<tr><td>Interoperability</td><td colspan="2">Isolated system 🟡</td><td colspan="2">Cross-chain communication</td><td colspan="2">Standardized interfaces 🔴 🔵</td><td>Y</td></tr>
<tr><td>Data Storage</td><td colspan="2">On-chain</td><td colspan="2">Off-chain</td><td colspan="2">Hybrid 🔴 🔵 🟡</td><td>Y</td></tr>
<tr><td rowspan="3">Value finance</td><td>Pricing mechanism</td><td colspan="2">Price-based 🟡</td><td colspan="2">Demand-based 🔵</td><td colspan="2">Feature-based 🔴</td><td>Y</td></tr>
<tr><td>Revenue model</td><td>Subscription</td><td>Freemium</td><td>Fee</td><td>Pay-per-use 🔴 🔵 🟡</td><td colspan="2">Passive income</td><td>Y</td></tr>
<tr><td>Currency acceptance</td><td>Fiat currency</td><td>Crypto currency 🔵</td><td colspan="2">Hybrid 🔴 🟡</td><td colspan="2">None</td><td>Y</td></tr>
</table>

🟡 Tecon, 🔴 C3BO, 🔵 3DOS.

Final taxonomy visualized as a morphological box with the three examples Tecon (Red), C3BO (Blue) and 3DOS (Orange), MD = Meta-Dimension, EX = Exclusivity, Y = Yes, N = No