

Deloitte.
University Press

3D opportunity for blockchain

Additive manufacturing links the digital thread

ABOUT THE AUTHORS

Stuart Trouton

Stuart Trouton is a manager within Deloitte Consulting LLP's Analytics and Information Management practice. He brings his mechanical engineering background and experience with information technology and cybersecurity to help clients create innovative solutions for their toughest problems. He is currently focused on developing advanced technology solutions, including blockchain for the supply chain and the digital thread for additive manufacturing.

Mark Vitale

Mark Vitale is a specialist leader with Deloitte Consulting LLP's Federal practice, working as an advisor to public sector clients on a wide range of supply chain management issues. With more than 30 years of supply chain operations experience, he has led multiple engagements with the US Department of Defense focused on operations strategy, supply chain planning, inventory optimization, network design, and operations cost improvement.

Jason Killmeyer

Jason Killmeyer serves as a senior consultant for Federal Strategy and Operations, working with government agencies to develop and implement supply chain risk management strategies in a modern environment. Killmeyer's background in emerging trends analysis and horizon scanning informs both that work and the discussions he has across the federal sector on how those emerging trends are becoming commercial and public sector realities.

Deloitte Consulting LLP's Supply Chain and Manufacturing Operations practice helps companies understand and address opportunities to apply advanced manufacturing technologies to impact their businesses' performance, innovation, and growth. Our insights into additive manufacturing allow us to help organizations reassess their people, process, technology, and innovation strategies in light of this emerging set of technologies. Contact the authors for more information, or read more about our alliance with 3D Systems and our 3D Printing Discovery Center on www.deloitte.com.

CONTENTS

Introduction | 2

Blockchain | 5

An overview

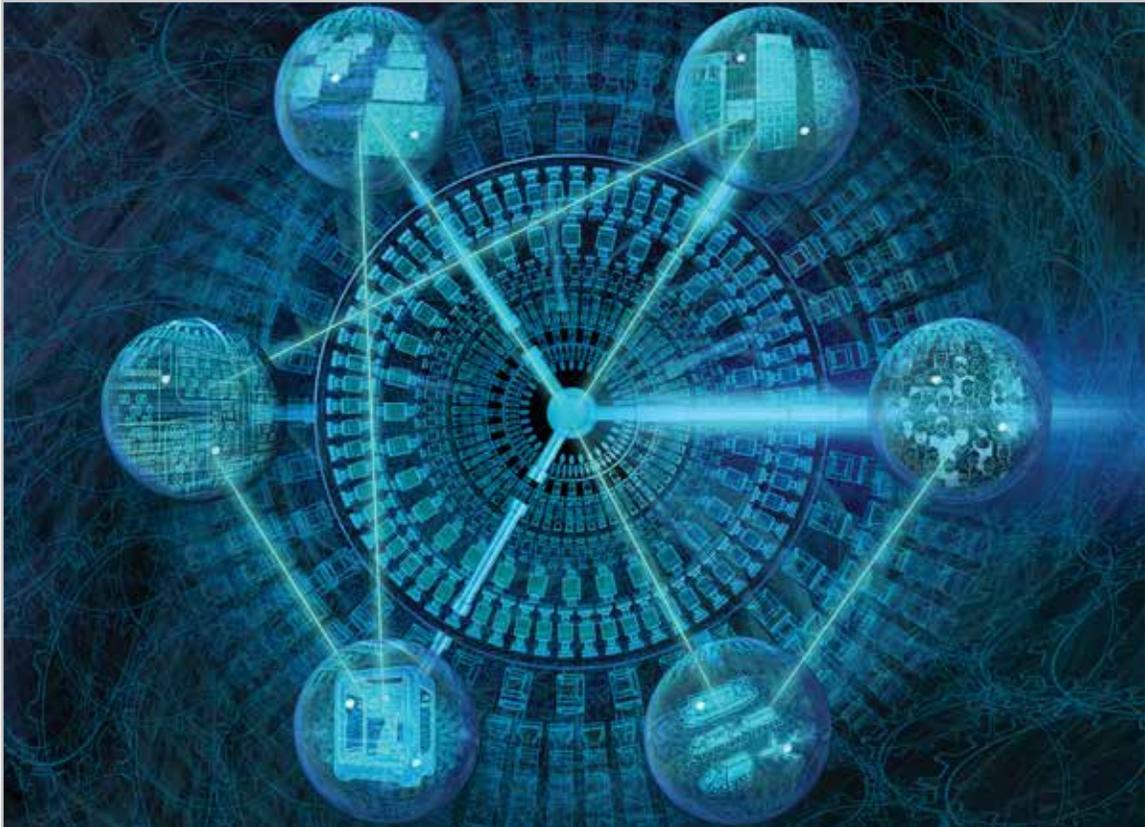
Challenges to building a digital thread for additive manufacturing | 8

Blockchain as a potential solution

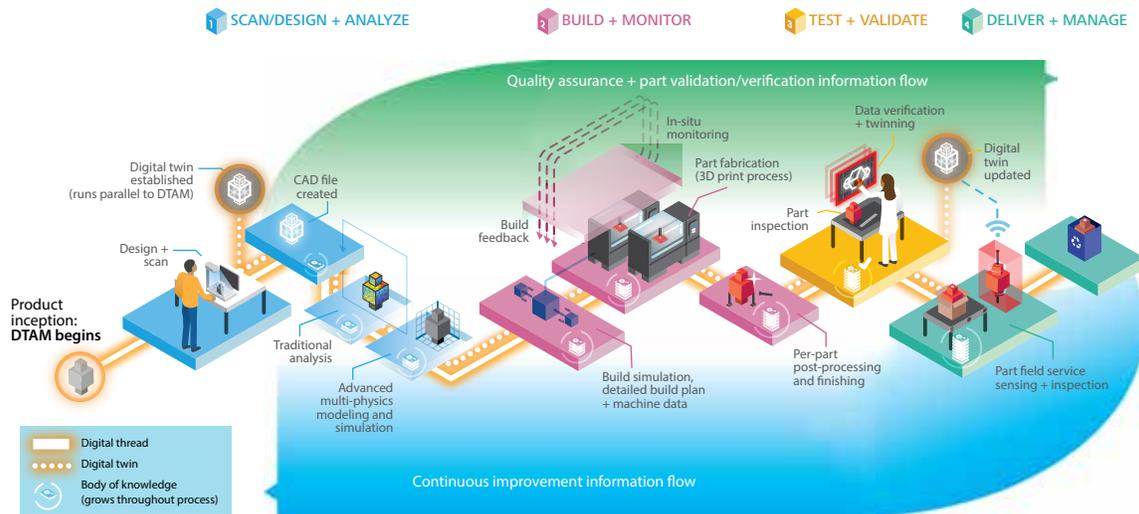
Blockchain and additive manufacturing | 13

Next steps

Introduction



From the creation of the additive manufacturing (AM) design to final production on the shop floor, AM files can be easily transmitted with the click of a mouse. The digital nature of AM means that parts and products are easier to share and transmit, enabling the creation of digital supply networks and supply chains. Additionally, it creates the opportunity to make AM part development fully documentable and attributable. On the other hand, however, there are cons that accompany these digital pros. In the absence of a strong data-protection framework, a digital design-and-manufacture process creates the potential for data theft or tampering.¹

Figure 1. The digital thread for additive manufacturingDeloitte University Press | dupress.deloitte.com

FOR these reasons, it seems crucial that we begin to view AM as an inherently digital production process, and thus consider it with the same perspective as other data-centric innovations. In March 2016, Deloitte University Press published *3D opportunity and the digital thread*, positing that the major element preventing AM from mass adoption was the absence of a digital thread—a single, seamless strand of data that stretches from the initial design concept to the finished part.² Put more simply, for AM processes to scale at the industrial level, a series of complex, connected, and data-driven events likely needs to occur. In this way, successfully deploying AM is less a physical- or hardware-associated production challenge and more a data- or

records-management one. This is referred to as the digital thread for additive manufacturing (DTAM).

The digital nature of the AM supply chain suggests the potential for a distributed model across a number of partners and disparate geographic locations. This distributed AM supply chain is enabled by the transmission of AM data and the comparative convenience of printing parts on location.⁴ Data availability and interconnectivity would help drive the adoption of AM in the supply chain by changing the paradigm and shipping data, not parts. Additionally, the DTAM enables product innovation through technologies such as topology optimization and advanced multiphysics modeling. The DTAM is

UNDERSTANDING THE DIGITAL THREAD: AN OVERVIEW

The digital thread is considered the backbone that carries the information throughout the AM process. Specifically, the DTAM is a single, seamless strand of data that stretches all the way from the initial design concept to the finished part, constituting the information which enables the design, modeling, production, validation, use, and monitoring of a manufactured part.³

As an individual object is designed, tested, produced, and used, it is described by data created throughout the DTAM. The ability to dissect, understand, store, and utilize this data, as well as to manage intense computing demands, allows innovators to scale AM production, manage the complexities of AM, and connect AM across the supply chain. Figure 1 depicts the DTAM.

also a key component of quality assurance for AM (QAAM) and is requisite for part certification.⁵

In the same way that the DTAM supports both supply chain scale and product innovation, the blockchain for AM has the potential to serve as a backbone and security layer for the DTAM, underpinning all of the transactions that occur throughout the digital and physical life cycle for AM. Indeed, the concept of blockchain has already been the subject of countless articles and speculated uses.

This paper, however, explores how the data management opportunities and challenges identified in the digital thread can be leveraged via the distrib-

uted ledger known as the blockchain: a distributed, append-only ledger for the recording of transactions. This paper will also examine how blockchain may add value to the digital thread, making AM more accessible to industrial and supply chain managers around the world and potentially solving the problem of data recordation for complex, certified parts. It will explore the utility of the technology in this space, namely as the *single transaction and recordation layer*⁶ for digital thread information, and identify areas where blockchain can add value—as well as where it may not. It will also pinpoint where further research is possibly required as these two technologies inevitably intersect.

The blockchain for AM has the potential to serve as a backbone and security layer for the DTAM.

Blockchain

An overview

WHILE the term “blockchain” has gained prominence in recent years as the subject of countless articles, the concept itself may be unfamiliar to many in manufacturing. The majority of early use cases have emerged within the financial services industry, initially in concert with the coverage of the cryptocurrency, bitcoin, the first use case for blockchain.⁷ Therefore, for the purposes of this article, it may be helpful to start by defining blockchain and clarifying some of its relevance to the supply chain and manufacturing sectors.

So, what is blockchain?

Simply put, blockchain is a distributed ledger that provides a way for information to be recorded and shared by a community. In this community, each member maintains his or her own copy of the information and all members must collectively validate any updates (see the sidebar: *Collective action and the blockchain*). The information could represent transactions, contracts, assets, identities, or anything else that can be described in digital form. Entries are permanent, transparent, and searchable, which makes it possible for community members to view transaction histories in their entirety. Each update constitutes a new “block” added to the end of the “chain.” A protocol manages how new edits or entries are initiated, validated, recorded, and distributed (see figure 2).⁸

Blockchain can exist as open source or in private, consortium, or other platforms.⁹ With blockchain, cryptology replaces third-party intermediaries as the keeper of trust, with all blockchain participants running complex algorithms to certify the integrity of the whole.¹⁰ Readers may note that cryptography and distribution as a resilience mechanism are concepts that existed before the advent of blockchain in

With blockchain, cryptology replaces third-party intermediaries as the keeper of trust.

early 2009. The combination of these concepts in a unique manner, however, is what allows for something that may be considered truly new: the replacement of existing intermediary institutions typically in place to facilitate value exchange via the reduction or elimination of counterparty risk.

To date, more than a billion dollars in venture capital funds have flowed into blockchain and cryptocurrency (the first use case for blockchain and its original *raison d’être*), focused on applications,¹¹ platforms, and other start-ups. Despite this exuberance, much of the blockchain ecosystem and its associated applications are still in the research and development phase.^{12, 13}

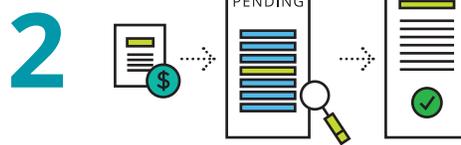
So why is this technology relevant to the supply chain? A range of major players and start-ups are exploring that very question. A key realization is that timely and accurate information about a product throughout its life cycle is in itself an asset. Blockchain serves as a simultaneous transaction and recordation layer,¹⁴ and so it has the potential to unite stakeholders on a single platform (not unlike other ERM or enterprise architecture solutions) around a single source of truth.¹⁵ As we build additional sensors to increase in-transit visibility and eventually move toward Internet of Things (IoT) and ubiquitous sensors,¹⁶ blockchain potentially serves as the data or transaction layer for all of that information moving within and between organizations in an encrypted fashion.

Figure 2. Blockchain: How it works

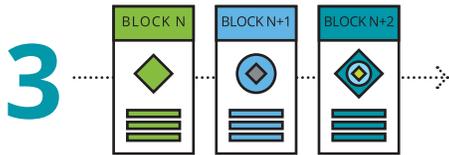
Blockchain allows for the secure management of a shared ledger, where transactions are verified and stored on a network without a governing central authority. Blockchains can come in different configurations, ranging from public, open-source networks to private blockchains that require explicit permission to read or write. Computer science and advanced mathematics (in the form of cryptographic hash functions) are what make blockchains tick, not just enabling transactions but also protecting a blockchain's integrity and anonymity.



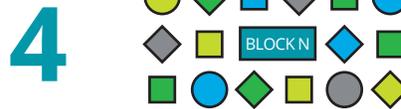
1 TRANSACTION Two parties exchange data; this could represent money, contracts, deeds, medical records, customer details, or any other asset that can be described in digital form.



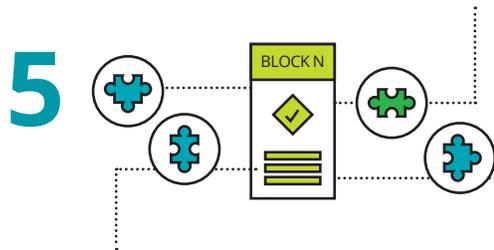
2 VERIFICATION Depending on the network's parameters, the transaction is either verified instantly or transcribed into a secured record and placed in a queue of pending transactions. In this case, nodes—the computers or servers in the network—determine if the transactions are valid based on a set of rules the network has agreed on.



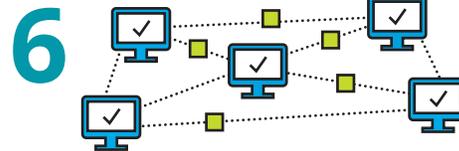
3 STRUCTURE Each block is identified by a hash, a 256-bit number, created using an algorithm agreed upon by the network. A block contains a header, a reference to the previous block's hash, and a group of transactions. The sequence of linked hashes creates a secure, interdependent chain.



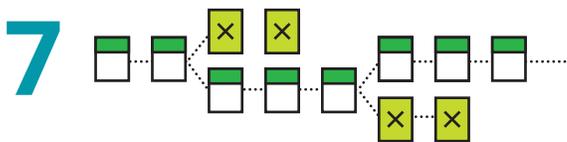
4 VALIDATION Blocks must first be validated to be added to the blockchain. The most accepted form of validation for open-source blockchains is proof of work—the solution to a mathematical puzzle derived from the block's header.



5 BLOCKCHAIN MINING Miners try to “solve” the block by making incremental changes to one variable until the solution satisfies a network-wide target. This is called “proof of work” because correct answers cannot be falsified; potential solutions must prove that the appropriate level of computing power was drained in solving.



6 THE CHAIN When a block is validated, the miners that solved the puzzle are rewarded and the block is distributed through the network. Each node adds the block to the majority chain, the network's immutable and auditable blockchain.



7 BUILT-IN DEFENSE If a malicious miner tries to submit an altered block to the chain, the hash function of that block, and all following blocks, would change. The other nodes would detect these changes and reject the block from the majority chain, preventing corruption.

Source: Deloitte Tech Trends 2016, *Blockchain: Democratized Trust*.

COLLECTIVE ACTION AND THE BLOCKCHAIN

Understanding consensus mechanisms and incentive structures across a distributed and untrusted network

If the system is distributed, how are collective action problems addressed?

Blockchain is essentially software, and the rule sets for a blockchain, or protocols, establish a consensus mechanism—the degree of proof or trust typically needed to validate updates and certify the integrity of the whole. Blockchain does not eliminate the need for trust between parties; it replaces the existing mechanism for gaining trust (bank, escrow, and so on) with cryptography, and maintaining that trust is not cost-free. The method via which trust is achieved is called the consensus mechanism, and the cost is referred to as the incentive structure—how the *maintenance* of trust is *sustained*. These are the two fundamental pillars of blockchain, referred to as the consensus mechanism and an incentive structure to sustain the expenditure of effort for that validation to take place and continue. The exact features of those two elements—the consensus mechanism and incentive structure—are tailorable across different ecosystems, but the success of the protocol often depends on those two foundations.

Recognizing how blockchain can intersect with other emerging technologies and understanding the broad set of potentially applicable asset classes may be key to the development of blockchain applications. The concept of an industrial blockchain and the fusion of AM with ubiquitous sensors and computing have the potential to reshape the industry. As the rapid proliferation of sensors and connected systems accumulate terabytes of information, a distributed ledger system may be a more appropriate

platform than the traditional centralized enterprise architecture for transacting information.

How does blockchain add value in the environment described above? One way to understand this, and the situations where the technology does add value, is to consider five fundamental characteristics of blockchain and their particular relevance to AM as seen in figure 3.¹⁷

Figure 3. Blockchain characteristics and their relevance to additive manufacturing

Blockchain characteristic	Relevance to additive manufacturing
Distributed —data maintained within and among stakeholders	Helps in management of activity in distributed supply chain expected to be found with AM
Near real-time —settlement and exchange are nearly instant ¹⁸	Changes to a design are made instantly which facilitates efficient AM processes
Trustless environment —cryptographic validation of transactions	Designed to protect against risks of unauthorized data access
Irreversibility —the transaction history is append-only	Helps with cyber risk and IP protection as it is intended to provide an indelible and traceable record of changes
Censorship-resistant —modifying past transactions would be expensive and immediately detected	

Source: Deloitte analysis.

Challenges to building a digital thread for additive manufacturing

Blockchain as a potential solution

ALTHOUGH industry has begun to build the DTAM,¹⁹ this effort faces considerable challenges. These challenges primarily concern the integration of software/product lifecycle management (PLM) platforms, multiple printers/printing technologies, and multiple disparate and disconnected physical manufacturing facilities or locations.²⁰ Additionally, organizations face challenges in the recordation of events that occur during the additive process, something that may be required for part certification and qualification, as parts need to be checked throughout the entire process and not just inspected at the end.^{21,22} Blockchain potentially provides the security layer and middleware to integrate and connect the digital thread; however, it will likely not be the solve-all solution to building the DTAM.

Before examining some specific potential use case scenarios, the following section will examine how blockchain's role as simultaneous transaction and recordation layer may apply to the data manage-

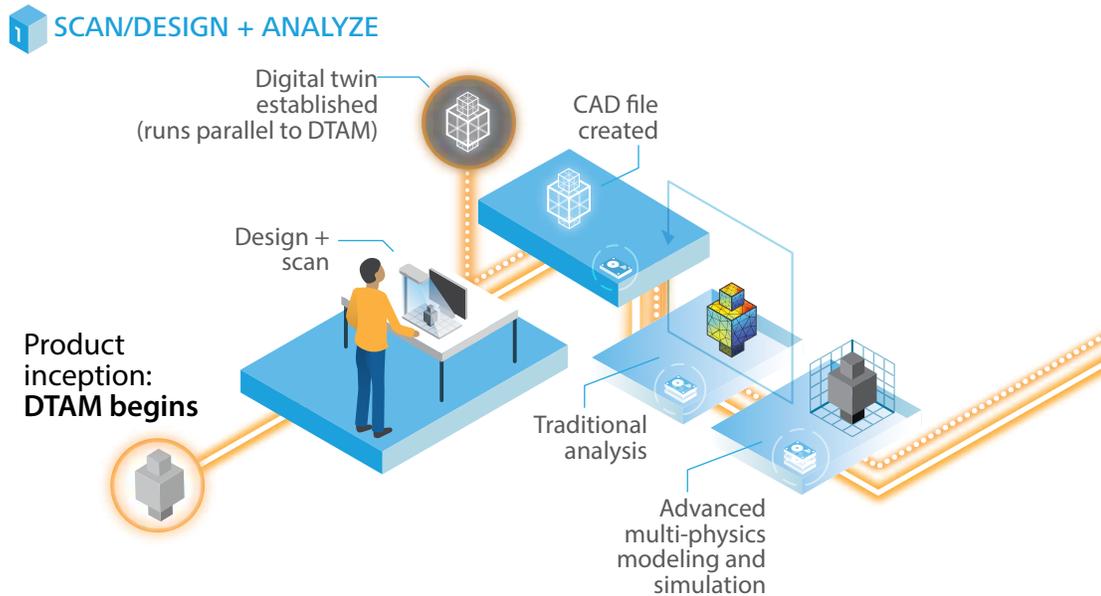
Blockchain potentially provides the security layer and middleware to integrate and connect the digital thread.

ment challenges inherent to building a sustainable digital thread. In particular, we look at the manner in which blockchain may allow for uniting a variety of inputs and platforms without the need to solve each associated data standardization or other asset management challenge inherent to the digital thread. This section breaks down aspects of the digital thread by phase, discusses associated challenges, and offers suggestions as to how blockchain may be able to solve them.

Scan/design and analyze

The DTAM begins with the scan/design and analyze phase (figure 4). In this phase, part designs are created, either by engineers working with CAD tools or by scanning existing parts.²³ This phase encompasses the first bits of digital data that get recorded and ends with a part model that is ready to print.²⁴

In this phase there are several handoffs of data that occur, often switching from a CAD system to analysis tools to other design software.²⁵ This often occurs in an environment with many engineers, different parts, departments, and so on. Companies often employ PLM systems to manage all these check-in, check-out transactions²⁶ with parts and their associated revisions. This effort is often complex and requires significant configuration and centralized control to work properly.²⁷ Blockchain, however, allows for append-only timestamp²⁸ version tracking of these changes. This can be distributed across multiple organizations and departments and act as

Figure 4. Detail of a digital thread: Phase 1

Deloitte University Press | dupress.deloitte.com

a ledger accounting for all state changes in a decentralized fashion.

This phase of the DTAM faces several challenges related to file formats and data standardization.²⁹ While blockchain doesn't explicitly solve these challenges, providing a secure transaction layer with standardized rule sets or associated metadata for each file format may serve as a shared language upon which information can be communicated—thus creating a format-agnostic accounting of changes to files, analysis performed, and transmission from software tool to software tool.³⁰ It provides a platform for which file signatures may be tracked across platforms to maintain traceability³¹ in the design and analysis process.

This functionality seems very relevant in the case of part scanners that may require calibration and often use proprietary software to transform scans into CAD or point cloud files that can be imported into other CAD tools or software. Blockchain could record calibration events to help verify scan integrity, by either recording the state change or even preventing the recording of a transaction (that is, the scan itself) on the blockchain for an improperly calibrated device if the range measured is a result

of a machine malfunction or is otherwise outside an acceptable range of outputs. Blockchain can also ensure files are not tampered with when moving between intermediary software tools.

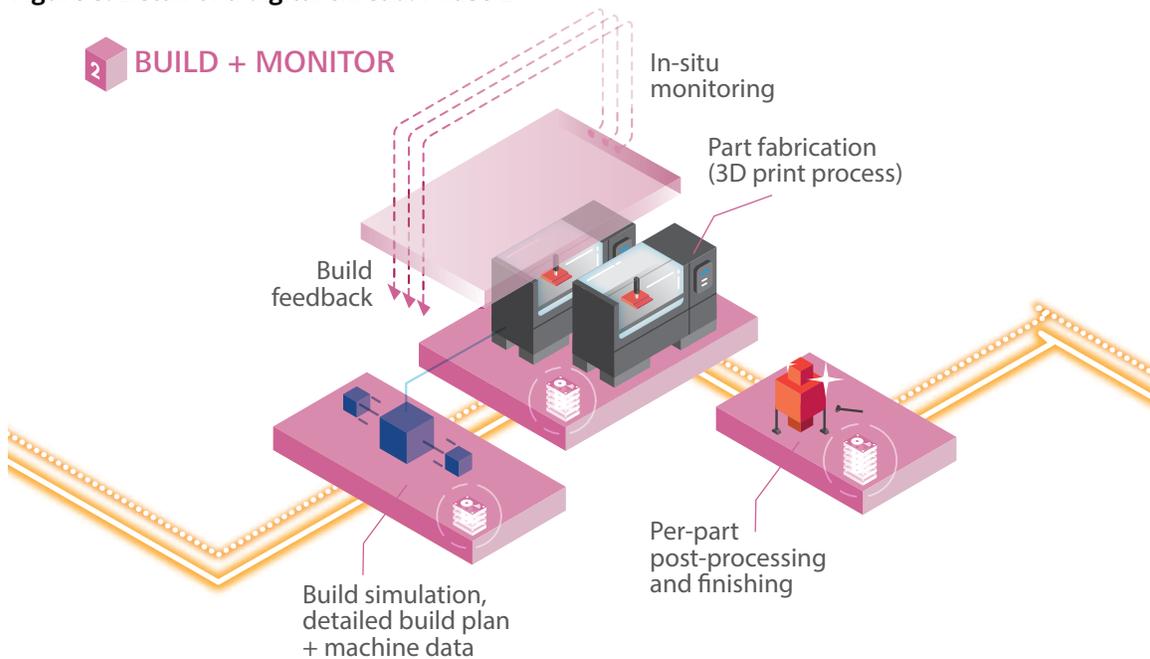
Blockchain is especially relevant in scan/design and analyze due to the almost exclusively digital nature of this phase.³² The technology is especially relevant as it provides append-only recordation that has implications for feedback and simulation loops which inform iterative design and real-time machine control in the build and monitor phase.

Build and monitor

The build and monitor phase of the DTAM is focused on transforming the digital model created in the scan/design and analyze phase into a physical part (figure 5).³³ This phase is critical, as there is a large amount of data created to enable the build process³⁴ and an even larger amount of data that can potentially be captured from sensor data during the build.³⁵

These data are especially important in the context of part certification, as unlike conventional subtrac-

Figure 5. Detail of a digital thread: Phase 2

Deloitte University Press | dupress.deloitte.com

tive manufacturing, AM requires a paradigm shift and focus on qualifying the entire build process. This phase also faces challenges from the potential distributed nature of AM,³⁶ scaling across a supply chain and builds occurring in multiple locations. Both of these require systems and infrastructure to track, control, process feedback, and collect data.

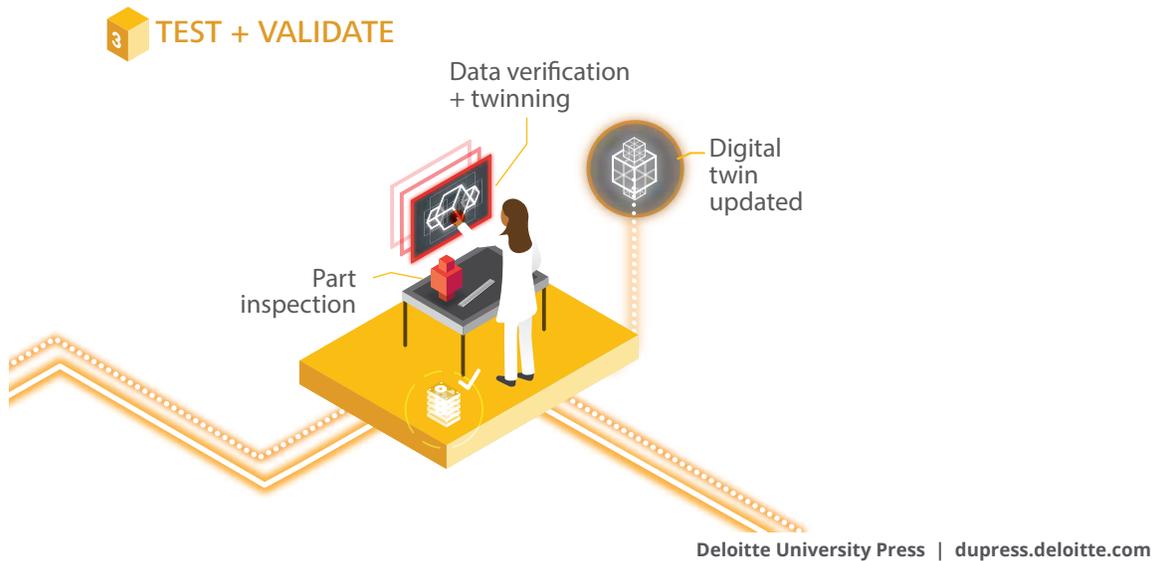
These challenges can potentially be addressed with blockchain. In the context of distributed-at-point-of-need manufacturing, blockchain may serve as the tamper-resistant transaction layer creating a reality not stored by any one machine, but instead decentralized and distributed amongst stakeholders.³⁷ In the instance of complex part manufacturing requiring audit trails for certification, blockchain may add value as well.³⁸ Currently, sensor data is not fully integrated in many current applications.³⁹ Machine control and sensor data collection aren't explicitly linked, and often machines are augmented with separate sensors not included with the OEM machine itself.⁴⁰ Blockchain can transact records of sensor data sets across these discrete segments for a particular part to maintain individual part history. Blockchain is not a file storage solution, but instead provides a mechanism to record digital fingerprints

of the capture data sets, similar to how sufficient transaction metadata allows for the validation and recording of cryptocurrency transactions.

In both instances, there is often a need to embed serials and unique identifiers to parts. These can be added by machines (and printed into parts). Blockchain can help maintain attribution for these parts by acting as the uniting layer in which to record the chain of custody and track on a per-part basis with a serial number/unique identifier.⁴¹ This may help avoid counterfeiting issues and can allow for the dissemination of some information about the part while obscuring certain private information.

Test and validate

The test and validate phase of the DTAM involves many inspection techniques that occur in both the digital and physical realms (figure 6).⁴² These vary in level of complexity and are explained in more detail in the *3D opportunity for the DTAM* paper. One of the challenges in this phase is in tying the records created for the inspection of the individually serialized unit part with the digital models responsible for its creation.⁴³

Figure 6. Detail of a digital thread: Phase 3

There are several reasons why this is needed, both from a quality assurance and certification perspective as well as for process tuning and continuous improvement. In the context of the digital twin, a complete digital representation of the physical part and test and validation data is important.⁴⁴ Understanding and tracking any flaws or tolerance measurements can be vital. Blockchain can transact records of test data sets for a particular part to maintain individual part history. Blockchain also offers append-only functionality and can validate that necessary steps took place as part of qualification and certification. As verification and validation data are needed across a distributed network of partners and organizations,⁴⁵ this may become especially important. Blockchain allows for the transaction and recordation layer to be one and the same.⁴⁶ Ensuring accurate appendage of test results or modification data to the original files is often critical.

Deliver and manage

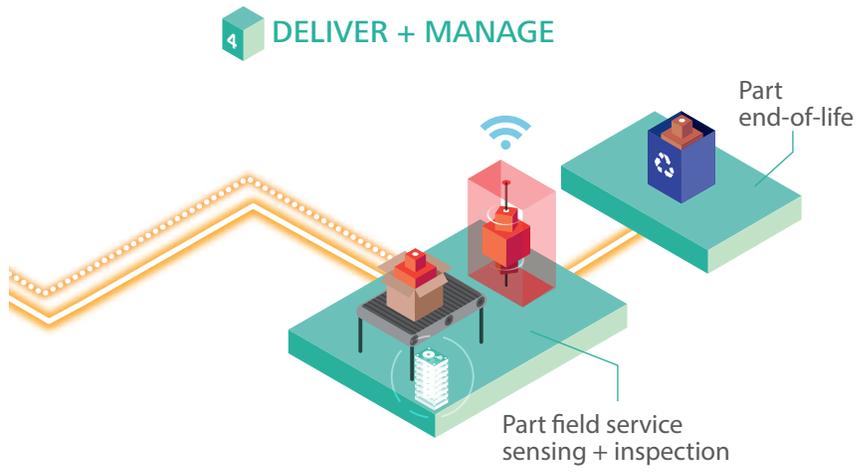
In the deliver and manage phase of the DTAM, parts are put to their intended use in the field. There is the opportunity to collect data on these parts through

integrated sensors and monitors which feed continuous improvement feedback loops going back to part design (figure 7).⁴⁷ The data created through these sensors are by nature disparate, as components or products are propagated for usage. Blockchain provides a platform for which sensor data⁴⁸ can be tracked across platforms and provide attribution to original part design, manufacture, and distribution. This can happen in a decentralized fashion not requiring central control. This is analogous to using blockchain for IoT-connected devices.⁴⁹

Promising use cases for blockchain beyond cryptocurrencies and other financial assets are only now beginning to reveal themselves. The unique characteristics of blockchain described above may eventually fit well with the AM problem set versus other enterprise architecture or databasing solutions.

Blockchain is by no means a silver bullet solution for safeguarding the digital thread. However, it has implications for each of the major stages of the thread. For this reason, blockchain is likely worthy of further study in the AM context. As with any enterprise software solution, the implementation can vary on a case-by-case basis.

Figure 7. Detail of a digital thread: Phase 4



Deloitte University Press | dupress.deloitte.com

Blockchain and additive manufacturing

Next steps

AM as a capability is positioned to significantly grow in scale in the near future. At approximately \$5 billion annually as of 2016 and predicted to be at least \$20 billion by 2020,⁵⁰ the industry seems at high risk of significant growing pains as it scales. In particular, the digital nature of the AM product poses novel problems in an otherwise traditional manufacturing environment.

The emerging concept of the “digital thread for AM” provides a conceptual answer to securing and organizing the data generated across the end-to-end AM process. The next step for industry leaders is to consider the potential technology solutions to enable the digital thread. This paper illustrates the unique potential of blockchain to address each of the components of the digital thread and provides illustrative examples of the specific value that blockchain could add. While all decisions should be made on a case-by-case basis, blockchain options may pro-

The next step for industry leaders is to consider the potential technology solutions to enable the digital thread.

vide an intriguing path for the AM industry to explore further. Companies and organizations should keep a finger on the pulse of developments in the blockchain space as they look to build secure and connected manufacturing infrastructure. With the ever-increasing need for connectedness and security, blockchain may provide the backbone enabling manufacturing of the future.

ENDNOTES

1. John Brown et al., *3D opportunity and cyber risk management: Additive manufacturing secures the thread*, Deloitte University Press, August 23, 2016, <http://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/3d-printing-cyber-risk-management.html?id=us:2el:3dc:dup3292:awa:dup:3dopp:dcpromo>.
2. For more information, see Mark Cotteleer, Stuart Trouton, and Ed Dobner, *3D opportunity and the digital thread: Additive manufacturing ties it all together*, Deloitte University Press, March 3, 2016, <https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing.html>.
3. Ibid.
4. Ibid.
5. Kim et al., "Streamlining the additive manufacturing digital spectrum."
6. Oliver Wyman, *Blockchain in capital markets: The prize and the journey*, February 2016, <http://www.oliverwyman.com/content/dam/oliver-wyman/global/en/2016/feb/BlockChain-In-Capital-Markets.pdf>.
7. Deloitte, *Out of the blocks: From hype to prototype*, May 2016, <http://www2.deloitte.com/content/dam/Deloitte/nl/Documents/financial-services/deloitte-nl-fsi-blockchain-from-hype-to-prototype-out-of-the-blocks.pdf>.
8. Eric Piscini et al., *Blockchain: democratized trust: Distributed ledgers and the future of value*, Deloitte University Press, <http://dupress.deloitte.com/dup-us-en/focus/tech-trends/2016/blockchain-applications-and-trust-in-a-global-economy.html>.
9. Deloitte UK, *Blockchain: Enigma. Paradox. Opportunity*, <http://www2.deloitte.com/uk/en/pages/innovation/articles/blockchain.html>, accessed October 21, 2016.
10. Ibid; Piscini et al., *Blockchain: Democratized trust*.
11. Jose Pagliery, "Record \$1 billion invested in bitcoin firms so far," *CNN Money*, November 3, 2015, <http://money.cnn.com/2015/11/02/technology/bitcoin-1-billion-invested/index.html>.
12. William Mouyagar, "The next phase of the blockchain is about business and innovation," *Startup Management*, September 4, 2016, <http://startupmanagement.org/2016/09/04/the-next-phase-of-the-blockchain-is-about-business-and-innovation/>
13. David Furlonger and Ray Valdes, "Hype cycle for blockchain technologies and the programmable economy, 2016," *Gartner*, July 27, 2016, <https://www.gartner.com/doc/3392717/hype-cycle-blockchain-technologies-programmable>.
14. Internal Deloitte discussion, phrasings.
15. Lory Kehoe and David Dalton, *Insights: Blockchain: Tracing transactions*, Deloitte; John Ream, Yang Chu, and David Schatsky, *Upgrading blockchains: Smart contracts use cases in industry*, Deloitte University Press, June 8, 2016, <https://dupress.deloitte.com/dup-us-en/focus/signals-for-strategists/using-blockchain-for-smart-contracts.html>.
16. *Gartner*, "2020 IoT projections," <http://www.gartner.com/newsroom/id/3165317>.
17. Ibid; Deloitte, *Out of the blocks*, <https://www2.deloitte.com/ie/en/pages/financial-services/articles/out-of-the-blocks-efma-report.html>.

18. Transaction processing and confirmation times vary based on which blockchain is used, and improvements to the processing time for blocks of transactions are likely to emerge in the future. In certain phases of the DTAM, significant data volume can be generated. It may not make sense to record the entirety of it to the blockchain, but rather record that the data was captured and record the fingerprint for that data.
19. Proto Labs, *Data, digital threads and Industry 4.0*, <https://www.protolabs.com/documents/united-states/whitepapers/Industry-4.0-WP-US.pdf>, accessed October 21, 2016.
20. Ibid; Cotteleer, Trouton, and Dobner, *3D opportunity and the digital thread*.
21. Brian Tilton, *3D Opportunity and the digital thread: A closer look at scan, design and analyze*, draft Deloitte IP.
22. Ian Wing, Rob Gorham, and Mark Cotteleer, *3D opportunity for quality assurance and parts qualification*, Deloitte University Press, November 18, 2015, <https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/3d-printing-quality-assurance-in-manufacturing.html>.
23. Ibid.
24. Ibid; Cotteleer, Trouton, and Dobner, *3D Opportunity and the digital thread*.
25. Ibid; Tilton, *3D Opportunity and the digital thread*.
26. Oleg Shilovitsky, "Can poor CAD file management stop system engineering efforts?" *Beyond PLM*, August 4, 2016, <http://beyondplm.com/2016/08/05/digital-habits-mbse-system-engineering-approach/>
27. Ibid.
28. Ibid; Deloitte, *Blockchain: Enigma. Paradox. Opportunity*, <https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/financial-services/deloitte-nl-fsi-blockchain-enigma-paradox-opportunity-report.pdf>.
29. Duck Bong Kim et al., *Streamlining the additive manufacturing digital spectrum: A systems approach*, Additive Manufacturing 5, January 2015.
30. Ranjit Bawa, Jacques de Villiers, and George Collins, *Autonomic platforms: Building blocks for laborless IT*, Deloitte University Press, February 24, 2016, <https://dupress.deloitte.com/dup-us-en/focus/tech-trends/2016/bi-model-it-on-autonomic-platforms.html>.
31. Deloitte press release, "Deloitte develops blockchain proof of concept to solve traceability issues in art," May 23, 2016, for ArtTrackLive blockchain prototype, <https://www2.deloitte.com/lu/en/pages/technology/articles/blockchain-proof-concept-solve-traceability-issues-art.html>.
32. Ibid; Tilton, *3D opportunity and the digital thread*.
33. Ibid; Cotteleer, Trouton, and Dobner, *3D opportunity and the digital thread*.
34. Ibid.
35. Wing, Gorham, and Cotteleer, *3D opportunity for quality assurance and parts qualification*.
36. Ibid.
37. Ibid; Piscini et al., *Blockchain: Democratized trust*.
38. Ibid; Ream, Chu, and Schatsky, *Upgrading blockchains*.
39. Ibid. Cotteleer, Trouton, and Dobner, *3D opportunity and the digital thread*.
40. Ibid.
41. Ibid.

3D opportunity for blockchain

42. Ibid.
43. Ibid.
44. Ibid.
45. Ibid.
46. Ibid; Kehoe and Dalton, *Insights: Blockchain*.
47. Ibid; Cotteleer, Trouton, and Dobner, *3D opportunity and the digital thread*.
48. *CIO.com* "Can the blockchain power industrial IoT?," <http://www.cio.com/article/3027522/internet-of-things/beyond-bitcoin-can-the-blockchain-power-industrial-iot.html>, accessed October 21, 2016.
49. Ibid.
50. Wohlers Associates, *Wohlers report 2016: 3D printing and additive manufacturing state of the industry annual world-wide progress report*, 2016.

ACKNOWLEDGEMENTS

The authors would like to thank **Jim Joyce**, of Deloitte Consulting LLP, and **Alexander Dancu**, formerly of Deloitte Consulting LLP, for their expertise and contributions to this article. They would also like to thank **Jonathan Holdowsky** and **Brenna Sniderman** of Deloitte Services LP for their invaluable contributions to the preparation of this article.

CONTACTS

Kelly Marchese

Principal
Supply Chain and Manufacturing Operations
Deloitte Consulting LLP
+1 404 915 2346
kmarchese@deloitte.com

Mark A. Vitale

Specialist leader
Federal Strategy and Operations Practice
Deloitte Consulting LLP
+1 216 830 6749
mvitale@deloitte.com

Mark Cotteleer

Research director
Center for Integrated Research
Deloitte Services LP
+1 414 977 2359
mcotteleer@deloitte.com

Deloitte. University Press



Follow @DU_Press

Sign up for Deloitte University Press updates at www.dupress.deloitte.com.

About Deloitte's Center for Integrated Research

Deloitte's Center for Integrated Research focuses on critical business issues that cut across industry and function, from the rapid change of emerging technologies to the consistent factor of human behavior. We uncover deep, rigorously justified insights, delivered to a wide audience in a variety of formats, such as research articles, short videos, or in-person workshops..

About Deloitte University Press

Deloitte University Press publishes original articles, reports and periodicals that provide insights for businesses, the public sector and NGOs. Our goal is to draw upon research and experience from throughout our professional services organization, and that of coauthors in academia and business, to advance the conversation on a broad spectrum of topics of interest to executives and government leaders.

Deloitte University Press is an imprint of Deloitte Development LLC.

About this publication

This publication contains general information only, and none of Deloitte Touche Tohmatsu Limited, its member firms, or its and their affiliates are, by means of this publication, rendering accounting, business, financial, investment, legal, tax, or other professional advice or services. This publication is not a substitute for such professional advice or services, nor should it be used as a basis for any decision or action that may affect your finances or your business. Before making any decision or taking any action that may affect your finances or your business, you should consult a qualified professional adviser.

None of Deloitte Touche Tohmatsu Limited, its member firms, or its and their respective affiliates shall be responsible for any loss whatsoever sustained by any person who relies on this publication.

About Deloitte

Deloitte refers to one or more of Deloitte Touche Tohmatsu Limited, a UK private company limited by guarantee, and its network of member firms, each of which is a legally separate and independent entity. Please see www.deloitte.com/about for a detailed description of the legal structure of Deloitte Touche Tohmatsu Limited and its member firms. Please see www.deloitte.com/us/about for a detailed description of the legal structure of Deloitte LLP and its subsidiaries. Certain services may not be available to attest clients under the rules and regulations of public accounting.

Copyright © 2016 Deloitte Development LLC. All rights reserved.
Member of Deloitte Touche Tohmatsu Limited