Blockchain implementation: Framework for maintaining digital thread

Carolyn LaMacchia
Bloomsburg University of Pennsylvania

ABSTRACT

This article presents a novel framework, based on blockchain technology, for maintaining the digital thread of a product produced through an additive manufacturing process. The digital thread is electronically recorded product design information that is maintained throughout the manufacturing, distribution, and use of a product. Product design information encompasses raw material, fabrication, and distribution requirements that support design and quality standards. With the potential of many players involved in a products life cycle and technology systems recording data, it is challenging to collect and synthesize the appropriate information that triggers necessary design changes. This is especially true for products created through additive manufacturing processes. The article describes the additive manufacturing process, the digital thread, and blockchain technology as background for the presentation of the framework.

Keywords: Additive Manufacturing, Blockchain, Digital Thread, Information Technology, Operational Technology

INTRODUCTION

Product specifications provide the step-by-step details to create a product in order to achieve the expected design. Specifications are documented in such a way that production employees know exactly how to construct a product for consistent results at a desired productively rate. Specifications are based upon an intended design for a product. Many specialists with both business and engineering skillsets consider multiple factors in developing a product design. Product specifications are recorded as an evergreen document. Once a product is placed in the production cycle, product specifications often change over time to respond to feedback from the production floor, quality issues, customer feedback, and consumer trends.
A product specification document is used to provide details for products created by an additive manufacturing (AM) process.

AM builds a product or product component by incrementally adding layers of raw material. This is different from a traditional manufacturing process which makes precision cuts to raw material or pours liquid materials into molds. AM is not always the most cost-effective choice but has benefits over traditional manufacturing in certain situations. AM machine mechanisms respond to directions from a digital file. The same AM machine can be used for a completely different product by exchanging the digital file. Traditional manufacturing machines may include programmable logic controllers that manage operations but these machines typically require some level of retooling to switch products or modify design. The inherent nature of AM process provides for flexibility on the production floor for addressing customization and timely design modifications. Another important difference between AM and traditional manufacturing is in the physical operation of the two methods. Since AM builds the product layer by layer, it can create complicated internal geometries that strengthen the design and use less raw material than traditional manufacturing processes.

Specifications for products created through an AM process include a variety of digital files detailing material requirements, computer aided design (CAD) file(s), AM machine settings (slicer), and post processing requirements. Like other production methods, specifications files must be maintained beyond the release of a product into market. The maintenance of digital product specifications is referred to as the digital thread. Various players with diverse skill sets provide input into the digital thread. These participants may be trading partners or personnel at remote production facilities. These production participants use separate technology architectures with separate databases to store information.

The article describes technologies that are integral to a framework for maintaining the digital thread for products produced through AM processes. This framework is built upon blockchain technology to facilitate the collecting and sharing of the digital thread data. Additive manufacturing, the digital thread, and blockchain technologies are described. A framework for electronically maintaining a product's digital thread is presented.

ADDITIVE MANUFACTURING

Additive manufacturing (AM) is the creation of an item from a digitally stored computer aided design (CAD) model. AM techniques deposit material layer by layer through a technically controlled machine. AM processes are sometimes called 3D printing. This layered approach can replace a solid internal structure with detailed internal geometries for the creation of a lighter-weight and stronger product while reducing raw material cost. A digitally stored design provides the flexibility for design customization; the digital file is changed, not the physical equipment. With the design flexibility, there is an opportunity to create a product with fewer components than would be created through a traditional machined process.

AM processing is appropriate in certain circumstances. It is particularly beneficial to the transportation and aerospace industries because lighter weight components require less fuel consumption (Altıparmak and Xiao, 2021). It also may be the best economic choice for situations where only small quantities of units are required on-demand as found in the spare parts industry (Altıparmak and Xiao, 2021). AM is a powerful tool for prototyping product designs because adjustments may be made relatively quickly to the CAD model. Designing and constructing an AM manufacturing facility or a traditional manufacturing facility requires time and capital investment but the AM facility, driven by CAD models, is much more flexible. And, in cases where the AM manufacturing facility requires just a 3D printer, there is more flexibility in the choice of location. AM manufacturing may be placed near its market reducing distribution costs.

Product design specifications for AM include multiple files directing and documenting a variety of steps. There is a bill of materials (BOM) which includes the list and quantity of raw materials and components required to create the product. CAD file(s) electronically store the three-dimensional designs. The CAD file is passed to an AM machine where the ideal fabrication environment specifying temperature and production speed is established. AM machines log information during fabrication describing the step-by-step process and providing clues for troubleshooting issues. Product design specifications describe post fabrication processing completed after AM fabrication. Post processing steps often require intensive manual labor and may include heat treatments, build plate separation, support removal, refinishing and polishing. With manual labor comes skillset requirements and the possibility of variable results.

The commonly recognized types of AM processes are described here to illustrate the wide variety and the market applications. Extrusion processes force layers of melted material, through a nozzle onto the build plate. Materials include thermoplastics, metal, ink, and composites. The simultaneous motion of the nozzle and the build plate follow a programmed trajectory. The material "dries" during the extrusion process. Examples of common post processes include removal of support, sanding, polishing, painting, and electroplating. Extrusion AM is applied to customized products, jigs, and fixtures. New product ideas are often evaluated with a prototype. Extrusion created prototypes benefit production facilities because they circumvent the cost and the time required for machine retooling. Design changes are digitally made to the CAD file not physically to equipment.

Material Jetting uses an inkjet printhead to deposit droplets of material forming a cross-section of the object. The process results in a finished object with a fine surface finish. Materials include polymers, metals, and ceramics. Little post processing of the 3D object is usually required. Material jetting is also used for prototypes and objects like prosthetics, small drones, and circuit boards. Binder Jetting deposits droplets of binder, through inkjet printing, onto a bed of powdered material. Raw materials include metals, ceramics, sand, and sugar. Post processing may include sintering for strength, sanding, and polishing. Binder jetting is applied for creating prototypes, tooling, tool inserts and parts, and medicinal tablets.

Laminated object manufacturing (LOM) uses consecutive bonding and cutting of layers of sheet-based materials. These raw materials may include paper, composite and metal. Post processing is challenging when the removal of support is required. LOM is used for concept demonstration, composite parts and multi-material metal structures. Directed energy deposition (DED) fuses powder or wire metal material using an energy source. Energy sources are laser, electron beam, or intense plasma. The geometry of DED parts is restricted to curved surfaces with limited overhands and without fine internal features. Post processing includes heat treatment for stress relief and machining to smooth the course finish. DED is used to repair metal component like engine housings, turbine blades, and railroad tracks. It is possible to bring the DED process to the field to make repairs on-site. The cold spray method for DED replaces the energy source fusion with a high-velocity impact of power.

Stereolithography (SLA), also known as vat photopolymerization, forms a chemical reaction to create an object by appling ultra violet light to layers of liquid resin. The resin may contain metal, ceramic, glass or carbon fibers. Post processing includes curing. The object and support are created as one part so support removal is challenging. SLA is used for prototypes, tooling, dental devices, and medical devices. Powder bed fusion (PBF) applies energy through rotating mirrors to fuse ink jetted binding material with powdered material including polymers, metals, and ceramics. The powered material supports the object during printing. Post processing includes removal of excess powder and sintering. PBF, a complicated, time consuming, and cost intensive process, is used to create mechanical parts.

Organizations use a wide variety of strategies which require capital investment in equipment and in training to implement AM. With prices of transportation, location of materials, and qualified labor, AM may be implemented at multiple sites throughout the supply chain. Maintaining the design is critical to insure a consistent, quality product as the design owner responds to quality and other issues (Altıparmak and Xiao, 2021). In some instances, AM is implemented in much of the product life cycle which requires a commitment to training and infrastructure. Although it is growing, the additive manufacturing industry is small when compared to conventional manufacturing methods.

The global AM market is valued at about 14 billion dollars and is projected to grow over 20% each year (Moroni, Petrò, and Shao, 2020). Healthcare, automotive, aerospace, and defense industries, in particular, are driving the growth (Moroni et al., 2020). Companies are both insourcing and outsourcing AM processes. Standards have emerged through the American Society for Testing and Material (ASTM) and the International Organization for Standardization (ISO) which indicates the coordinated approach to a quality AM environment (ISO and ASTM, 2016).

DIGITAL THREAD

The digital thread refers to the electronic coding and storage of product design and specification information throughout the lifecycle of the product. The electronic record for a particular product requires data collection at multiple stages: prototyping, design, manufacturing, distribution, and customer service (Alkhader, Alkaabi, Salah, Jayaraman, Arshad, and Omar, 2020). A complete and appropriate electronic record supports product design improvements, manufacturing and distribution agility, and customer satisfaction. With AM, the digital thread includes the BOM, design model based on CAD software, machine operations information, post processing steps, packaging information and distribution information (Alkhader et al., 2020).

Organizations focusing on core competencies adopt horizontal integration and outsource selected processes. As a result, over a product's life cycle, multiple organizations may contribute data in the development of a product's digital thread (Badshah, Waqas, Muhammad, Abbas, and Abbas, 2022). Establishing a digital thread is challenging but worthwhile. Strategies are developing to not only address the design of the data record but also include a secure process for recording and sharing data. Organizations leverage technology as they establish strategies to remain competitive and profitable. Technology is integrated into multiple aspects of the product life cycle and the management of the organization. Maintaining the digital thread impacts data managed by both information technology (IT) and operation technology (OT) systems (Parker, 2022). With the wide variety of feedback from multiple systems, the digital thread relies upon the convergence of data from IT and OT system (Kay, 2018; Parker, 2022; Toriello, 2022).

Data has long been considered an asset for an organization and is used as a tool for directing business processes and strategy. The purpose of IT systems is to securely record and manage data necessary for business processes. Business processes must be documented within the IT system and represent business activities like a customer sale or material purchase. If the data is not recorded, then it is as if it did not occur. There are several common categories of IT systems that are widely used by organizations to record the data of business processes. For example, Enterprise Resource Planning (ERP) systems, Customer Relationship Management (CRM) systems, and Supply chain Management (SCM) systems are computer applications that often share databases through direct transactions or interfaces in order to build a secure and reliable record that represents an organization's business activities (Parker, 2022).

The purpose of OT systems is to securely record and manage the data necessary to support manufacturing operations related to the production of an organization's product. Production facilities include multi-step processes that prepare materials into an intermediate or final stage. Data is recorded and monitored as materials pass through the process in order to assure quality and productively standards. In addition to recording data, these systems also control the manufacturing process and factory environment. There are several categories of OT systems that are used in industry to record operational data that are known as Manufacturing Execution Systems (MES) along with Industrial Control Systems like Programmable Logic Controllers and Supervisory Control and Data Acquisition (SCADA) systems.

Although some data may be shared through interfaces, typically IT and OT systems function separately. Organizations are discovering the value of streamlining data collection and triggering processes between the two categories of systems (Kay, 2018). The convergence of Information Technology (IT) and Operational Technology (OT) systems enhances business and manufacturing quality and efficiency. As an example, barcoded assembly parts required on the production floor may be scanned as used. Scanning collects production status information for the OT system and gathers inventory maintenance and purchasing reorder information for the IT system. This automated step replaces manual transfer of data between systems through paper means or manually keying data. Implementation of IT/OT convergence provides for a cleaner data exchange, simplifies the execution of tasks (Toriello, 2022). In addition, IT/OT convergence supports a real-time digital environment where an organization is agile and can respond quicker to environmental conditions (Kay, 2018).

Consider many manufacturing processes, raw material and packaging material purchasing is managed through the IT system while utilization of these materials is managed through the OT system. Human resource records and training are recorded in IT systems; production performance is recorded in OT systems. Delivery charges are recoded in the IT system and are executed during OT operations. The digital thread becomes more and more relevant to ensure product quality beginning with the initial design through production and supply chain distribution. The scattering of data through multiple IT and OT systems creates a challenge for managing the digital thread (Kay, 2018).

BLOCKCHAIN

The digital world provides many benefits and challenges. Well-organized digital records promote agility and support managerial efforts. Digital records introduce security issues including theft of trade secures and tampering of operations (Zīle and Strazdiņa, 2018). Blockchain networks establishes reliable sharing of data and interoperability among various systems with the use of distributed ledgers/data repositories, cryptography, and computation (Luo, Liao, Li, Ye, and Chen, 2022). Blockchain gets its name from a sequential set of information, referred to as blocks, secured together through cryptography. Blockchain technology can be used to support the management of a decentralized manufacturing ecosystem. Blockchain can provide the technology platform to supports a secured repository of a product's digital file and a platform to share data among multiple trading partners (Zuo and Qi, 2022). This is just one more blockchain implementation example that may be added to a growing list of implementation strategies.

Blockchain technology should be considered in situations where a database is needed to record transactions and where there are multiple data editors. These editors may be unknown to one another and have conflicting interests (AlShamsi, Al-Emran, and Shaalan, 2022). The appropriate blockchain category is selected once the need for the blockchain infrastructure is determined. There are three categories of blockchain based on membership: public, consortium (also known as federated), and private (AlShamsi et al., 2022).

Public blockchains, like Bitcoin and Ethereum, are open to anyone. There are no limits to the number of members. The number of nodes who are validating transactions vary by the size of the network. There is no centralized authority controlling the posting of transactions. Each block includes a block identification number (referred to as the height), the hash of the previous block, a timestamp, nonce, the hash of the block, and the transaction data that is specific to the application. A block's validity is determined by miners. The blockchain protocol sets a number known as the difficulty level. Miners determine a nonce which when combined with the transaction data and hashed, creates a hash value that is less than the established difficulty level. Determining the appropriate nonce that, when combined with transaction data, leads to the creation of a hash value below the threshold is very difficult and resource intensive. But, this proof of work process is very effective at insuring the validity of the transactions (AlShamsi et al., 2022). Posting of new transactions and transaction modifications are posted only after proof of work is established by the majority of nodes on the network. Miners receive compensation for their work and this value fluctuates. Once posted to a public blockchain, transactions are viewable to all members and cannot be overridden. Members of the blockchain remain anonymous but there is complete transparency in the contents of the blocks. There is no regulator governing the management of the blockchain; the technology acts as the regulator (Touloupou, Themistocleous, Iosif, and Christodoulou, 2022).

A few issues are notable with public block chains. Each transaction has a cost to compensate and incentivize miners for their proof of work. Transaction costs fluctuate. The proof of work process is resource intensive (Luo et al., 2022). Although public block chains are considered trustworthy in a potentially untrustworthy environment, there is an issue referred to as the 51% attack. This occurs when 51% of all nodes are from a single organization. The blockchain looses its validity in this case (Touloupou et al., 2022). Public blockchain also have given rise to cryptojacking which occurs when cybercriminals off-load the resource-intensive processes on an unaware victim while receiving compensation for proof of work processing.

Consortium, or federated, blockchains share information among a limited number of members. Members and nodes on this blockchain must get permission to join the blockchain. In this category of blockchain, the members work together and the identity of each member is known. While the majority of nodes on public blockchains must reach consensus to post blocks through the proof of work process, consortium blockchain protocol set the approval process which is typically through low computational algorithms (Touloupou et al., 2022). Transaction verification cost is at a set price and less resource intensive. And, unlike the public blockchain, transactions may be removed if multiple members agree.

Private blockchains share information among a limited number of members who are approved by a centralized authority. The centralized authority has a high degree of trust and auditability. Transactions are viewable but only to those with access. Private blockchains do not need to rely on proof-of work to establish consensus (Touloupou et al., 2022). The blockchain is essentially just database transactions that include cryptographic auditability, immutability, and identity that is related to a specific transaction (Touloupou et al., 2022). Any transaction can be traced to a specific party. Unlike databases where data additions and adjustments may not be traceable. Resource requirements are lower and performance is much better for private blockchains when compared to public blockchains because private blockchains do not rely on proof-of work to establish consensus. There are several open-source technologies available free of charge to establish a private blockchain. The platform may be independently build or established through available technologies like Hyperledger, Enterprise Ethereum, or Corda R3 (Touloupou et al., 2022).

FRAMEWORK

The purpose of this framework is to provide a technical foundation for the maintenance of AM produced product design specifications. Given that design specifications are an evergreen document, the digital thread is important for perfecting product designs and maintaining quality standards uniformly across AM operations. Design specifications for AM processing are complex and include multiple file structures created for separate steps completed through machining and human manipulation. Changes in design specifications should be centrally controlled by the design owner and distributed to all appropriate parties in the AM operation. Information either supporting the performance of the current design or supporting a change in the design specifications should be available for evaluation by the design owner. The framework, based on blockchain technology, supports the digital thread by communicating information that is used to support design changes and communicating design revisions. The framework simplifies and organizes the complex nature of AM processing.

Technology Platform

With the need for a shared database, a blockchain is the appropriate choice as the technology platform for the framework A private blockchain is a better choice than a public or consortium blockchain because there is one trusted party – the design owner. To appropriately maintain the digital thread, there should be just one owner of the product specifications that has the sole authority to modify the specifications. Performance requirements, driven by the number and size of transactions, establish the appropriate number of redundant copies of the shared database. The design owner is responsible for sharing the original design, posting revised designs, and evaluating information shared by AM processing facilities and business units.

Other members of the blockchain, those who are involved in the business and production processes, perform some step that ultimately brings the product to market. This framework refers to these members as the design implementers. These parties may be internal or external to the design owner's organization. Design implementor's membership in this private blockchain must be approved by the design owner.

Each design owner has the sole authority to post and maintain all product specification files for their particular product. A design owner may be an organization or an individual and the design owner may own multiple product specifications. The blockchain includes multiple product specifications so it is possible that there are multiple design owners within the blockchain. Other members of the blockchain, the design implementers, are responsible for sharing data from the execution of their product specification step. Each member posts information using a digital signature that uniquely identifies the member. The member transactions are posted to the blockchain encrypted with the public key of the design owner. Once posted to the blockchain, the transaction data is viewable to the design owner only after decryption with the design owner's private key. The design owner analyzes members' transactions and issues a new design only when appropriate. Figure 1 in the Appendix provides a diagram of the technology platform processing.

Transaction Data

Data included in processing designs varies by AM process and product type. The framework's design accommodates the multiple design and process types. The agreement between the design owner and the design implementor(s) should include specifications on blockchain data reporting. It is important to note that providing a standard transaction layout promotes consistency and implementation ease. Uniformity in the transaction data is essential for appropriate evaluation across the multiple implementations of the design. Posting transactions to the blockchain and interacting through the blockchain avoids establishing multiple interfaces among systems. Separate design interactions are not needed with each information technology and operational technology systems.

Each transaction stored in the blockchain must uniquely identify the situation and include information that ties the information to both the original design specifications, the specific step in the manufacturing/distribution/marketing process, and the execution of the specific AM step by the specific business unit. Each transaction on the blockchain data includes the identifying information followed by a data file of various formats. The data file format and contents are specific to the step in the AM process or business process. Transaction identifying information includes the following:

Date/time Stamp – Sequences the information.

Source ID – Identifies the source of the data which may be either a design owner or design implementor.

Product ID – Identifies the product. Each product has this unique ID which is included on all data including the original design specification.

Design Version – Identifies the version of the product design. The Design Version is included on all data including the original design specification. Based on timing, it is possible that multiple versions of a design are in production.

Process Step – Identifies the AM Process Step. Information matches design specification.

Digital Signature – Unique to each design implementor and promotes the integrity, authentication, and non-repudiation of the transaction.

Transaction data information follows the transaction identifying information. Typically, this information will include a data file. A standard naming convention should be established for each data file name in case the file is separated from the transaction identifying information. The data file contents include data specific to the AM process step of the product or feedback from various business units to contribute to quality and troubleshooting efforts. Table 1, in the Appendix, is a list of the transaction data collected by a sample AM process.

Opportunities and Challenges

Design implementation transactions include data describing the completion of steps in the design process are posted to the blockchain. The source of the data varies. It may be an information system, as in the case of purchasing, or it may be an operations system, as in the case of AM machine performance file and the checklist completed as a human applies a step in the post process. The latest version of the design specification is posted to the blockchain by the design owner and is visible to all design implementors. The design implementors files are encrypted with the design owner's public key, so they are only readable after description with the design owner's private key. It is very challenging to ensure that all design implementors post all files in the appropriate format so that there is consistence for data about each step. Therefore, the design owner should prioritize which transactions will have the tendency to provide the best feedback to evaluate design specifications.

The purpose of the blockchain is to maintain the digital thread. While the blockchain transactions provide clues to help troubleshoot situations encountered during AM fabrication, these clues lead to modifications in design specifications. Design owners may post frequently encounter problems or workarounds within the specifications. The AM fabrication process may need a separate technical support process to address issues encountered by design implementors. This support process is separate from the blockchain. Design owners may consider the periodic review of support process data because this area may lead to modifications in design specifications.

Many AM processes include post processing steps that require technicians with unique skillsets. The skillsets require an investment in training and lead time as training is complete. There may be situations where the trained technicians are temporarily not available to complete post processing steps. The blockchain can support the identification of internal labor availability at various locations. The fabricated AM product or component may be outsourced to a different facility for post processing. The specific design implementor data for these outsourced fabricated products are identifiable from insourced fabricated products. This type of tracking supports quality in human completed post processing activities.

Design implementors from various locations may be ordering raw materials and components to produce a particular design. There may be a higher unit cost for these materials when purchases are made separately and from different suppliers. The blockchain data provides the opportunity for the design owner to evaluate purchases and propose collaboration on purchases from selected suppliers to the blockchain members. This can result in a lower unit cost for materials because of the economy of scale. Care must be made so that additional transportation cost of the materials does not eliminate the savings of bulk purchases

FUTURE RESEARCH AND CONCLUSION

The framework presents a technical foundation for the maintenance of design specifications of AM produced product. The next step in the research process is to establish a prototype framework using a mock production facility using locally available 3D printing facilities. The prototype will implement an open source blockchain platform and simulate separate design implementors for the various steps in the creation of a product. Evaluation of the prototype will highlight additional opportunities, challenges, and refine the framework design.

The framework recognizes that the design specifications are evergreen. Improvements in design may originated from the many specialist in the business and production units that contribute to the ultimate sale of the product. The design provides for flexibility in AM machines and post processing facilities. With the blockchain distributed databases, the information is managed regardless of the location or responsibility of the blockchain participant. Work can be shifted among facilities in cases where there is a training issue at a plant. Bulk raw material purchases are also possible. Maintaining a products digital thread leads to these benefits as well as the significant benefit of consistent quality products.

REFERENCES

Alkhader, W., Alkaabi, N., Salah, K., Jayaraman, R., Arshad, J., & Omar, M. (2020). Blockchain-Based Traceability and Management for Additive Manufacturing. IEEE Access, 8, 188363–188377.

AlShamsi, M., Al-Emran, M., & Shaalan, K. (2022). A Systematic Review on Blockchain Adoption. Applied Sciences (2076-3417), 12(9), N.PAG.

Altıparmak, S. C., & Xiao, B. (2021). A market assessment of additive manufacturing potential for the aerospace industry. Journal of Manufacturing Processes, 68, 728-738.

Badshah, A., Waqas, M., Muhammad, F., Abbas, G., & Abbas, Z. H. (2022). A Novel Framework for Smart Systems Using Blockchain-Enabled Internet of Things. IT Professional, IT Prof, 24(3), 73–80.

ISO, ASTM International Issue Framework for 3-D Printing Technical Standards. (2016). Professional Safety, 61(12), 21.

Kay, N. (2018). Finding common ground for IT/OT convergence: Finding a common understanding between information technology (IT) and operations technology (OT) means avoiding a lot of issues with overall facility operations. Control Engineering, 65(6), 8.

Luo, Q., Liao, R., Li, J., Ye, X., & Chen, S. (2022). Blockchain Enabled Credibility Applications: Extant Issues, Frameworks and Cases. IEEE Access, 10, 45759–45771.

Moroni, G., Petrò, S., & Shao, H. (2020). On standardization efforts for additive manufacturing. Proceedings of 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing (pp. 156-172). Springer, Cham.

Parker, K. (2022). IT/OT convergence moves automation markets forward. Control Engineering, 69(6), 18–20.

Toriello, M. (2022). Creating the Digital Thread. Insight, 25(1), 34–37.

Touloupou, M., Themistocleous, M., Iosif, E., & Christodoulou, K. (2022). A Systematic Literature Review Toward a Blockchain Benchmarking Framework. IEEE Access, 10, 70630–70644.

Zīle, K., & Strazdiņa, R. (2018). Blockchain Use Cases and Their Feasibility. Applied Computer Systems, 23(1) 12-20.

Zuo, Y., & Qi, Z. (2022). A Blockchain-Based IoT Framework for Oil Field Remote Monitoring and Control. IEEE Access, 10, 2497–2514.

APPENDIX

Figure 1. Transaction processing through the framework.

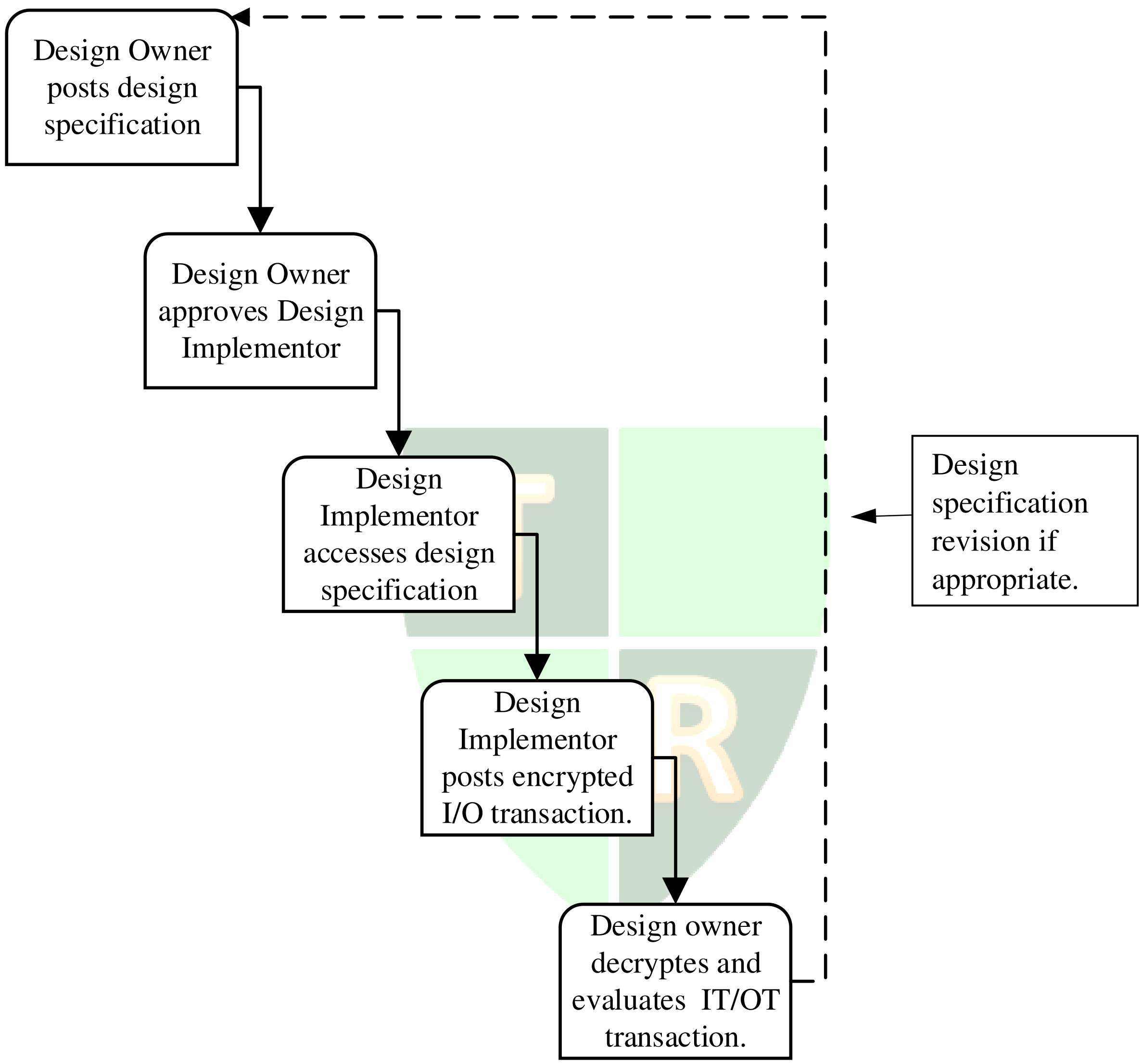

Table 1 – Sample blockchain transaction types.

Transaction Type	Data File(s)	Source System
Design Owner:		
Design files posted only by the design owner.	CAD files and pre/post fabrication instructions.	Various information technology (IT) and operations technology (OT) systems
Design Implementor:		
Pre-processing posted by procurement.	BOM - Raw materials for AM process and post production	Information Technology
AM Fabrication posted by AM Machine operations.	Log file	Operational Technology
Conditioning posted by technical specialist operations.	Log file	Operational Technology
Subtractive Post Processing posted by technical specialist operations.	Post processing checklist	Operational Technology
Additive Post Processing posted by technical specialist operations.	Post processing checklist	Operational Technology
Assembly posted by technical specialist operations.	Assembly checklist	Operational Technology
Packaging posted by technical specialist operations.	Packaging feedback	Operational Technology
Customer Feedback posted by customer service operations.	Customer ratings, defects, and returns.	Information Technology