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Blockchain-based customization towards decentralized consensus on product requirement, quality, and price

Ang Liu *, Dawen Zhang, Xingzhi Wang, Xiwei Xu

University of New South Wales, Sydney, NSW 2052, Australia

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ABSTRACT

As product customization becomes increasingly complex, it calls for a new architecture to enhance collaborations among numerous stakeholders who unnecessarily trust each other. This paper presents a blockchain-based collaborative customization framework, in which, blockchain is exploited as computational infrastructure to moderate, maintain, and manage a decentralized consensus on customization. Collaborative customization is made more transparent by enabling stakeholders to broadcast data, more flexible by fluctuating customization price against requirement fulfillment, more efficient by automating transactions through smart contracts, and more traceable by chaining transactions to constitute product identity. A practical example is presented to apply the framework to elevator customization.

1. Introduction

The sweeping trend of Industry 4.0 calls for profound transformations of today's customization paradigm towards more data-driven collaborative customization. The manufacturing sector, on a global scale, is undergoing an unprecedented paradigm shift from centralized manufacturing to decentralized manufacturing [1–4]. The unprecedented abundance of data generated by a customized product throughout its customization process paves the way for exploiting widely distributed manufacturing resources through more effective collaborations. Mass customization can be achieved through four primary approaches, namely adaptive, cosmetic, transparent, and collaborative customizations [5]. Traditionally, the focus of collaborative customization lies in engaging individual customers in product development by soliciting their demands, expectations, and preferences to constitute the conceptual foundation of customization. Recent studies on collaborative engineering suggest that customization, as a collaborative engineering endeavour, involves multidimensional collaborations among a large number of stakeholders (e.g., customers, designers, manufacturers, suppliers, distributors, service providers, and regulators), who have diversified objectives, preferences, and information accesses [6]. The dynamic interactions, negotiations, and transactions among numerous stakeholders have coupled impacts on the overall effectiveness of customization. For the scenario of complex collaborative customization that involves countless stakeholders, an inevitable challenge is how to establish, sustain, and reinforce a collective consensus concerning different facets of customization (e.g., customer involvement, product specification, product variety, manufacturing flexibility, price fluctuation, and service provision).

The current practice of customization is characterized by a centralized consensus paradigm, where manufacturers serve as trusted authority to reach separate consensuses with all relevant stakeholders. Such a centralized paradigm is born with several shortcomings. Firstly, manufacturers are naturally exposed to the uncertainty of consensus breakings, which are often beyond their scope and control, e.g., customers tend to blame manufacturers (as opposed to suppliers) for quality defects caused by inferior materials/components. Secondly, limited by the exclusive nature of any centralized paradigm, it is difficult for mutually competing stakeholders to jointly promote customization. In practice, it is not uncommon that those dominant manufacturers tend to constrain their suppliers from supplying other manufacturers. Lastly, the intangible trust associated with product brand is a determining factor that affects customer decisions on a customized product [7]. Nonetheless, the centralized paradigm makes it difficult for small and medium-sized manufacturers (SMM) without strong brands to compete with established manufacturers. A dilemma for SMM is whether to compromise the customization price, if not quality, to counterbalance the "trust tax" levied unfairly by centralization.

As an emerging technology, blockchain empowers distributed stakeholders to manage data in a highly transparent, cryptographic, and collaborative manner, where no individual stakehold-

* Corresponding author.
E-mail address: ang.liu@unsw.edu.au (A. Liu).

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ers can manipulate the collective consensus. Blockchain is growingly known for its disruptive ability to moderate, maintain, and manage a decentralized consensus among stakeholders who unnecessarily trust each other. Such a decentralized consensus is greatly valuable for enhancing market entry and competition [8]. Despite the increasing applications of blockchain in IP protection, IoT, and supply chain [9–14], no efforts have been devoted to exploring its applicability to customization. Inspired by the envision of Industry 4.0 for full-scale decentralization, this paper presents a blockchain based collaborative customization framework (BCCF), in which, the key notions, principles, and mechanisms of blockchain are exploited to reach a decentralized consensus on customization.

The rest of this paper is organized as follows. Section 2 presents a theoretical framework of blockchain-based collaborative customization. Section 3 instantiates a practical application of the framework for elevator customization. Section 4 draws conclusions and outlines some future work.

2. Blockchain-based collaborative customization framework

The term "blockchain" refers to a data structure or a peer-to-peer network that maintains blockchain. As a data structure, a blockchain is an ordered list of blocks, where each block contains a list of transactions. Each block is "chained" back to the previous block, by containing a hash of the representation of the previous block. The hash value is generated by a cryptographic hash function. Hash function is a one-way function, meaning that it is practically impossible to derive the input from the hash value as an output. Therefore, data stored in the blockchain transactions may not be deleted or altered without invalidating the chain of hashes. In addition, every transaction is signed by the transaction sender using private key. Such a digital signature is a valid proof of the authenticity of the data sent by the transaction sender. Trust in the blockchain is achieved from the interactions between nodes within the network. The participants of blockchain network rely on the blockchain software and the consensus protocol used by the peer-to-peer network rather than relying on trusted third-party to facilitate transactions.

In place of the traditional paradigm of reaching a centralized consensus primarily through the trustworthiness of manufacturers, BCCF leverages blockchain as computational infrastructure to arrive at a transparent, traceable, and decentralized consensus on <whether and to what extent a product has been customized>. As shown in Fig. 1, BCCF consists of two closely intertwined layers: customization layer and blockchain layer. The customization layer has three domains: stakeholder, requirement, and attribute. The data and information generated in the customization layer are projected into the blockchain layer. The blockchain layer has two domains, data and logic, which are integrated into smart contracts.

2.1. Customization layer of BCCF

Stakeholder Domain accommodates stakeholders involved in a customization project, such as customer, retailer, designer, manufacturer, service provider, regulator, supplier, distributor, financer, etc. Since various stakeholders play different roles in customization, they have unique access to a variety of data that can reflect the state of customization. Traditionally, such data is mostly kept confidential and occasionally shared with the center of manufacturers, which hinders the transparency of customization and the mutual trust among stakeholders. To reach a decentralized consensus, as many stakeholders as possible should be engaged in broadcasting and recording data on the blockchain layer. In the context of Industry 4.0, even a smart CPS (cyber-physical system) or CPPS (cyber-physical production system) can be regarded as a special 'stakeholder' with first-hand access to machine metadata. Every stakeholder has a pair of two digital "keys" [14] on blockchain. A private key is used to broadcast data and authorize transactions, whereas a public key is used to authenticate the broadcasted data. Stakeholders are enabled to vote for the utility of data (i.e., the state of being useful for reaching a decentralized consensus) in a peer-to-peer fashion. The voting outcome constitutes a stakeholder's reputation, and a stakeholder is rewarded for broadcasting high-utility data.

Requirement Domain accommodates various customization requirements and prices raised by the stakeholders. A requirement constitutes a range of target customization values with acceptable tolerances. Requirements can be decomposed and organized into a hierarchical structure, through which, all requirements are linked, hence paving the way for chaining transactions on blockchain. In correspondence to the requirement range is a price range that specifies different prices a stakeholder agrees to pay/charge for fulfilling a customization requirement to different extents. It needs at least two parties, namely 'requester' and 'fulfiller', to reach a consensus on whether and to what extent a requirement has been fulfilled. Depending on the consensus, transactions occur between requesters and fulfillers (i.e., asset senders and receivers in typical blockchain terms) to transfer fund/asset/token based on the agreed prices. Under the decentralized paradigm, transactions may occur directly between any pair of stakeholders, e.g., customer and service provider, manufacturer and supplier, manufacturer and regulator, etc. As a result, stakeholders are naturally coupled with each other through transactions. Unlike the centralized paradigm where most transactions are moderated and hence recorded by the centralized authority of manufacturers, blockchain enables any rele-

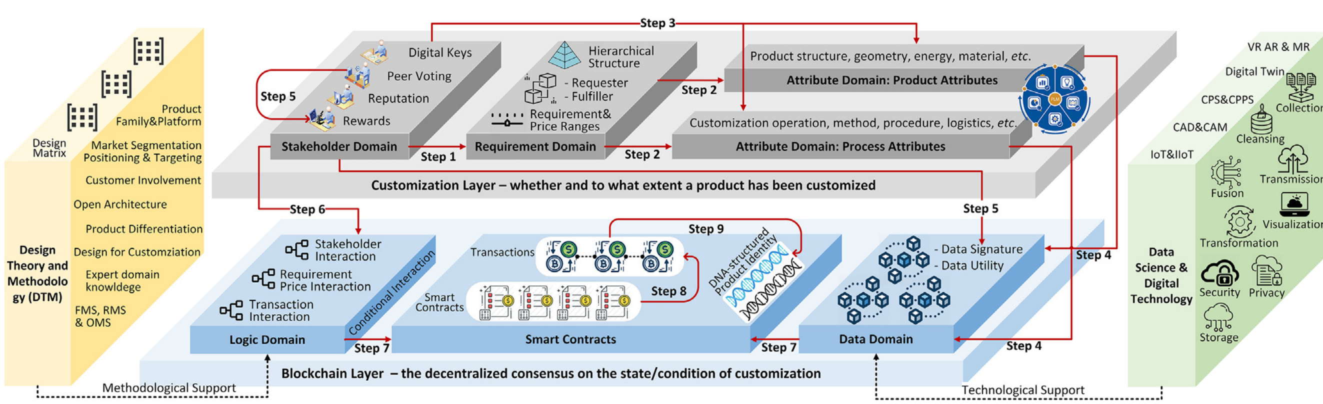

Fig. 1. Blockchain-based collaborative customization framework.

vant stakeholder (e.g., regulator) to serve as independent record keeper.

In the traditional paradigm of centralized consensus, customization requirements are largely predefined by manufacturers based on available resources, then customers are enabled to select different combinations of requirement-parameter pairing. In the proposed paradigm of decentralized consensus, on top of the off-the-shelf requirements predefined by manufacturers, customers are further enabled to broadcast entirely new and unseen before requirements on Blockchain, then different manufacturers can engage in a competitive bidding process in terms of whether, how, in what ways, when, and to what extent the new requirement can be fulfilled. For the customization of complex products, a broad requirement can be decomposed into sub-requirements, which are biddable by different kinds of stakeholders such as manufacturers, suppliers, distributers, and service providers, etc. Transaction price serves to moderate the dynamics of stakeholder interactions. The final transaction price is affected by the novelty, difficulty, and viability of requirement fulfillment. For the sake of transparency and traceability, the back-and-forth negotiations involved in the processing of finalizing a new requirement can also be broadcasted on blockchain. This is especially important for certain customization scenarios, in which, requirement specification must involve the iterative interplay among designer, manufacturer, and customers [15].

Attribute Domain accommodates physical attributes derived from a customized product as well as its customization process. A customized product can be characterized by a set of measurable attributes such as geometry, material, energy, structure, physical properties (e.g., density, colour, odor, etc.), and so forth. Different stakeholders can perceive, measure, and report the customization state (or condition) of the same product attribute at different times, through different methods/devices, and against different contexts. Besides, a customization process can be characterized by a set of process attributes such as particular environments, operations, machines, procedures, logistics, etc. Both product and process attributes can be measured throughout a product's lifecycle (e.g., design, production, usage, service, and recycling), leading to a set of continuously timestamped data. Stakeholders can raise specific requirements on both product and process attributes. Hence, they are equally meaningful for reaching a decentralized consensus.

2.2. Blockchain layer of BCCF

Data Domain accommodates data broadcasted on the blockchain layer. Data is obtained from the customization layer concerning stakeholder, requirement, and attribute. On top of the self-contained information, each data unit must have a timestamp, a stakeholder signature, and a link to the previous data. Data can only be broadcasted if signed by its stakeholder using his/her unique private key. The broadcasted data can be authenticated using the public key. Once broadcasted, data can no longer be altered without a new consensus of the network majority. Since not every data unit makes an equal contribution to reaching a consensus, the utility of data is determined through peer voting by all stakeholders. Unlike product reviews posted on the Internet that can be altered easily by a centralized authority, blockchain ensures the immutability of voting outcomes through cryptographic techniques [14]. Such a voting-based rewarding mechanism also prevents stakeholders from overly broadcasting redundant data.

On blockchain, data is not only broadcasted to increase transparency and visibility, but also chained (linked) to enhance immutability and integrity. In practice, customization data can be chained in multiple ways. Firstly, time-stamped data on a certain product attribute (e.g., weight and energy) can be chained to reflect the attribute's state dynamics throughout the product lifecycle. Secondly, the state of a product attribute can be reflected, directly or indirectly, through the type, sequence, and combination of its related process attributes. Hence, some product and process data can be chained. Lastly, depending on if a collection of attributes is customized sequentially, concurrently, iteratively, or jointly by different stakeholders, their datasets can be chained accordingly.

The data domain is governed by data science and facilitated by digital technologies, as shown in Fig. 1. The operation of a fully functional blockchain platform, as a computational infrastructure, concerns holistic aspects of data science such as data collection, cleansing, transmission, transformation, privacy, security, storage, and visualization. In practice, attribute data can be obtained from many sources such as CAD & CAM, CPS & CPSS [16], and especially IoT & IIoT (e.g., sensors and RFID) [13]. Some existing enterprise software systems (e.g., CRM, MES, ERP, and PLM) can be linked, partially and conditionally, to blockchain platform to broadcast a subset of enterprise data in exchange for more trust.

Logic Domain accommodates various logic fragments that regulate the conditional interactions in the customization layer. Firstly, logic defines the consequences imposed on relevant stakeholders according to their involvement and performance in customization (evidenced by data). For instance, a supplier should be rewarded for supplying high-quality material and broadcasting the provenance data. Secondly, logic defines the interactions between requirement fulfillment and price fluctuation. It ensures, from the logical and computational perspective, that fulfilling a higher requirement leads to a higher transaction price, and vice versa. Lastly, logic defines how data triggers a transaction and how transactions invoke each other. Logic is programmed primarily in the fashion of what-if (e.g., what price if a requirement is fulfilled).

Design Theory and Methodology (DTM) are followed to propose and synthesize logic fragments in a rational manner. This is where the previous studies of customization are incorporated into BCCF, as shown in Fig. 1. The underlying principle is to arrive at a desirable customization state without significantly increasing the cost and complexity. For example, logic can be proposed to incentivize customers, via a lower price, to prioritize customizing target attributes that can be handled readily by RMS (reconfigurable manufacturing systems) and OMS (on-demand manufacturing systems) [16–17]. Stakeholders may follow different rationales to develop logic. For example, designer, manufacturer, and service provider can propose multiple logic fragments about the same attribute in consideration of product/process variety [18], the flexibility of manufacturing systems, and product service integration. Expert domain knowledge plays an imperative role in developing practically viable logic, which is how BCCF can be tailored to different products. Some design matrices are useful for making visible the complicated interactions in the customization layer: the stakeholder-stakeholder matrix indicates the couplings among stakeholders; the stakeholder-requirement matrix indicates who is involved in which transaction; the requirement-attribute matrix indicates what data triggers which transaction; the attribute-attribute matrix indicates the possibilities of chaining attribute datasets logically. These design matrices serve to intertwine the customization and blockchain layers methodologically.

Smart Contract (SC) integrates data and logic to enforce transactions between stakeholders based on the consensus. The second generation of blockchains, such as Ethereum and Hyperledger fabric, provides a general-purpose programmable infrastructure for deploying and running programs known as smart contracts (SC). SC can express triggers, conditions, and business logic to enable and automate programable transactions. A Turing complete programming language designed for blockchains, such as Solidity on Ethereum blockchain, can afford to implement SCs with sophisticated conditions concerning customization

As computer protocols running on blockchain [14], SC can execute transactions without involving third parties or human operators. SC is composed of two essential elements: data and logic. SC is triggered by data that reflects the state of a customizable attribute. Once the state meets the requirement (as evidenced by data), SC will automatically invoke transactions between stakeholders (i.e., requirement requester and fulfiller) according to the predefined logic fragment concerning the customization price. Since SC runs on blockchain, the finalized transactions are naturally broadcasted. On blockchain, transactions can be conducted in the fashion of token exchange. SC can be formulated locally in terms of a customizable product/process attribute as well as globally in terms of a whole customization project. Since SCs can invoke each other, multiple local SCs can be integrated towards a global SC.

Compatible with cloud manufacturing, smart contracts (SC) can be deployed directly on a cloud-based blockchain platform. Among different SC deployment strategies (i.e., public, private, and consortium) [14], consortium blockchain is most applicable for BCCF. Specifically, multiple stakeholders in the same industry form a consortium to jointly manage a blockchain platform for deploying SCs. Note that, SC is by nature a highly customizable object. Therefore, manufacturers are empowered to shift from the center of trust and responsibility to the driver of customizing SCs based on sound logic. Leading manufacturers can still drive a customization project by defining what makes a viable SC, how SCs are integrated, and under what conditions a SC is triggered.

2.3. Systematic process and framework applicability

In BCCF, a customization project is represented as an orderly series of transactions among stakeholders in terms of fulfilling specific requirements on customizable attributes. A more complex customization project involves higher requirement, more attribute, and hence a greater transaction price. Since the customization information is documented in the form of transaction blocks on blockchain, it enhances transparency, immutability, traceability, and eventually trust in collaboration. Through smart contract (SC), a customization project is executed automatically by a collection of data-triggered, self-enforced, and interconnected SCs. In this way, the enhanced trust is further leveraged to improve efficiency. Unlike massively produced products, each customized product is born with a DNA-structured identity as represented by its chains of transactions. Such a unique identity is greatly valuable for long-term quality control, provenance tracking, health diagnosis, etc.

As highlighted by the red arrows in Fig. 1, a decentralized consensus is reached through an iterative process of nine steps.

1) Stakeholders raise customization requirements and prices.
2) Requirements are imposed on product/process attributes.
3) Stakeholders obtain data that reflect the state of the attributes.
4) Attribute data is broadcasted and stored on blockchain.
5) Stakeholders sign off data on blockchain, vote for the utility of data, and receive rewards for broadcasting high-utility data.
6) Stakeholders propose logic fragments based on DTM.
7) Data and logic are integrated towards smart contracts.
8) Smart contracts execute transactions between stakeholders.
9) Transactions are broadcasted and stored on blockchain to constitute the unique identity of each customized product.

Fig. 2 illustrates a systematic flowchart that can be followed to evaluate the applicability of blockchain to the customization of various products (i.e., represented by different colors of arrows). Note that, for the customization of certain products (e.g., medical device), where a centralized consensus is either irreplaceable or sufficient to support collaboration, it is unnecessary to replace the conventional database with blockchain. In general, BCCF is most applicable to the complex customization of industrial systems that are characterized by numerous stakeholders, decentralized operations, high requirement for transparency & immutability, and extended product lifecycle. This flowchart is equally useful for assessing the applicability of blockchain to other manufacturing activities (apart from customization) that involve data.

3. Practical example – elevator customization based on blockchain

The growing popularity of multifunctional buildings is putting forward further challenges to elevator customization. Different from the conventional elevators designed for single-purpose buildings, elevators in multifunctional buildings must cope with more diversified user demographics, more implicit design couplings, more uncertain operation environments, higher requirements for robustness and adaptability, as well as novel architectural components (e.g., new materials and structures). Therefore, it is increasingly important for manufacturers to engage more stakeholders in elevator customization through a more collaborative fashion. Against this background, an explorative study is conducted to apply the proposed framework to elevator customization, which involves numerous stakeholders who conduct complex transactions on countless product/process attributes against various contexts (e.g., purpose, environment, and regulation). In particular, most elevators tend to afford a very long lifecycle. The modern elevators, even in usage, continues to produce data, receive services, and undertake regulations.

The customization specifics of two elevators are broadcasted on the blockchain platform. Elevator A is a passenger elevator for a 30-floor office building, whose customization involves 13 stakeholders, 32 requirements, 107 attributes, as well as 107 transactions. Elevator B is a cargo elevator for a 4-floor shopping mall, whose customization involves 11 stakeholders, 29 requirements, 101 attributes, as well as 101 transactions. Various customer requirements can be classified into four types. The first type of requirements is relevant to building specifications, which arise in the early stage of an elevator customization process. The second type of requirements is relevant to detailed elevator configurations in terms of specific requirements (e.g., brand, model, and price) on different components (e.g., machine, frequency inverter, elevator car, guide rail system, speed governor, and buffer). The third type of requirements is relevant to elevator decoration and accessories. Not only interior designers can raise specific requirements based on a particular decoration style that fits into the building environment, but also customers can make specific propositions to add additional accessories (e.g., entertainment and advertisement equipment). The last type of requirements is relevant to elevator installation and operation, which appear near the end of the elevator customization process. For example, regulators and building contractors can impose requirements on the compliance with waterproof treatment and vibration isolation.

In the context of Industry 4.0, we are especially interested in the elevator attributes whose customization state can be measured and reflected by IoT devices. This is critical for minimizing human involvement (and intentional misreporting) in data collection, transmission, and broadcasting. Table 1 presents, as illustrative examples, a subset of elevator attributes regarding soundproofing, the effectiveness of which was affected by multiple factors (e.g., defective elevators, building structure, and installation precision)

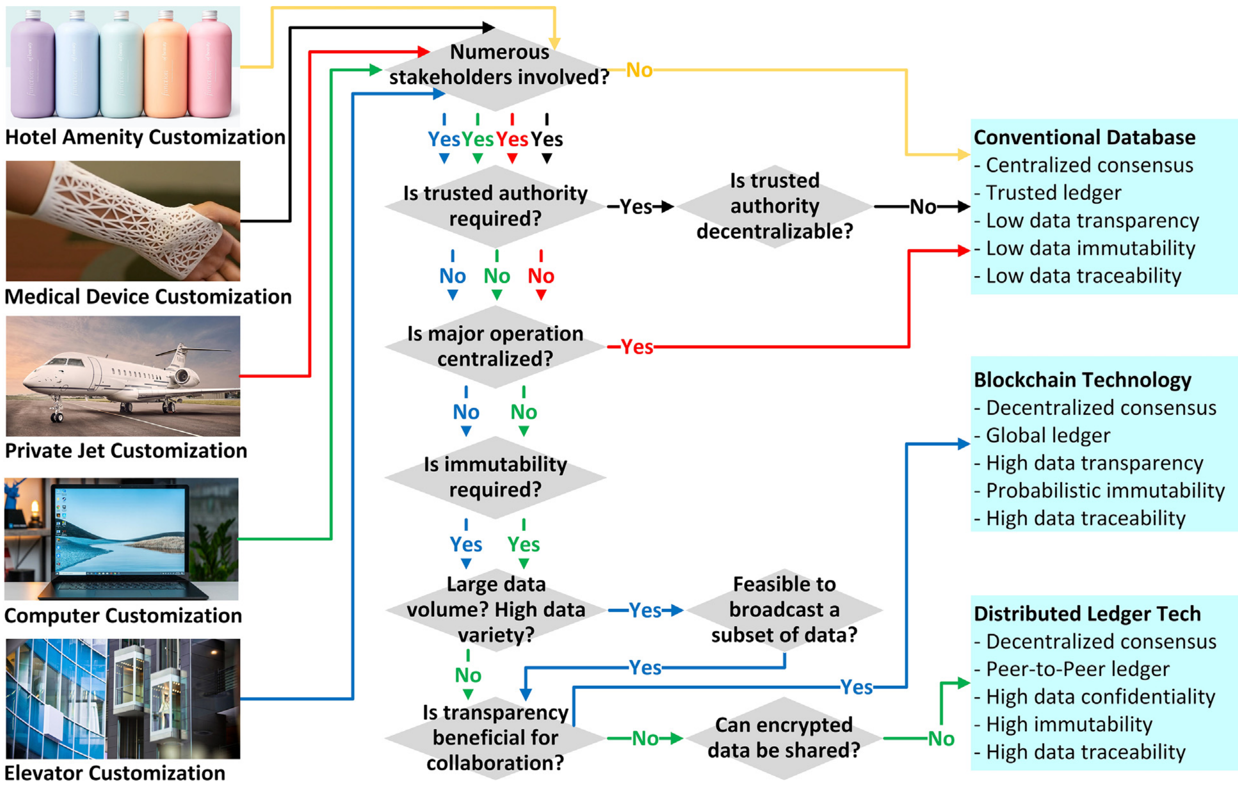

Fig. 2. Applicability of blockchain to customization of various products.

Table 1
Examples of elevator attributes regarding soundproofing.

Attribute	Reqt (A)	Reqt (B)	Data Collection Device
Machine noise	≤55 dB	≤70 dB	Temperature, pressure, & liquid level sensor
Structure-borne machine nose (due to vibration)	≤80 dB	≤80 dB	Structure-borne noise sensor & vibration sensor
Lift noise (due to vertical vibration)	≤25 mg	≤20 mg	Speed sensor, force gauge, & data logger
Noises caused by guide rail & rollers	≤55 dB	≤65 dB	Humidity & liquid level sensors
Structure-borne roller noise (lateral vibration)	≤30 dB	≤60 dB	Low-frequency vibration sensor
Door operation noise	≤60 dB	≤70 dB	Sound level sensor

that can be influenced, if not manipulated, by different stakeholders.

Fig. 3 illustrates the verification-transaction process during the soundproofing customization. In the beginning, customers raised a specific requirement on soundproofing. This requirement was decomposed, with the guidance of elevator designers, into a collection of sub-requirements that are distributed to different stakeholders. For example, the manufacturer was required to control its product noise and vibration under a certain level. The building contractor was required to the sound isolation treatment of load-bearing walls. And the installer is responsible for preventing installation errors occur (e.g., geometry un-alignment of guide rails). A number of IoT devices serve to collect, communicate, and report data that reflects whether and to what extent each requirement is fulfilled. These attributes were measured progressively and iteratively by a small group of stakeholders (e.g., supplier, architect, manufacturer, and building contractor) and then broadcasted on blockchain.

After the attribute data was broadcasted on the blockchain, smart contracts could verify the level of requirement fulfilment. Once relevant requirements were fulfilled, transactions would be automatically triggered, then payments would exchange among the participating stakeholders simultaneously. By making such previously confidential data transparent and traceable to the whole network, blockchain benefited a larger audience of stakeholders (e.g., service providers, regulators, and property management) in terms of provenance tracking, quality control, and service provision. More importantly, the elevator customization price was fluctuated against the soundproofing effectiveness (as evidenced by data).

Fig. 4 visualizes the data and smart contract (SC) broadcasted on blockchain. The blue bubbles at the top represent the incoming data that reflects the state of different elevator attributes. The large circle in the middle represents a global SC, which consists of a number of local SCs (i.e., the outer circle of smaller nodes). The DNA structure represents the unique identity of Elevator A on blockchain, where the two intertwined chains represent the series of transactions between different requirement requesters and fulfillers (i.e., asset senders and receivers). The elevator identity is distinguished in terms of the transaction stakeholder, timestamp, sequence, and price. The grey icons at the bottom represent the stakeholders who engage in the transactions. In summary, the attribute data triggers local SCs, SCs execute transactions between stakeholders, and transactions constitute the DNA-structured identity. The interactive visualization can be viewed via the online link as follows: https://blockchain-for-customization.github.io.

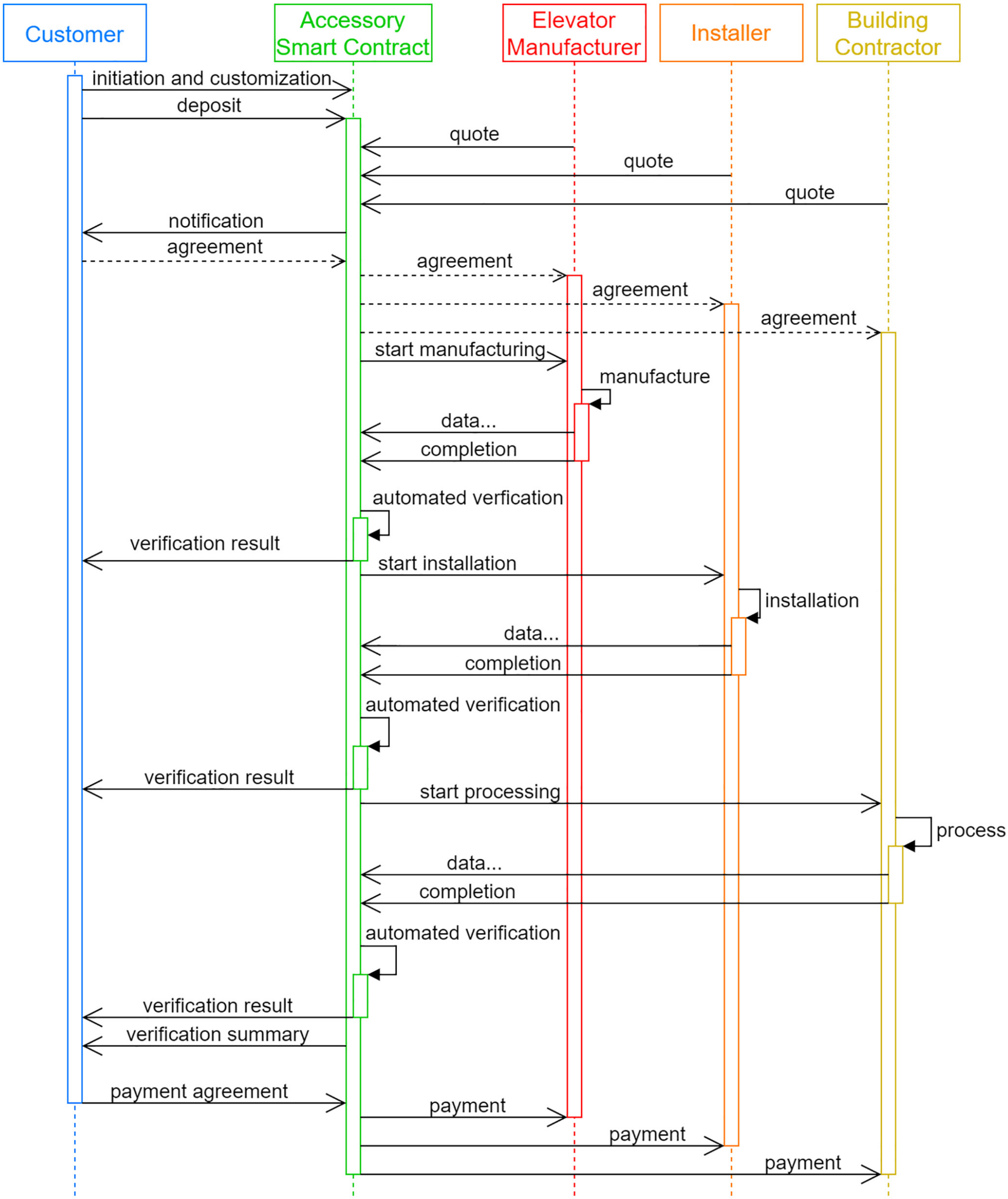

Fig. 3. Verification-transaction process of soundproofing customization.

The strategic roadmap of applying the proposed framework in practice involves several key stages. Firstly, a set of stakeholders who are willing to share data through blockchain should be identified, and a consortium blockchain involving all the key stakeholders should be established. The enterprise may need new IT capability to be able to maintain blockchain and deploy smart contracts. It also needs new IT components to bridge the consortium blockchain and its existing IT system of the enterprise. Next, the operation and governance of the consortium blockchain should be decided and maintained by a certain stakeholder or based on

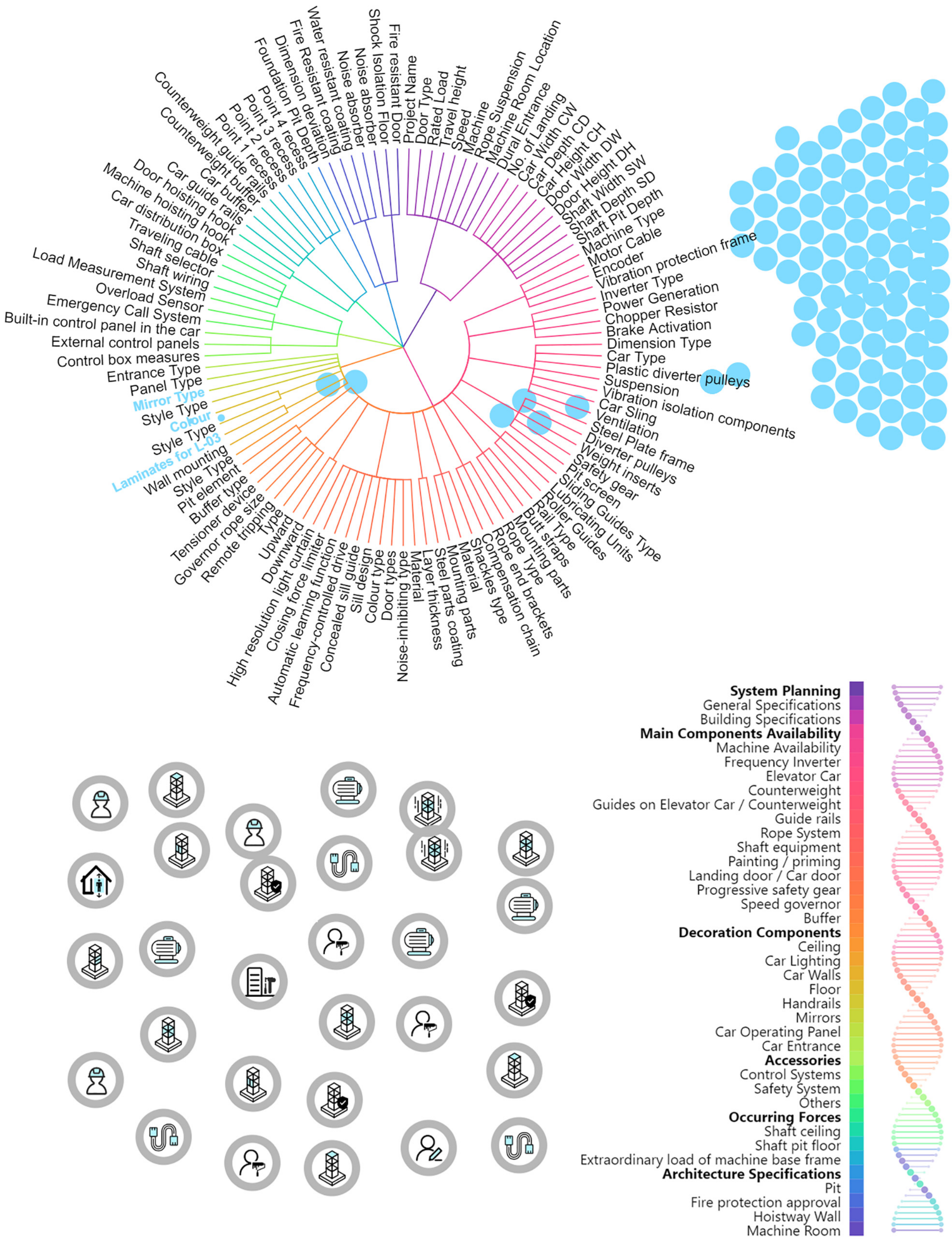

Fig. 4. Illustrative blockchain platform for elevator customization.

consensus to add new stakeholders into the consortium in the future. In terms of infrastructure, large manufacturers may rely on dedicated computing resources, while small and medium-sized manufacturers can rely on cloud computing. A set of IoT devices with sensors are required for the purposes of data collection and mutual verification across different data streams. In addition, system migration solutions are needed to facilitate the transformation from centralized to decentralized data management.

4. Conclusion and future work

This paper presents a novel customization framework that exploits blockchain to support collaboration among numerous stakeholders who unnecessarily trust each other. The framework has some notable advantages especially for the complex customization of industrial systems. Firstly, the consensus about the state of customization is moderated, maintained, and managed in a fully decentralized fashion, where no single stakeholder can manipulate the collective consensus. Hence, it will promote entry of the traditionally disadvantaged stakeholders (e.g., SMM and service providers) who are now empowered to broadcast data, as a way, to counter the absence of an established brand. Secondly, the customization price is made contingent to the decentralized consensus, where more successful customization endeavours (as evidenced by data) will be rewarded and vice versa. Lastly, the decentralized consensus breaks invisible boundaries set by the centralized authority, leading to more collaboration possibilities.

With respect to the limitation of this work, it should be noted that the proposed framework in the current form is still a conceptual framework. Therefore, no numerical results are included to quantify the benefits of blockchain for customization through decentralized consensus. The future work lies in two directions. Firstly, since certain customized products will continue to generate data throughout its product lifecycle, we will investigate the interplay between blockchain and digital twin [19–20], towards a more streamlined process of customization data management. Secondly, we will investigate how the profound transformation from the centralized consensus to a decentralized one reshapes stakeholder behaviours and interactions in customization, e.g., how to prevent collusions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Mourtzis D, Doukas M, Psarommatis F. A multi-criteria evaluation of centralized and decentralized production networks in a highly customer-driven environment. CIRP Ann 2012;61(1):427–30. https://doi.org/10.1016/j.cirp.2012.03.035.
[2] Bonnín Roca J, Vaishnav P, Laureijs RE, Mendonça J, Fuchs ERH. Technology cost drivers for a potential transition to decentralized manufacturing. Addit Manuf 2019;28:136–51. https://doi.org/10.1016/j.addma.2019.04.010.
[3] Minguillon FE, Lanza G. Coupling of centralized and decentralized scheduling for robust production in agile production systems. Proc CIRP 2019;79:385–90. https://doi.org/10.1016/j.procir.2019.02.099.
[4] Lanza G, Ferdows K, Kara S, Mourtzis D, Schuh G, Váncza J, Wang L, Wiendahl H-P. Global production networks: Design and operation. CIRP Ann 2019;68(2):823–41. https://doi.org/10.1016/j.cirp.2019.05.008.
[5] Gilmore JH, Pine BJ. The four faces of mass customization. Harvard Business Rev 1997;75(1):91–102.
[6] Lu S-C-Y, Elmaraghy W, Schuh G, Wilhelm R. A scientific foundation of collaborative engineering. CIRP Ann 2007;56(2):605–34. https://doi.org/10.1016/j.cirp.2007.10.010.
[7] Fogliatto FS, da Silveira GJC, Borenstein D. The mass customization decade: an updated review of the literature. Int J Prod Econ 2012;138(1):14–25. https://doi.org/10.1016/j.ijpe.2012.03.002.
[8] Cong LW, He Z. Blockchain disruption and smart contracts. Rev Finan Stud 32(5); 2019: 1754–1797.
[9] Christidis K, Devetsikiotis M. Blockchains and smart contracts for the internet of things. IEEE Access 2016;4:2292–303. https://doi.org/10.1109/ACCESS.2016.2566339.
[10] Abeyratne SA, Monfared RP. Blockchain ready manufacturing supply chain using distributed ledger. Int J Res Eng Technol 5(9); 2016: 1–10.
[11] Li Z, Barenji AV, Huang GQ. Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. Rob Comput Integr Manuf 2018;54:133–44. https://doi.org/10.1016/j.rcim.2018.05.011.
[12] Papakostas N, Newell A, Hargaden V. A novel paradigm for managing the product development process utilising blockchain technology principles. CIRP Ann 2019;68(1):137–40. https://doi.org/10.1016/j.cirp.2019.04.039.
[13] Lee J, Azamfar M, Singh J. A blockchain enabled cyber-physical system architecture for industry 4.0 manufacturing systems. Manufact Lett 2019;20:34–9. https://doi.org/10.1016/j.mfglet.2019.05.003.
[14] Xu X, Weber I, Staples M. Architecture for blockchain applications. Berlin, Germany: Springer; 2019. p. 1–307.
[15] Modrak V. Mass customized manufacturing: theoretical concepts and practical approaches. CRC Press; 2017.
[16] Hu SJ. Evolving paradigms of manufacturing: from mass production to mass customization and personalization. Procedia CIRP 2013;7:3–8. https://doi.org/10.1016/j.procir.2013.05.002.
[17] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. J Manuf Syst 2010;29(4):130–41. https://doi.org/10.1016/j.jmsy.2011.01.001.
[18] Daaboul J, Da Cunha C, Bernard A, Laroche F. Design for mass customization: product variety vs. process variety. CIRP Ann 2011;60(1):169–74. https://doi.org/10.1016/j.cirp.2011.03.093.
[19] Haag S, Anderl R. Digital twin – proof of concept. Manufact Lett 2018;15:64–6. https://doi.org/10.1016/j.mfglet.2018.02.006.
[20] Huang S, Wang G, Yan Y, Fang X. Blockchain-based data management for digital twin of product. J Manuf Syst 2020;54:361–71. https://doi.org/10.1016/j.jmsy.2020.01.009.