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DASC2M: DESIGN OF A DELAY-AWARE SIDECHAINING MODEL FOR SECURE SUPPLY CHAIN MANAGEMENT ARCHITECTURE DEPLOYMENTS

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Abstract: Supply chain management (SCM) architectures require high security & high quality of service (QoS) in order to effectively track &record product-related information. A wide variety of SCM models are proposed by researchers to perform this task. These models use encryption standards like elliptic curve cryptography (ECC), hashing, key-exchange mechanisms, etc. in order to improve system security. Due to which quality of service (QoS) parameters like retrieval delay, throughput, and energy efficiency are reduced. To maintain a good level of QoS, various machine learning optimizations are also proposed by researchers. It is observed that blockchain-based models are capable of achieving both these constraints for small to medium scale SCM architectures. This is due to their immutability, traceability, transparency, and distributed computing capabilities. Due to immutability, entries stored on the chain cannot be modified, thus all SCM transactions are tamper proof. While, due to distributed computing, the model is capable of adding blocks from different entities. Thus, making blockchains a suitable choice for a wide variety of SCM application deployments.But as length of blockchain increases, this performance is exponentially reduced, which limits scalability of blockchain-based SCM architectures. To improve this scalability, a novel delay-aware sidechaining model is proposed in this text. The proposed model is capable of scaling existing blockchain SCM architectures and creates delay-aware sidechains which are aggregated using a Genetic Algorithm (GA) approach. The proposed model was tested on a wide variety of SCM deployments, and an average delay reduction of 23% was observed when compared with single blockchain-based implementations. Furthermore, the computational complexity was also observed to be 15% lower when compared with single blockchain, which makes the proposed SCM model highly scalable. The reduction in computational complexity is due to reduced reading & verification delays, which reduces hash evaluation effort, thereby improving overall SCM performance for various deployment scenarios.

***Index Terms* – Blockchain, SCM, blockchain, sidechain, delay-aware, Genetic Algorithm**

I. INTRODUCTION

Blockchain based SCM models are highly secure due to their tamper proof, traceable, distributed processing, and highly trustworthy data storage operations. A typical blockchain-based SCM model is depicted in figure 1, wherein entire flow from supplier to consumer can be visualized. It is observed that product information is shared with the producer and processor entities, which are responsible for manufacturing the products. The producer shares these details to the transport provider in form of pickup & logistic details. These details are shared with the retailer in the form of delivery information, which is used to track original product. The processor processes payments from retailers and appends them with order details before updating them into a distributed blockchain. This blockchain is usually a combination of public & private chains, which makes it a consortium-based chain that can be managed via multiple entities [1]. Each block in the chain stores following product supply chain information,

Product details & initial price

- Product to manufacturer mapping
- Manufacturer to distributor mapping
- Distributor to retailer mapping
- Retailer to consumer mapping

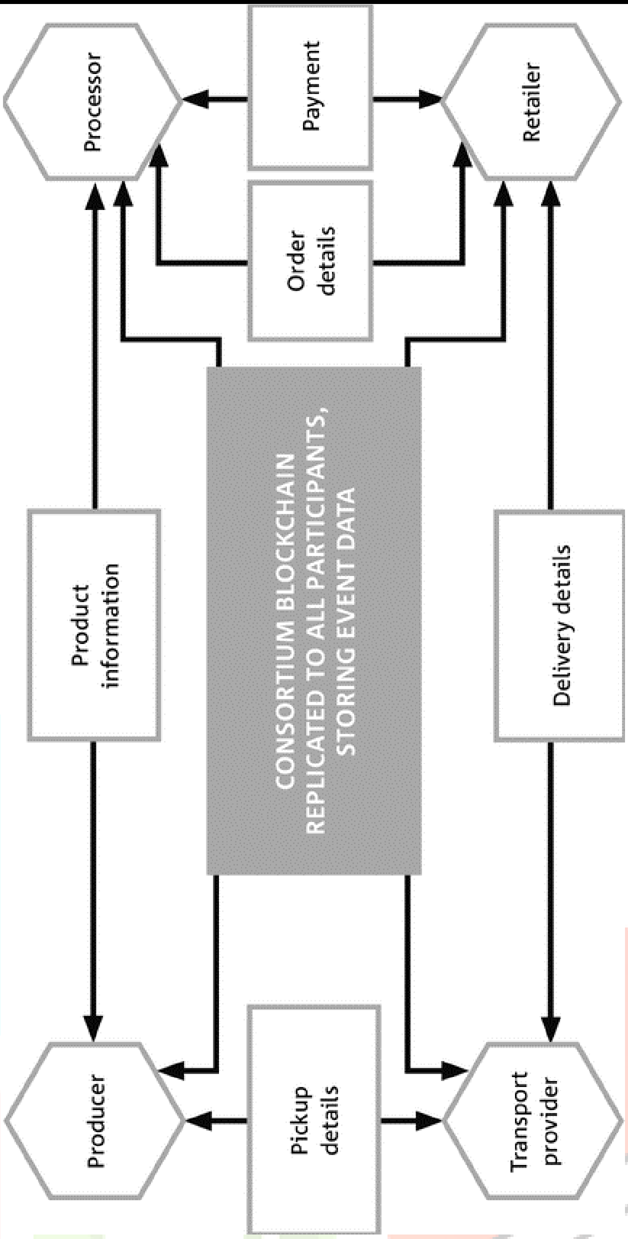

Figure 1. A typical blockchain-based SCM model

These mappings are linked with each other via hash values, which assist in final blockchain storing & tracing operations [2, 3, 4]. Each storage operation requires some delay, which can be represented via equation 1,

$$D_{store} = N * (D_{read} + D_{compare} + D_{hash}) + D_{write} \dots (1)$$

Where, D_{store}, D_{read}, $D_{compare}$,D_{hash},& D_{write} represents delay for storage, reading, comparing, hashing and writing one block, while represents total number of blocks in the SCM blockchain. It can be observed that, as number of blocks in the SCM blockchain increase, this delay also increases exponentially. Due to which, overall quality of service (QoS) performance of the SCM architecture is reduced. In order to improve this performance, a wide variety of optimization techniques are proposed by researchers. A survey of these techniques is discussed in the next section, which will assist readers to identify best practices for QoS aware blockchains. Based on this review, it can be observed that machine learning based sidechaining models have better QoS efficiency than linear sidechains. Inspired by this observation, a novel delay-aware sidechaining model is discussed in section 3 of this text, which aims at improving SCM Network's QoS without compromising model's security. QoS performance of the proposed model is compared with various reviewed approaches, wherein it can be observed that the proposed model has lower delay, and better QoS when compared with these approaches. Finally, this text concludes with some interesting observations about the proposed model and recommends methods to further improve its performance.

II. LITERATURE REVIEW

A wide variety of SCM models are proposed by researchers, and each of them vary in terms of computational complexity, delay needed for storage & retrieval of SCM transactions, area of application, etc. Each of these models are developed for context-sensitive applications but can be extended to other SCM deployments without modifications. For instance, work in [5, 6] proposes Ethereum based blockchain deployment for forward supply chain Management (FSCM), & use of InterplanetaryFile Storage System (IPFS) for storing CoVID& agriculture related data. These models utilize single blockchains for data storage, due to which their performance is limited when evaluated on large-scale SCM data stores. In order to improve this performance, work in [7] indicates that sidechains & sharding must be utilized. This assists in reducing number of operations needed for blockchain creation & management, thereby improving overall SCM deployment capabilities. Similar findings can be observed from [8, 9], wherein researchers have estimated that smaller blockchains have better throughput when compared with single chained implementations. Based on this observation, work in [10, 11, 12] proposes design of smart contracts, distributed ledger technology tags (DLT Tags), and private blockchain implementations for reducing delays and improving throughput of SCM storage. These models are observed to have better traceability, and lower complexity when compared with long chained blockchain implementations. Applications of the model for internet of things (IoT) [13], Hyperledger for vendor managed inventory [14], and fuzzy logic with integrated consensus (FLIC) [15] are proposed by researchers. These models aim at reducing computational redundancies while SCM storage, thus improving overall scalability of the designed model deployment.

Similar applications that discuss automatic smart contracts (ASC) [16], small farm deployment issues [17], agriculture product traceability [18], deep reinforcement learning (DRL) [19], and tamper proof traceability [20] are discussed by researchers. Out of these models the ASC and DRL models are highly optimized for secure & low overhead SCM deployments, and thus can be used for practical system design scenarios. Similar implementations are proposed in [21, 22, 23], wherein researchers have proposed use of Industry 4.0 in blockchain powered SCM, Medical devices & supply management for CoVID-19, and drug traceability in healthcare supply chain. These models utilize smart contracts, in order to provide tamper proof, and high security blockchain implementations for SCM, which makes them useful for small to medium scaled applications. But the delay needed for block addition & verification is high, due to use of single blockchain deployment. These issues are resolved via use of smaller sized chains are discussed in [24, 25], wherein multiple applications for storing smaller blockchains are discussed. Based on these discussions it is observed that sidechaining models are highly useful for design of low delay, and high efficiency SCM system deployments. Motivated by this observation, next section discusses design of the proposed delay-aware sidechaining model for secure supply chain management architecture deployments. This is followed by its performance evaluation, and comparison with various state-of-the-art reviewed approaches.

III. DESIGN OF THE PROPOSED DELAY-AWARE SIDECHAINING MODEL FOR SECURE SUPPLY CHAIN MANAGEMENT ARCHITECTURE DEPLOYMENTS

From the literature survey it is observed that a wide variety of blockchain-based models are available for improving performance of SCM deployments. Out of these, the most efficient models utilize sidechaining or blockchain sharding in order to divide central blockchain into multiple sidechains, and then manage these chains using machine learning-models. A similar sidechaining model is discussed in this section, but due to its low complexity sidechain creation process, the proposed model delay-aware, and has better QoS performance when compared with existing methods. Flow of the proposed model is depicted in figure 2, wherein entire process of sidechain creation & management is depicted.From this flow it can be observed that, any new SCM operation is initially given to a QoS validation engine, wherein a dummy transaction is initiated, and its delay is evaluated. Based on this delay value, existing blockchain is updated, or a new sidechain is created. This updated sidechain configuration is given to a sidechain manager which is modelled using GA approach and assists in storing SCM transactions in a delay-aware manner for faster retrieval purposes.

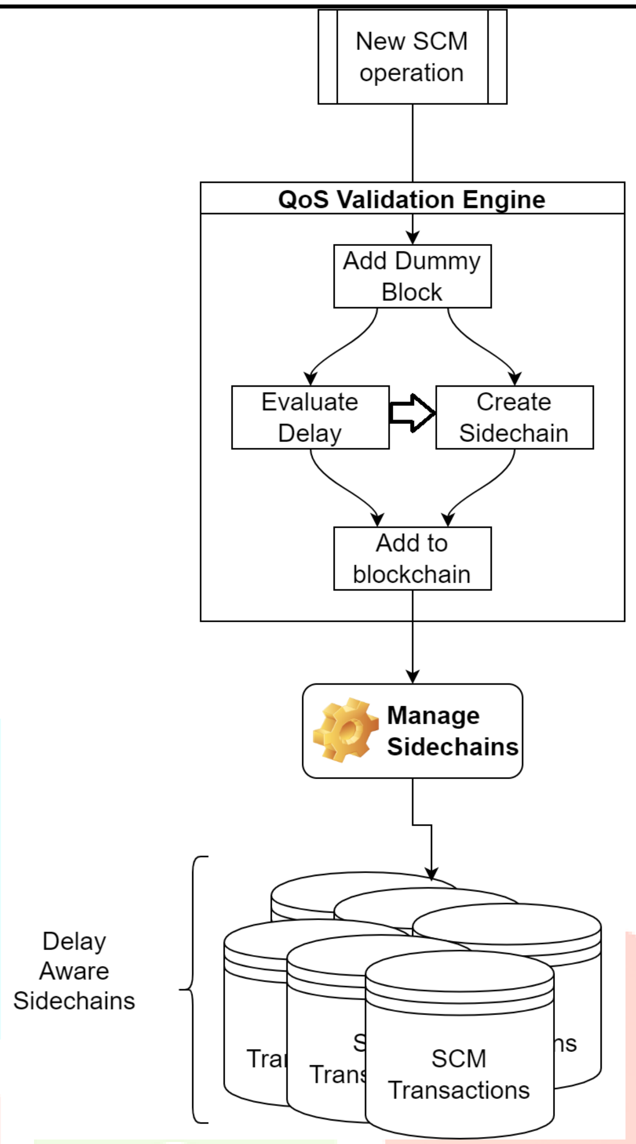

Figure 2. Design of the proposed SCM model based on delay awareness

Design of these models is depicted in different sub-sections of this text, which will assist researchers in replicating them in part (or as a whole) depending upon their SCM requirement.

3.1. Design of the QoS validation engine

While adding a new block to the SCM sidechain, a dummy transaction is initialized. Each SCM block uses the structure observed in table 1, which assists in storing & tracking transactions.

Table 1. Block structure for storing SCM transactions

Prev. Hash	Product ID	Manufacturer ID	Distributor ID
Time stamp values	Product Cost	Cost by Manufacturer	Cost by Distributor
Nonce	Retailer ID	Cost by Retailer	Current Hash
Meta Data	Final Cost	Customer ID	Sidechain ID

Here, identifiers (IDs) of product, manufacturer, distributor, retailer, and customer are stored to maintain atomicity of transactions. While previous hash, & current hash are evaluated using secured hash algorithm in 256-bit mode (SHA256), timestampsare used to identify & verify transactional correctness, and nonce is a random number generated to uniquely identify block's hash. Apart from these primary fields, cost at each SCM stage and its meta data (tracking information, handling instructions, etc.) are also stored on the chain. The hashes are evaluated via equation 2 as follows,

$$Hash = SHA256\begin{bmatrix} P_{info}|M_{info}|D_{info}|R_{info}| \\ C_{info}|\ nonce|timestamp \end{bmatrix} \dots (2)$$

For every dummy block, the sidechain ID is stored as the current maximum ID of generated sidechains. Using this information, and via equation 1, delay to add a block to the most recent sidechain is evaluated. This delay is compared with an average delay value, which is evaluated via equation 3 as follows,

$$D_{avg} = \frac{\sum_{i=1}^{N_{SC}} D_i}{N_{SC}} \dots (3)$$

Where, N_{sc} represents number of sidechains that are currently formed,
while D_{avg} &D_i represents average block addition delay, and block addition delay for current sidechain.
A new sidechain creation request is generated if $D_{store} > D_{avg}$, otherwise the block is stored on the most recently formed sidechain. To create a new sidechain, a GA model is used, which is described in the next section of this text.

3.2. Design of GA for delay-aware sidechain management

If request for a new sidechain is generated while transactions are being added to the sidechain, then a GA model is activated. This model assists in management of sidechains, so that the following constraints are satisfied,

- Delay needed to add a block to the chain is low
- Number of sidechains are optimum

To satisfy these constraints, the following GA model is evaluated,

- Initialize GA parameters, which include,
  - Number of iterations (N_i)
  - Number of solutions (N_s)
  - Flexibility factor (F_{fact})
  - Number of sidechains currently present (N_{sc})
- Initially mark all solutions as 'to be mutated'
- For each iteration in 1 to N_i
  - For each solution in 1 to N_s
    - If this solution is marked as 'not to be mutated', then go to the next solution
    - Else, generate a new solution via the following process,
      - Select a random chain from the list of chains via equation 4,

$$C_{select} = random(1, N_{sc}) \dots (4)$$

      - Evaluate solution fitness, which is average delay for adding N dummy transactions in the chain via equation 5,

$$fitness = New_d = \sum_{i=1}^{N} \frac{D_i(C_{select})}{N_{sc}} \dots (5)$$

Where, represents average delay of adding new blocks into the current sidechain.

      - If this delay is more than D_{avg}, then mark the solution as 'to be mutated'
    - Count total number of solutions per iteration which are marked as 'to be mutated' (T_{s_i}) via equation 6,

$$T_{s_i} = \sum_{i=1}^{N_s} |S_i == Mutate| \dots (6)$$

  - Repeat this for all iterations, and identify value of T_{s_i} for the last iteration
- If at the final iteration, T_{s_i} is more than solution threshold (T_{sol}), then a new sidechain is generated, else chain with lowest number of blocks is used for adding new blocks into the system. Value of T_{sol} is evaluated via equation 7 as follows,

$$T_{sol} = F_{fact} * \frac{\sum_{i=1}^{N_s} T_{s_i}}{N_s} \dots (7)$$

The value of F_{fact} is selected via equation 8, and it assists in creating an optimum number of sidechains for the current SCM model.

$$F_{fact} = F_{fact_{old}} + \frac{\left[Max\left(\cup_{i=1}^{N_{sc}} L_i\right) * F_{fact_{old}} - AVG\left(\cup_{i=1}^{N_{sc}} L_i\right)\right]}{Max\left(\cup_{i=1}^{N_{sc}} L_i\right)} \dots (8)$$

Where, L_i represents length of chain for the i^{th} sidechain. Due to use of previous flexibility factor, equation 8 can reduce number of unnecessary sidechains, thereby reducing delay needed for sidechain management. Hashes for each block are stored on a separate chain, along with sidechain ID, which assists in fast retrieval of data whenever necessary. The model uses Proof-of-work (PoW) consensus for block validation, with private blockchain deployment. Due to this process, overall delay of SCM operations is reduced, which can be observed from the next section of this text, where delay values are compared with existing blockchain-based models.

IV. RESULTS AND COMPARATIVE EVALUATION

To evaluate performance of the proposed model, many SCM transactions were added to it. Configuration of these transactions were taken from standard SCM datasets, which included the following sources,

- Auto Supply Chain Data (https://data.mendeley.com/datasets/n24z7r2z28/2/files/89b1d403-2c23-41e8-888b-793ac998dd0d)
- Supply Chain Logistics (https://brunel.figshare.com/articles/dataset/Supply_Chain_Logistics_Problem_Dataset/7558679)
- Global Garment Supply Chain Data (https://old.datahub.io/dataset/global-garment-supply-chain-data)
- NYSERDA New York Offshore Wind Supply Chain Dataset (https://data.world/data-ny-gov/tb54-h6gg)

All these datasets are freely available and can be downloaded & used with Open-source licensing. These sets were combined to form 25000 SCM transactions, and each of them was added sequentially into blockchain via the proposed DASC2M model, and using FSCM [5], DRL [19], and FLIC [15]. While adding these transactions, delay (D) &percentage of computational power (PC) needed for performing them were evaluated. These values were averaged for each batch that consists ofa number of transactions (NT), and can be observed from table 2 as follows,

Table 2. Delay needed for adding a SCM block to the blockchain

NT	**D (s) FSCM [5]**	**D (s) DRL [19]**	**D (s) FLIC [15]**	**D (s) DAS C2M**
100	0.46	0.37	0.45	0.26
200	0.52	0.39	0.49	0.29
300	0.57	0.44	0.55	0.35
400	0.66	0.48	0.60	0.44
500	0.70	0.52	0.78	0.59
1k	0.95	0.87	1.21	0.81
2k	1.66	1.23	1.68	1.05
3k	2.06	1.59	2.09	1.27
5k	2.55	1.94	2.52	1.50
6k	3.03	2.30	2.95	1.72
7k	3.51	2.66	3.38	1.95
9k	3.99	3.01	3.81	2.18
10k	4.47	3.37	4.24	2.40
12k	4.96	3.73	4.67	2.63
14k	5.44	4.09	5.10	2.86
16k	5.92	4.44	5.53	3.08
18k	6.40	4.80	5.96	3.31

20k	6.88	5.16	6.39	3.53
22k	7.37	5.51	6.82	3.73
24k	7.85	5.87	7.25	3.93
25k	8.33	6.23	7.52	4.09

From this evaluation& from figure 8, it can be observed that the proposed model is 50% faster than FSCM [5], 23% faster than DRL [19], and nearly 39% faster than FLIC [15], which makes it highly useful for a wide variety of high-speed SCM applications.

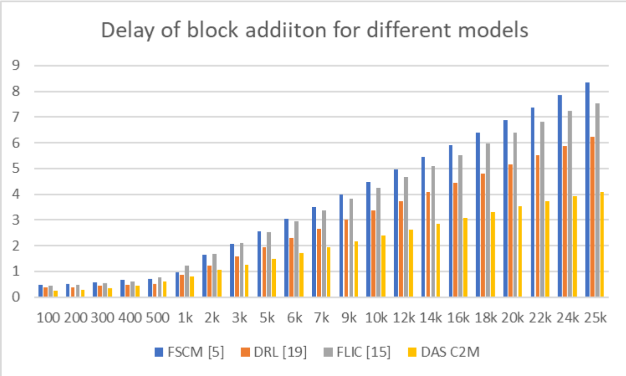

Figure 8. Delay of block addition for different models

This reduction in delay is due to use of delay-aware sidechain creation process, which generates new sidechains for every set of SCM transactions. Similarly, the computational complexity in terms of percentage of computational power can be observed from table 3 as follows,

Table 3. Percentage of computational power needed for SCM transactions

NT	**PC (%) FSCM [5]**	**PC (%) DRL [19]**	**PC (%) FLIC [15]**	**PC (%) DAS C2M**
100	8.00	6.50	6.90	5.83
200	8.20	6.90	7.23	6.06
300	8.35	7.30	7.48	6.32
400	8.79	7.55	7.93	6.67
500	8.93	8.23	8.63	7.37
1k	10.30	9.58	9.63	8.06
2k	10.90	9.96	10.05	8.66
3k	12.50	10.29	11.28	9.53
5k	12.70	12.18	12.55	10.90
6k	15.60	14.02	14.68	12.38

7k	16.50	15.89	16.18	13.84
9k	19.20	17.76	18.25	15.71
10k	22.50	19.62	20.52	18.07
12k	27.90	21.49	23.47	20.54
14k	31.90	23.35	25.96	22.83
16k	36.25	25.22	28.57	25.19
18k	40.60	27.08	31.17	27.54
20k	44.95	28.95	33.78	29.89
22k	49.30	30.81	36.38	32.24
24k	53.65	32.68	38.99	34.59
25k	58.00	34.54	41.60	31.05

Based on this evaluation and figure 9, it is observed that the proposed model is 29% efficient than FSCM [5], 15% efficient than DRL [19], and 19% efficient than FLIC [15] in terms of processing complexity, which makes it highly useful for low to medium processing-performance systems.

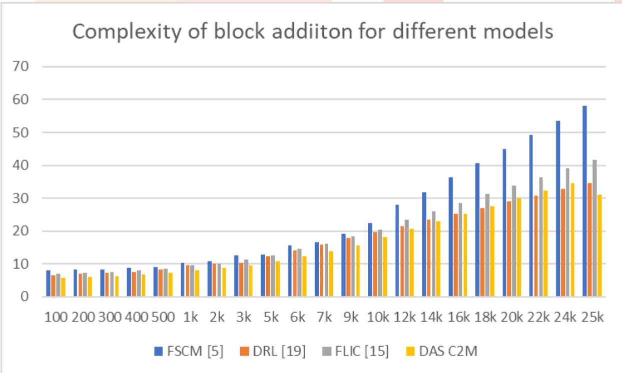

Figure 9. Complexity of block addition for different models

This improvement is due to reduction in number of operations needed for hash generation, which makes the model highly efficient, and useful for large-scale SCM application deployments. Thus, the model has lower delay, and lower computational complexity when compared with various state-of-the-art approaches, which makes it highly scalable, and improves its deployment capabilities for multiple types of SCM application scenarios.

V. CONCLUSION

The proposed SCM model uses delay-aware sidechaining for storing & retrieving information, which makes it highly useful for a wide variety of low-complexity applications. These sidechains are managed via an efficient GA model, which reduces overall delay needed for sidechain creation & maintenance, thereby lowering the complexity of transaction storage & tracking. Due to these advantages, the proposed model is observed to consume 50% lowerdelay than FSCM [5], 23% lower delay than DRL [19], and nearly 39% lower delay than FLIC [15], thereby making it useful for various high-speed & secure SCM deployment applications. Furthermore, the proposed model uses small sized blockchains for adding SCM data, due to which its computational complexity also reduces. It is observed that, the proposed model has 29% lower power requirements than FSCM [5], 15% lower power requirements than DRL [19], and 19% lower power requirementsthan FLIC [15], which makes it useful for low-power SCM applications. But as the number of transactions increase (over 1 million), the model generates a large number of sidechains, which are complex in terms of management, and data retrieval purposes. Thus, in future, researchers can modify the sidechain generation and management process via use of deep learning or Q-learning approaches which will assist in optimizing number of sidechains created for large sized SCM deployments. Furthermore, researchers can also validate the model on different kinds of public & private blockchain environments, which will further assist in evaluate its performance on different blockchain architectural models. After this validation, researchers can deploy custom consensus models in order to further facilitate higher trust & better traceability of SCM blocks for multiple application deployment scenarios.

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