# Optimizing Supply Chain Management using Permissioned Blockchains

Aritri Priya Saha
Auburn University
Auburn, Alabama, USA
aritri.saha@auburn.edu

Ujjwal Guin
Auburn University
Auburn, Alabama, USA
ujjwal.guin@auburn.edu

## Abstract

The semiconductor supply chain has encountered unprecedented volatility in chip demand and supply, a trend expected to persist over the next decade. Fueled by increasing demands for enhanced performance and power efficiency, the semiconductor industry has undergone a paradigm shift towards heterogeneous integration, leading to the emergence of 2.5D/3D chips. These chips integrate diverse chiplets, sourced globally, into a single chip. Current blockchain solutions in hardware supply chain management focus predominantly on enhancing resiliency for end users or system integrators, providing robust mechanisms for tracking and tracing chip movements. However, these solutions often neglect the critical needs of manufacturers at earlier stages of the supply chain. Addressing this gap, this paper proposes a novel blockchain-enabled provenance framework that equips manufacturers with early visibility into the inventory levels of chiplet distributors and system integrators. Additionally, our framework enables any downstream member to swiftly locate any available chiplets and chips registered on the chain by manufacturers. This visibility enables manufacturers to proactively respond to market shifts, thereby helping to avert supply chain disruptions. Implemented using Tendermint, our framework extends benefits to all stakeholders in the supply chain by enhancing transparency and creating incentives for manufacturers to participate on the blockchain alongside system integrators. This strategic approach not only mitigates the effects of demand volatility but also contributes as a motivation factor for blockchain adoption in hardware supply chains.

## CCS Concepts

• **Hardware** → **3D integrated circuits**; **Economics of chip design and manufacturing**; **VLSI design manufacturing considerations**.

## Keywords

Heterogeneous integration, chiplet, supply chain, permissioned blockchain, inventory management, Tendermint.

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## 1 Introduction

The semiconductor industry has increasingly embraced globalization and a growing number of companies choose to operate fabless to optimize manufacturing costs without compromising quality. Due to globalization, the industry has seen significant advancements aimed at minimizing costs while continuing the trend of transistor miniaturization and making Moore's Law relevant today. However, the globalized hardware supply chain has faced numerous unprecedented challenges over the years. A notable one is the global chip shortage that was kickstarted by the COVID-19 pandemic. The steep growth of consumer electronics industries during the lockdown and the shutdown of manufacturing plants at several locations inadvertently caused a bottleneck in the hardware supply chain [16]. Despite the rapid return to normalcy in the economy, the supply chain has yet to recover from the disruptions caused by sudden factory shutdowns and shifting consumer demands. Due to the highly capital-intensive nature of the semiconductor industry, it is practically infeasible to adjust it quickly to meet demand fluctuations. Even though the pandemic may be a rare event, it can be safe to say that supply chain disruptions could occur again in the future. In response, the White House initiated the Chips and Science Act in 2022, a remarkable $52.7 billion investment for bolstering semiconductor fabrication in USA [19]. Many other countries also invested heavily in building fabrication units [9, 10]. As a result, fabrication will remain globalized, and the rise of heterogeneous integration further aggravates this situation as there will be hundreds of manufacturers producing chiplets all across the globe. Thus, it is essential to monitor the demand for chips and electronic devices so that manufacturers and material suppliers can manage their production and supply capacity.

Recently, blockchain technology has emerged as an optimal solution to enable the traceability of ICs in the supply chain [6, 8, 20, 27]. While existing studies have proposed blockchain-based solutions for enhancing supply chain provenance [8, 22], these approaches focus primarily on the basic traceability of components throughout the supply chain. However, they often fall short of safeguarding sensitive data related to the semiconductor design and manufacturing processes. In an industry where protecting intellectual property and maintaining data confidentiality are paramount, the limitations of existing blockchain implementations present significant challenges that must be overcome for broader adoption and effectiveness. Zhong et al. [27] proposed a modular blockchain framework to address end-to-end traceability of parts while preserving privacy, trade secrets, and integrity of the parts. Despite the proposed robust mechanisms, blockchain adoption in the semiconductor industry

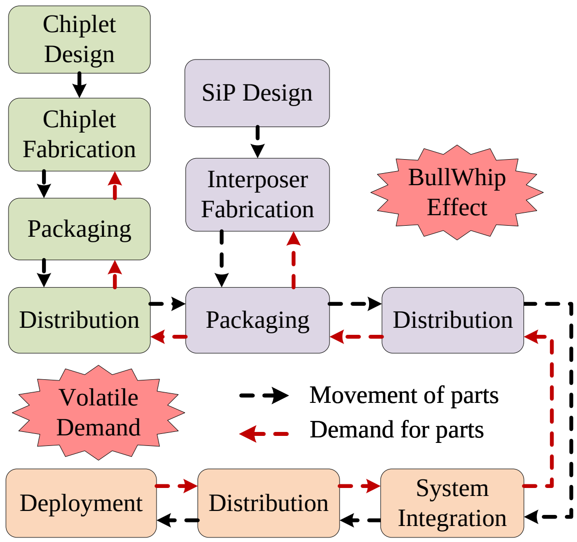


**Figure 1: Semiconductor supply chain.**

has been slow. Concerns remain about the motivation of manufacturers to join the chain, as the end users or system integrators seem to benefit the most from tracking and traceability.

Figure 1 presents the overall semiconductor supply chain showing the demand and movement of parts. The supply chain of 2.5/3D ICs starts with the design and fabrication of chiplets, which are tiny ICs that deliver a subset of functionality. These chiplets are then combined with others on an interposer in a system in a package (SiP). Traditionally, packaging is primarily handled by outsourced semiconductor assembly and test companies (OSATs), which mainly compete based on low labor costs. However, for heterogeneous integration, the packaging companies can be onshore. There are several advantages compared to the traditional system-on-chip (SoC) architecture, as heterogeneous integration enables the assembly of different known-good chiplets fabricated with different technology nodes. Once the ICs are fabricated and tested, they travel through various distributors before ending up in electronic systems.

Traditionally, for conventional blockchain-based provenance systems, the traceability of parts is ensured from the end user's side. Unfortunately, this does not provide any parts' inventory information to their manufacturers. This is particularly pivotal as it addresses the inherent challenges of supply chain disruptions triggered by unpredictable demand fluctuations. These disruptions often disproportionately impact manufacturers, amplifying minor demand variations from downstream – a phenomenon commonly referred to as the "Bullwhip Effect" [26]. To address this shortcoming, we propose implementing an inventory management system where the manufacturers can be aware of the part's inventory. By granting manufacturers early visibility into demand forecasts, our proposed infrastructure can mitigate the adverse effects of the Bullwhip Effect, offering them the opportunity to respond proactively to market shifts. Simultaneously, it safeguards the trade secrets of system integrators, ensuring confidentiality and trust across the supply chain as it is built upon the framework proposed in [27]. This method not only fosters trust and transparency but also serves as an incentive for widespread blockchain adoption. Our framework lays the foundation for a resilient and efficient supply chain network by fostering a transparent and traceable network.

The contributions of our paper are described as follows. We propose a scalable and modular blockchain framework designed specifically for the supply chain management of parts, i.e., chiplets and chips. This permissioned blockchain infrastructure ensures complete traceability of part movements while enabling manufacturers to monitor available inventory levels. Our system is tailored to support supply chain entities, from manufacturers to distributors, effectively responding to market fluctuations. Our model enhances supply chain responsiveness and efficiency by enabling swift access to data on available parts. Furthermore, our framework expands the modular design proposed in [27], allowing the safeguarding of trade secrets across different supply chain segments without impeding the overall flow of parts across the supply chain. This ensures that trade secrets and integrity remain protected while maintaining the transparency necessary for operational efficiency.

The rest of the paper is organized as follows. Section 2 covers prior works on using blockchain for supply chain management and provenance. In Section 3, we present our proposed architecture and the underlying principle behind the framework. We analyze the effectiveness of our proposed framework in Section 4. Finally, we conclude the paper in Section 5.

## 2 Related Work

The concept of blockchain was first introduced by Satoshi Nakamoto, which ultimately opened doors to greater lengths of research on incorporating this technology across different applications. Few prior works have explored vendor-managed inventory through blockchains [15, 17], where the suppliers observe the customer's inventory and make replenishment decisions accordingly. However, these works rely on optimizing inventory through vendors, whereas the semiconductor supply chain inventory management is more complex. A significant amount of research has also delved into integrating blockchain for supply chain management in the realm of pharmaceutical industries [1, 2], fashion apparels [18, 23], and agriculture [14].

Over the years, significant work has been carried out to improve supply chain resiliency through traceability, transparency, and reliability rather than inventory management [8, 12, 13, 24]. Guin et al. introduced a blockchain-based framework to ensure the authenticity of devices using an unclonable identifier (ID) generated from an SRAM PUF [12]. Cui et al have proposed a confirmation-based ownership transfer among the assets moving across the chain using Hyperledger fabric [8]. Zhong et al. have proposed a modular framework to protect trade secrets across the supply chain [27]. Yang et al. [25] proposes a two-stage mathematical semiconductor planning model using data from the blockchain. Fu et al. [11] conducted a study proposing a supply chain framework with intelligent decision-making capability with roughly the same goal. The authors in [5] have proposed a blockchain-integrated framework in the domain of heterogeneous integration but specifically catered only towards the assurance of the integrity of the system-in-packages.

Blockchain research has extended across many domains, not limited to the semiconductor industry, for security enhancement.

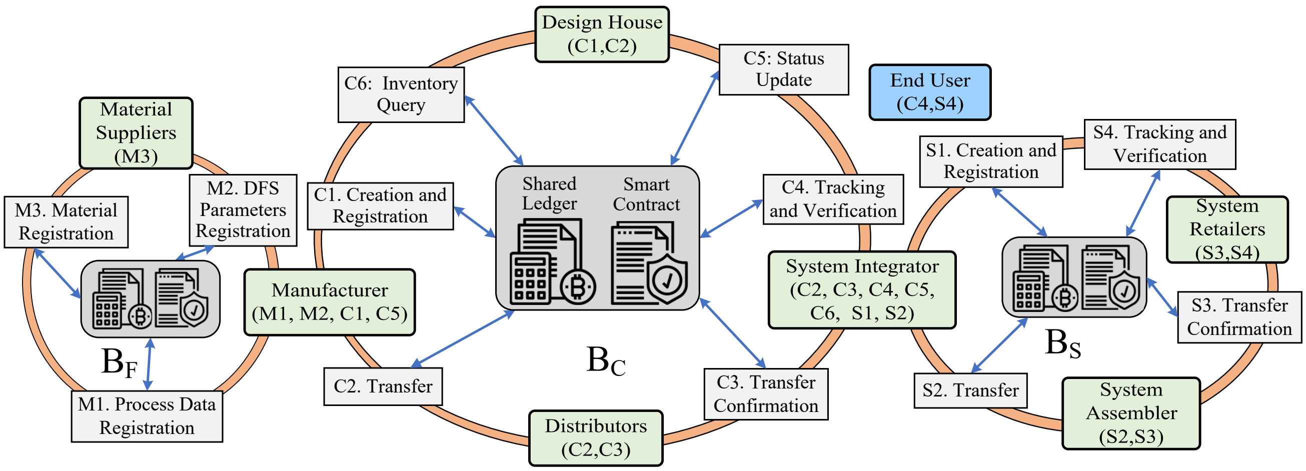


**Figure 2: Proposed Blockchain Traceability Framework.**

However, fewer works have explored the careful and controlled extraction of data catered towards improving supply chain resiliency. Our framework is built on top of the proposed architecture provided by [27], utilizing many of the functions provided in [8] to provide a complete and more comprehensive approach to improving supply chain resiliency, by putting manufacturers as well as system integrators on the forefront of decision making in the chain, along with the existing security measures.

## 3 Proposed Approach for Optimizing Supply Chain Management

A major issue currently persisting in the semiconductor supply chains is associated with frequent disruptions leading to significant loss for entities participating in the chain. It is necessary to articulate the movement of chips across the supply chain to allow controlled visibility for each entity. Our proposed framework, depicted in Figure 2, allows manufacturers access to the number of undeployed parts in the chain without exposing any other details from the blockchain infrastructure. It also allows system integrators to quickly reach out to the component blockchain to find the availability of chiplets that have not been deployed yet.

Table 1 summarizes the various entities and their roles in the electronics supply chain. Figure 2 shows the layered blockchain framework that is extended over our previously proposed framework [27] for inventory management. It is built upon three separate blockchain ledgers, which are manufacturing life cycle ($B_F$), component life cycle ($B_C$), and system life cycle ($B_S$) ledgers. While the figure shows an abstract view of the overall semiconductor supply chain, our framework allows the incorporation of additional chains when required. We omit the design life cycle as it is irrelevant for inventory management.

Each participating entity in our chain is shown with a green box in Figure 2 while the functions they are allowed to perform through restrictions imposed by the application logic are shown with the grey boxes. Each life cycle stage is analogous to a separate blockchain, and each blockchain has its own application logic and shared ledger. We first have the manufacturing life cycle, $B_F$, which deals with the fabrication of chiplet and chips. It comprises material suppliers and manufacturers, and the details of the functions '*M1: Process Data Registration*', '*M2: DFS Parameters Registration*', and '*M3: Material Registration*' can be found in [27].

**TABLE 1:** Participating entities in the electronics supply chain.

| Entity | Description |
|---|---|
| Design House | Designs parts, i.e., chiplets or 2.5/3D ICs. |
| Manufacturer | Owns a foundry and fabricates chiplets or 2.5/3D ICs. |
| Material Supplier | Supplies materials to a foundry. |
| System Integrator (SI) | Designs electronic systems, and commonly identified as original equipment manufacturers (OEMs). |
| System Assembler | Manufactures electronic systems, e.g., Raspberry Pis are made in a Sony factory. |
| Distributor | Distributes chiplets or ICs. |
| System Retailer | Distributes electronic systems, e.g., Newark, PiShop, and Amazon. |

The core of the inventory management framework is the component blockchain, $B_C$, and comprises entities ranging from manufacturers, part design houses, distributors, and system integrators. The new parts can only be registered by either the manufacturers or design houses through '*C1: Creation and registration*' function. Once the new parts are registered in the blockchain, the manufacturers can update the newly manufactured chiplets and chips. The '*C2: Transfer*' function is called once they sell the chips and chiplets to begin the process of transfer. Once the distributors or system integrators receive the shipment, they invoke '*C3: Transfer Confirmation*'. At this point, the ownership transfer is completed and recorded in the ledger. For verifying the part's travel through the supply chain, the end user or system integrator can invoke

'*C4: Tracking and Verification*'. One can find the details of these functions in [8, 27].

```
type partTypes{
     type part{
           String partID;
           String manufacturer;
           String currentOwner;
           String ownerRole;
           String transferTo;
           Enum transferStatus;
           Enum deploymentStatus;
           List<string> trace; };
     String designHouse; }
```

**Figure 3: Data structure for parts.**

To implement the inventory management framework, we need to add two additional functions, resulting in the need to capture more data. Figure 3 shows the updated data structures for each part type registered on the chain. Each part type's data structure includes two fields: registered parts and the associated designer or design house. Each part within a type is associated with a unique hashed part ID (*PID*) derived from a physically unclonable function (*PUF*) or electronic chip ID (*ECID*), the manufacturer or its current owner, the owner's role in the chain, transfer status, deployment status, and a trace array that chronologically records all its previous owners. Note that the part's lifecycle ends when the deployment status flag is set. For example, a chiplet's journey concludes when an IC manufacturer incorporates it into a system-in-package. Similarly, an IC's lifecycle ends when deployed in an electronic system. Throughout the paper, we use "part" interchangeably to represent either a chiplet or an IC.

**Algorithm 1:** Updating the status of parts once they are used.

**Input** : Part Type (PT), Part IDs (PIDs)

```
1 function UpdateStatus (PT, PIDs) is
2     for all PID in PIDs do
3         part ← fetchPart(PT, PID);
4         if ((part.ownerRole == ICM/SI ) && (
            part.transferStatus != IN_TRANSFER)) :
5             part.deploymentStatus = deployed;
6     end
7     Update part details in Ledger;
8 end
```

First, '*C5: Status Update*' can be invoked by the IC manufacturers (*ICM*) or system integrators (*SI*) once a part is used up in an IC or a system. Algorithm 1 presents an overview of our proposed function. Only *ICM* and *SI* currently owning the part can invoke this function. The user sends transactions containing the IDs of $n$ parts that have been deployed. For each part with the respective ID, the function performs a check, Lines 4-5, to validate the current owner's role and that the part is not in the middle of a transfer. If these criteria are met, the function changes the deployment status flag of the part to "deployed" in Line 5 and subsequently updates it in the ledger. Once a part is deployed, it indicates that it has been integrated into an IC or a system and is no longer held in the inventory of any organization.

**Algorithm 2:** Determining the quantity of available parts in the supply chain.

**Input** : Part Type (PT)
**Output** : Number of available parts (*count*)

```
1  function AvailabilityOfParts (PT) is
2      parts[] ← fetchAllPartsWithType(PT)
        allAvlParts, avlParts ← [];
3      for part in parts do
4          if (part.deploymentStatus != deployed) :
5              allAvlParts.append(part) ;
6              if (part.owneRole != SI) :
7                  avlParts.append(part) ;
8      end
9      if (currentUser is M/DH) and :
10         return count ← len(allAvlParts);
11     inv, owner ← [];
12     if (currentUser is SI) :
13         for part in avlParts do
14             owner ← append(part.currentOwner);
15             inv[owner.index(part.currentOwner)] ++;
16         end
17         return owner : inv;
18 end
```

The primary objective of this paper is to allow manufacturers and *SIs* to get real-time visibility over the number of undeployed chiplets or chips in the supply chain using the '*C6: Inventory Query*' function. This function allows chiplet and IC manufacturers to determine the quantity of available or undeployed parts of a specific type in the supply chain, without disclosing ownership details. Conversely, SIs can use the function to ascertain ownership details, including quantities held by various entities. Algorithm 2 presents the implementation details of '*C6: Inventory Query*'. Upon receiving the part type as input, the function constructs two arrays, Line 2. Lines 4-8 populate these arrays: *allAvlParts* includes all undeployed parts, and *avlParts* filters parts not owned by SIs. If the current user is the manufacturer or designer of the part type, the function returns the total count of all available parts (Lines 9-10). If the user is an *SI*, the function retrieves updates on undeployed parts held by other distributors and manufacturers. The algorithm parses through *avlParts*, counting undeployed parts for each unique organization listed in the *owner* array and incrementing counts in the *inv* array accordingly (Lines 12-16). Upon completion, the *owner* array contains names of organizations with undeployed parts of that type, and *inv* presents their respective inventory counts (Line 17).

Our framework ends with the system blockchain. The system lifecycle $B_S$ is the last phase of our semiconductor supply chain,

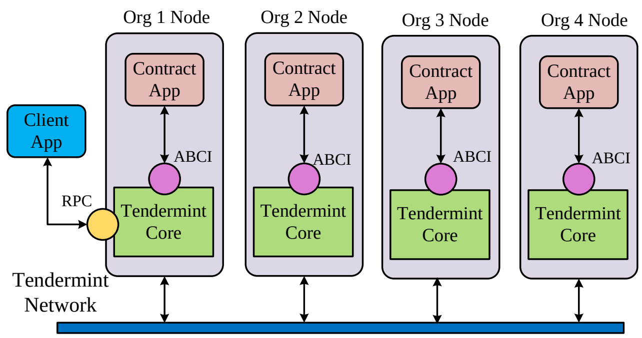


**Figure 4: Proposed blockchain-based framework implemented with Tendermint.**

which is primarily used for integrating ICs. It starts once the component distributors transfer the component to the system integrators and ends once the finished system is deployed to an end user. This chain allows the tracking of each system in the chain and gives access to fabrication and traceability data from corresponding chains. This chain allows controlled access to the functions '*S1: Creation and Registration*', '*S2: Transfer*', '*S3: Transfer Confirmation*' and '*S4: Tracking and Verification*'. Details of this chain can be found in [27]. In addition, the functions '*C5: Status update*' and '*C6: Inventory Query*' can be implemented for the system blockchain as well.

## 4 Results and Discussions

In this section, we demonstrate our proposed framework with a reference blockchain implementation. Additionally, we provide an analysis to showcase the benefits of utilizing our blockchain framework for production planning. Part manufacturers can use this framework to mitigate loss due to fluctuating demand in the semiconductor industry.

### 4.1 Blockchain Implementation

We have implemented our proposed framework involving the Component blockchain using Tendermint [4]; however, this framework can be extended for use in other permissioned blockchain frameworks such as Hyperledger fabric [3]. Tendermint is a blockchain software that runs the Byzantine Fault Tolerance (BFT) state machine replication at its core to create and maintain a blockchain network. It also allows for secure and consistent replication of an application on multiple machines and ensures that every machine computes the same state and transaction logs. Tendermint's Application Blockchain Interface (ABCI) enables communication between the application logic and the blockchain. This modularity is vital to processing an application's operational logic without interfering with the underlying consensus mechanism.

We use a Python script to demonstrate a client application for sending transactions to the blockchain server. The client application is particularly pivotal as it ensures that transmitted data is formatted correctly before sending it over to the server and interpreted correctly once it receives the messages after querying the server. Every transaction is also associated with its invoker's unique organization ID and role, which are sent as metadata and used to verify access control in our application logic. The transactions are submitted to the blockchain network via HTTP requests to the Tendermint node's RPC interface[7]. Tendermint's consensus mechanism ensures that all transactions are validated by the participating organizations' (validator) nodes, according to the application's operational functions mentioned in Figure 2, before being committed to the ledger. Therefore, the BFT consensus mechanism accounts for a verified and tamper-resistant ledger, recording all verified transactions between participating members. One can find the implementation details (i.e., pseudocode of all the functions) of our proposed infrastructure in [21].

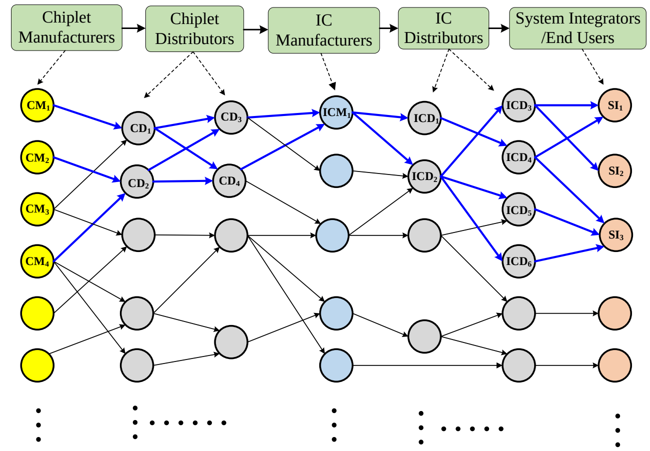


**Figure 5: Semiconductor supply chain represented as a directed acyclic graph.**

To demonstrate the functionality of our proposed framework, we have deployed four validator nodes, each running in a separate Docker container. These validator nodes are configured to connect to the replicated contract application, which is also containerized and runs in its own Docker container. This setup, as illustrated in Figure 4, ensures isolation, scalability, and ease of management, allowing us to emulate a realistic and distributed network scenario. We assume that users have been supplied with identity certificates by trusted certificate authorities, and the blockchain server is aware of the user's identity for validation.

### 4.2 Simulation Platform

To validate the effectiveness of the proposed infrastructure, we have created a simulation platform for the semiconductor supply chain using Python. Figure 5 shows a directed acyclic graph (DAG) of the supply chain with hundreds of nodes acting as chiplet and IC manufacturers, distributors, and system integrators. The arrows represent the connection between the supply chain entities as parts travel from seller to buyer. A chiplet travels from its manufacturer ($CM_1$) through many distributors ($CD_1$, $CD_3$, and $CD_4$), before finally reaching an IC manufacturer ($ICM_1$) where it is integrated into an IC. The chip is then sold off to multiple distributors ($ICD_1$, and then $ICD_2$) from the IC manufacturer ($ICM_1$). The chips then travel across different distributors ($ICD_3$, $ICD_4$, $ICD_5$, $ICD_6$) and finally are integrated into various systems by different system integrators or end users ($SI_1$, $SI_2$, and $SI_3$).

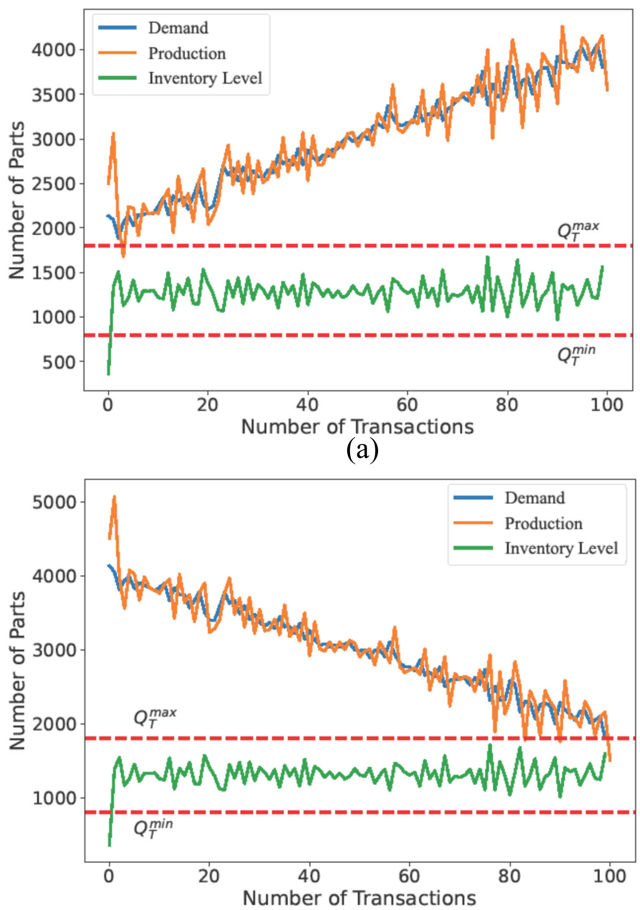


**Figure 6: Simulation for inventory management. Figures (a) and (b) show the production control to meet the increasing and decreasing demands, respectively.**

We have added hundreds of random transactions to initialize the simulation platform and evaluate the performance. The transactions can be formatted as follows:

$$T_i = \{PT, S_i, D_i, n, \{ID_1, ID_2, \dots ID_n\}\} \quad (1)$$

where, $PT$, $T_i$, $S_i$, $D_i$, $n$, and $ID$ represent the part type, $i^{th}$ transaction, source entity, destination entity, number of parts and their IDs, respectively.

Demand in the semiconductor industry is determined by the rate of the deployment of parts. Demand forecasting is particularly difficult due to rapid technological advancements combined with fluctuating demand. Figure 6 shows how manufacturers can plan their production based on demand and inventory levels. Note that the X-axis represents the number of transactions, and the Y-axis represents the number of parts. For simplicity, we have considered a total of 100 transactions and set the threshold values, $Q_T^{min}$ and $Q_T^{max}$, of 800 and 1800, respectively, and vary the demand from 2000 to 5000. We will demonstrate two cases of how to manage inventory to increase and decrease demand. We have defined two thresholds, $Q_T^{min}$ and $Q_T^{max}$, based on historical data obtained from blockchains, which form the basis of our demand prediction. Here, $Q_T^{min}$ represents the minimum number of available parts expected to be in the supply chain, below which manufacturers start planning to increase production. On the other hand, $Q_T^{max}$ indicates the maximum number of available parts in the supply chain, beyond which manufacturers plan to reduce production. These parameters can be fine-tuned later based on prior demand and supply experiences.

First, we consider the increasing demand scenario. When manufacturers observe increased demand, as shown in Figure 6(a), they can decide whether to slowly increase or slowly decrease their production capacity depending on the threshold value. If the quantity of available parts surpasses $Q_T^{max}$, the manufacturers can reduce their production capacity as historical data indicates that $Q_T^{max}$ is the ceiling after which demand will most likely decrease. Similarly, when the inventory level reaches below $Q_T^{min}$, the manufacturers can opt to increase their supply to ensure that inventory levels remain within the limits. Second, when there is an overall decrease in the demand for parts of a particular type, as illustrated in Figure 6(b), the manufacturers can choose to increase or decrease their production by observing the inventory levels. Additionally, if the number of available parts decreases below $Q_T^{min}$, the manufacturers must steeply increase their production capacity to meet the demand on time. These figures clearly demonstrate that the chip inventory levels remain well within the predefined acceptable range, even in the face of significant fluctuations in demand. This stability highlights the effectiveness of our inventory management strategies, ensuring that supply remains consistent and able to meet varying levels of demand without risking shortages or excesses.

## 5 Conclusion

In this paper, we proposed a blockchain framework to improve supply chain resilience by equipping chiplet and IC manufacturers and system integrators with a real-time inventory of parts. Our framework allows manufacturers to query the blockchain to find information about the number of available parts and make informed decisions about their production planning. It allows system integrators to query the blockchain to find specific parts from distributors that have not been sold, ultimately mitigating demand fluctuations and allowing manufacturers and distributors to eliminate excess inventory. Our paper concludes with a reference implementation of the framework using Tendermint. To validate the effectiveness of our proposed infrastructure, we developed a comprehensive simulation platform for the semiconductor supply chain using Python. We conducted simulations to demonstrate how manufacturers can optimize production by combining real-time monitoring of demand fluctuations with continuous observation of parts inventory. This approach ensures more accurate planning and responsiveness to changing market conditions.

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