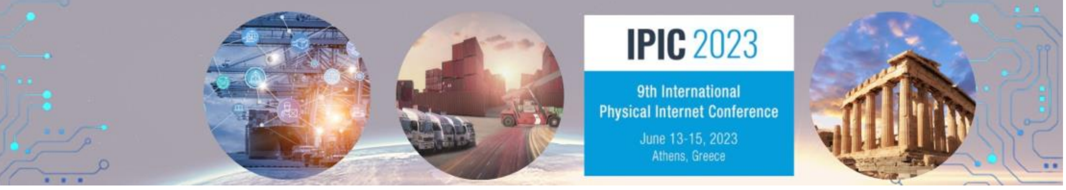

Physical Internet Center

Hyperconnected and Autonomous Distribution System for Societally Critical Products

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Abstract: *Societally critical products are crucial for maintaining people's well-being and ensuring the continuity of vital societal operations. However, disruptions can severely impact their supply chains due to increased demand and supply chain disruptions. The paper defines the importance of these products and presents a conceptual framework for a hyperconnected and autonomous distribution system that encompasses physical, organizational, information, and operational aspects. We present the results of research at Georgia Tech during the COVID-19 pandemic, which involved designing and operating an innovative system for efficiently distributing personal protection equipment. The study provides the foundation for a systemic approach to distributing societally critical products, integrating autonomous operations and hyperconnectivity based on Physical Internet concepts. The paper also discusses the challenges of large-scale adoption, implementation, and operation of such a distribution system.*

Keywords: *Physical Internet, Hyperconnected Distribution, Autonomous Operating Systems, Multi-Agent Systems, Societally Critical Products, Personal Protection Equipment*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; logistics and supply networks; Modularization; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation; machine learning,*

Physical Internet Roadmap*: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

Societally critical products (SCP) refer to products that are essential to the well-being and functioning of society. The world recently experienced an unprecedented outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), commonly known as COVID-19, declared a pandemic by the World Health Organization on March 11, 2020. As a result, educational institutions across the United States, ranging from elementary schools to universities, temporarily suspended in-person classes and research activities. Although reopening was widely recognized as important (Panovska et. al, 2020), institutions lacked the strategies to do so safely (Dibner et. al, 2020). The Center for Disease Control (CDC) issued reopening guidelines that included consistent prevention strategies, such as universal and properly fitting masks and physical distancing. As a result, there was a surge in demand for critical supplies such as personal protective equipment (PPE), including gloves, masks, sanitizers, and disinfectants, while the supply was limited due to production constraints. Many organizations and individuals prioritized securing a sufficient stockpile of PPE during the COVID-19 pandemic, with concerns about price or other factors often taking a secondary role.

The COVID-19 pandemic has demonstrated that everyday products we rely on can become SCPs during pandemics and epidemics, underscoring their critical role in safeguarding public health. The ability of regular products to become societally critical products highlights the importance of having a robust and adaptable distribution system that can quickly respond to changing needs and demands during times of crisis. Ensuring that essential goods and services are available and accessible to all can help mitigate the impact of emergencies and build more resilient communities.

In the first part of the paper, we define and stress the importance of societally critical products (SCPs). We present the synthesis of our action research at Georgia Tech during the COVID-19 pandemic on the design, implementation, operation, and continuous improvement of an innovative system for enabling the efficient, seamless, and resilient supply and distribution of personal protection equipment. In the second section, we expand on our research and propose a comprehensive systemic approach for SCP distribution, which combines autonomous operations and hyperconnectivity, in accordance with Physical Internet (PI) principles, extending beyond PPEs. We present a conceptual framework for the hyperconnected and autonomous distribution system for SCPs, concentrating on the physical, organizational, information, and operational layers. Finally, we conclude the paper by highlighting further research, innovation, and field experimentation opportunities, and emphasizing the importance of integrating the supply and distribution of societally critical products seamlessly.

2 Societally Critical Products (SCP)

Essentials are necessary for the population and the economy at large to sustain a satisfactory quality of life and work, including ensuring supply chain continuity, given the circumstances. Essentials cover a broader spectrum of products than societally critical products (SCP). Essential products, which include food, consumables, and non-pharmaceutical medicine, can become societally critical products in certain situations, such as during natural disasters or other emergency situations where supply chain disruptions can have significant consequences on society. Demand for SCPs can also change rapidly depending on the circumstances, and ensuring their availability is crucial for maintaining societal stability and well-being.

Given the lack of a clear definition of key attributes for SCPs in existing literature, we propose a set of defining characteristics (Figure 1) as a novel contribution to the field:

1. Essentiality: SCPs are products or materials that are indispensable for human survival, health, or safety. They are critical for meeting basic needs such as food, water, shelter, sanitation, and healthcare and ensuring social and economic stability.
2. High Demand: SCPs are prone to experience a surge in demand during situations such as emergencies, crises disasters, and pandemics.
3. Limited Availability: SCPs may have limited availability due to various factors such as supply chain disruptions, production constraints, or transportation difficulties. This can lead to shortages and competition for these products, notably resulting in price hikes or rationing.
4. Equitable Distribution: SCPs must be distributed equitably and made accessible to everyone who needs them, especially vulnerable populations such as the elderly, children, and those with disabilities or chronic illnesses. This requires cooperation and coordination between various stakeholders, including governments, NGOs, and the private sector.
5. Time-Sensitive: SCPs must be delivered in a timely manner to be effective. Delayed or inadequate delivery of SCPs can have serious consequences for public health and safety.

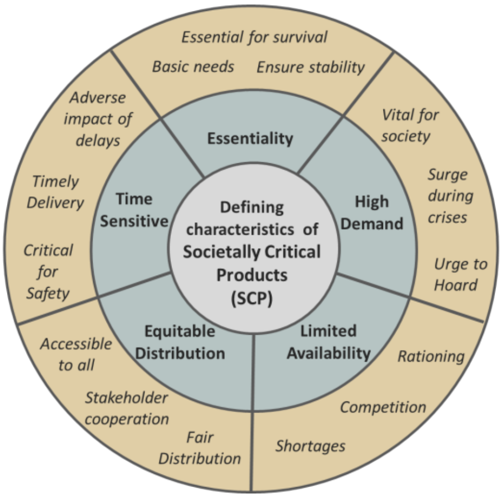

Figure 1: Characteristics of Societally Critical Products (SCP)

SCPs become even more important during a pandemic as their demand surges and their supply chain ecosystem may be disrupted. The scarcity of SCPs can lead to panic, hoarding, and a lack of access to the products for those who need them the most. The sudden surge in demand for these common products during the COVID-19 pandemic highlighted their critical importance in protecting individuals and preventing the further spread of the virus. For example, face masks, hand sanitizers, and cleaning products became SCPs essential to public health and safety. Without these products, the pandemic could have been much worse. Similarly, during outbreaks of other contagious diseases, regular products like disinfectants, tissues, and personal protective equipment also become SCPs crucial to limit the spread of the disease.

In times of scarcity or crisis, it may be necessary to ration these products to ensure that they are distributed fairly and equitably among the population. Rationing is the process of limiting the distribution of a product or service to a specific amount or group of people. Rationing societally critical products can ensure fair access, manage demand during scarcity, and prioritize distribution to those in need. It prevents hoarding and panic buying, ensuring an even distribution of the available supply. Rationing may become necessary to ensure that essential goods and services are available to everyone.

In summary, SCPs are products or materials necessary for meeting basic needs and maintaining social and economic stability during emergencies, disasters, or crises. Their essentiality, high demand, limited availability, equitable distribution, and time-sensitivity make them unique in terms of their importance and the challenges associated with ensuring their availability and distribution during times of crisis or emergency. Regular products may not have these distinctive features or may not be as crucial for maintaining societal stability and well-being.

3 Living Lab Initiative

Before the COVID-19 pandemic, Georgia Tech (GT) used a decentralized model for sourcing and replenishing PPEs and cleaning supplies, with each department managing its own stock and re-ordering as deemed pertinent. However, during the pandemic, this model proved to be inefficient and risky due to supply scarcity, uncertainty, and a lack of preparedness among lab teams to manage decisional complexity. In response, GT's Supply Chain & Logistics Institute implemented a hyperconnected supply chain and distribution system that leveraged a distributed network of software agents capable of autonomous prediction and decision-making, along with human-centric operations that relied on users for consumption information. The system successfully served researchers in over 200 labs across 40 buildings on campus throughout the pandemic, managing the distribution of massive quantities of PPEs, including 450,000 units of gloves across sizes and types and 200,000 units of disposable masks, without any significant stockouts or urgent requests for several months.

Drawing insights from the living lab initiative, the initial model for sourcing PPEs and cleaning supplies was revised and enhanced by integrating state-of-the-art advancements in supply chain management and engineering, such as autonomous prediction and decision-making mechanisms. The resultant generic conceptual model, characterized by its scalability, extends beyond PPE applications and is adaptable to various domains and industries, offering a structured approach to enhancing SCP inventory management and distribution processes. This model achieves efficiency through the implementation of cutting-edge technology and minimizes the reliance on human-centric operational procedures.

4 Conceptual Framework of the Proposed System

Our proposed concept envisions a fully automated and interconnected network of systems that can efficiently and effectively distribute essential goods and services to people and communities around the world. This section describes the framework focusing on the physical, organizational, information, and operational layers. Each layer plays a critical role in creating a seamless and efficient operating system that can respond quickly and effectively to changes in the business environment.

4.1 Physical Layer

We propose a topological multi-tier physical network structure, where physical nodes represent the facilities that are active in the system. The physical nodes are organized into tiers based on their location and function. At the lowest tier, there are tier-0 physical nodes, which are locations of specific active users or small groups of users who consume critical products. These nodes could be workstations of researchers, medical professionals, or employees in a manufacturing facility who require specific products to carry out their work. Next are the tier-1 physical nodes which correspond to facilities that include several tier-0 nodes and/or include a product depot. These nodes are larger than tier-0 nodes and serve as hubs for the distribution of critical products within a specific area, mostly within a building. Examples of locations for tier-1 nodes include healthcare centers, research centers, and manufacturing centers.

Tier-2 nodes correspond to buildings that host a set of tier-1 physical nodes. These buildings could be distribution centers, warehouses, or logistical hubs that manage the distribution of critical products on a larger scale. Tier-3 nodes correspond to a space grouping a set of tier-2 nodes. These could be large warehousing complexes, industrial parks, or campuses. Higher-tier nodes can be defined at local, regional, country, continent, and planetary tiers. Physical flows of products between physical nodes result from the organizational and decisional layers defined in the system. This topological multi-tier physical network structure enables the system to run autonomously and adapt to changing circumstances in real-time.

The physical layer also embodies the physical realization of the logical paths between nodes. This model assumes that the lead time of transportation between nodes can be approximated. We form the inter-relationships of the components in the physical layer in the organizational, information, and operational layers.

4.2 Organizational Layer

The organizational layer of the distribution system establishes a network of functional nodes, each with specific responsibilities. This system is designed to operate autonomously and adapt to changing circumstances in real-time. The system comprises multiple tiers of functional nodes, all hosted within physical nodes. The number of tiers in an actual distribution system may vary according to context and requirements, and the following model based on five-tier network serves as a conceptual example:

- End Users (Tier-0 Functional Nodes): As the final consumers in the system, end users may maintain a small autonomy stock for uninterrupted workflow.
- Nano-Fulfillment Centers (Nano-FCs, Tier-1 Functional Nodes): Situated near end users, these centers provide direct services and maintain an autonomy stock, continually restocking from the subsequent tier.
- Micro-Distribution Centers (Micro-DCs, Tier-2 Functional Nodes): These centers are responsible for autonomy stock maintenance and nano-fulfillment center replenishment. Each group of Tier-0 nodes is served by a single Micro-DC and its corresponding physical node.
- Distribution Center (DC, Tier-3 Functional Nodes): Tasked with aggregating and distributing resources to micro-DCs, the distribution center manages supplies between tiers and upholds an autonomy stock for smooth network operation.
- Supply Center (Tier-4 Functional Nodes): This center sources and procures materials from external suppliers, replenishing the DC while maintaining its own autonomy stock.

In this system, functional nodes are housed within physical nodes—actual locations where distribution functions occur. Each functional node exists within a physical node, with tier-0 functional nodes occupying one or more tier-0 physical nodes. Meanwhile, functional nodes within tiers 1 through 4 are situated in corresponding physical nodes. Each unit that houses tier-0 nodes is assigned a singular tier-1 functional node (Nano-FC) and its corresponding physical node. In essence, Nano-FCs operate as small-scale fulfillment centers, serving end users directly, whereas Micro-Distribution Centers cater to the Nano-Fulfillment Centers.

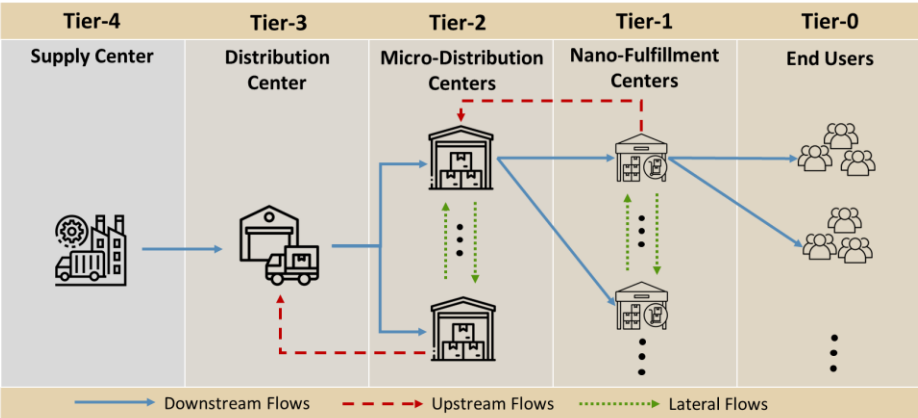

Figure 2: Typical flows within and across functional nodes

The distribution system's organizational layer combines functional and physical nodes to create an adaptive and efficient network that can respond to real-time changes. Each tier contributes to maintaining a continuous supply and distribution flow and fulfilling the end users' needs. The actual number of tiers in a distribution system will depend on various factors, and the distribution network can be designed to accommodate specific requirements.

In a multi-tier distribution network organization, the primary flow of products and resources is typically downstream, from higher to lower tiers. However, under certain circumstances, lateral and upstream flows may also be allowed to optimize the network's efficiency and adapt to changing requirements (Figure 2). Lateral flows facilitate redistribution within a functional tier, while upstream flows enable the retrieval of stock from lower tiers. Such flows may be necessary if a node no longer requires specific items or if a node is scheduled for closure.

4.3 Information Layer

Our proposed multi-tier shared distribution system relies on sharing resources and information across supply chain levels. Emphasizing information sharing, the proposed architecture aims to coordinate across and within tiers. Collection and analysis of user consumption data and resource burn rate are for example key to maintaining efficient inventory levels and resource availability.

Innovative methods for seamless data collection and user confidentiality include electronic key card systems, which offer secure, contactless access. These systems use encrypted communication to prevent unauthorized access and can be configured for different user access levels. Data from key card usage aids in pattern identification, resource allocation, and security improvements. The system also utilizes smart dispensers to track consumption and enable resource distribution. These dispensers feature remote monitoring, adjustable configurations, and automated inventory management. User authentication integration helps manage resource allocation and minimize waste.

Smart lockers, as proposed by Faugere (2017), provide an efficient way to record usage of critical products while minimizing contact and potential contamination. Critical product containers can be exchanged without physical contact, reducing the points of contact and potential contamination. The smart locker system tracks usage and provides data for efficient inventory management and allocation. Dynamic vision sensors using Time-of-Flight (ToF) technology collect accurate, real-time resource usage data in common areas. By analyzing depth information, ToF sensors inform restocking decisions, while gesture recognition capabilities yield deeper consumption pattern insights. These sensors can be combined with infrared or thermal sensors for comprehensive environmental and resource usage understanding.

Integrating advanced technologies and traditional practices offers comprehensive distribution network visibility and traceability. Balancing information sharing with sensitive data protection is crucial, requiring clear data access protocols, robust database security measures, and stakeholder awareness of proprietary information safeguarding responsibilities. This multi-faceted approach ensures a seamless, secure, and efficient multi-tier shared distribution network.

4.4 Decisional Layer

The decisional layer is a crucial aspect of the proposed multi-tier distribution network. It employs advanced decision-making technologies and processes, including predictive analytics, machine learning, and simulation modeling. These tools facilitate real-time decision-making in response to shifting dynamics in the economic environment, ensuring efficient inventory management and distribution.

Our model is demand-driven and encompasses several tiers of functional nodes, as well as a supply layer connecting suppliers to the primary supply center. The usage log of each user is employed to update demand forecasting models, enabling accurate consumption predictions for each location. Periodic evaluations of inventory levels against the forecast are conducted to determine the robust-days-of-inventory, a metric that accounts for both current stock and consumption rates. When inventory levels drop below a predefined threshold, it triggers inventory replenishment and re-ordering from suppliers at the supply center level. The decisional layer also accounts for uncertainty in lead time when placing orders with suppliers, ensuring that the distribution network remains responsive to fluctuations in demand and supply conditions. In the following subsections, we describe the various facets of the decisional layer. These components' technical details and models are published in independent research articles.

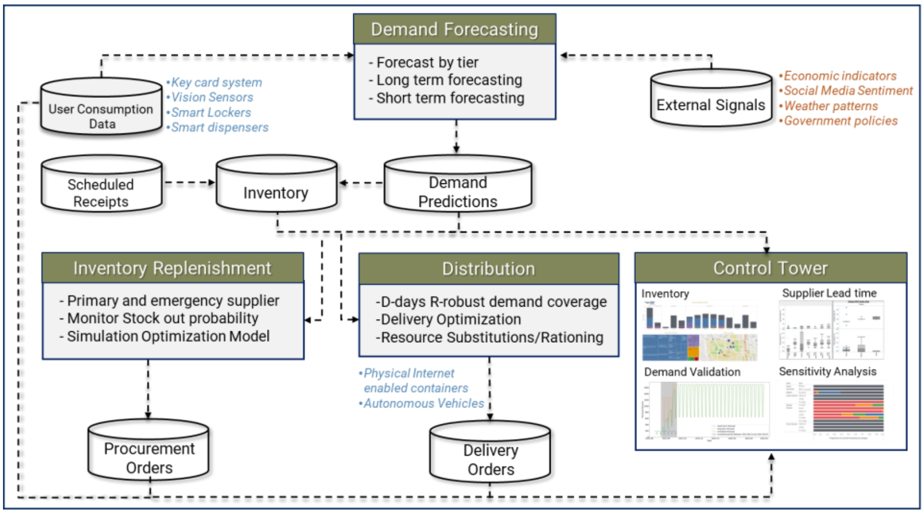

Figure 3: Conceptual Framework of the Decisional Layer of the Proposed Model

4.4.1 Demand Forecasting

The dynamic and adaptive data-driven model used for demand prediction in the lowest tier of the distribution network ensures accurate forecasting of critical items' requirements as formulated in Yim et al. (2021). Long-term and short-term decision forecasting for critical products involves leveraging user resource burn rate data to create accurate predictions of future demand, ensuring that adequate supplies are available when needed. Both forecasting methods are essential for keeping efficient inventory levels and facilitating effective decision-making within the distribution network.

Short-term decision forecasting focuses on predicting demand for critical products over a relatively brief period, such as days or weeks. This forecasting method is crucial for addressing immediate needs and ensuring that resources are readily available for users. Short-term forecasting employs user resource burn rate data and other real-time variables, such as seasonal fluctuations or sudden changes in consumption patterns, to generate accurate predictions. This information is vital for making quick adjustments to inventory management and replenishment strategies to maintain optimal stock levels and avoid shortages.

Long-term decision forecasting aims to predict demand for critical products over more extended periods, such as months or years. This method is essential for strategic planning, as it enables organizations to anticipate future requirements and make informed decisions regarding procurement, capacity planning, and infrastructure development. Long-term forecasting utilizes historical user resource burn rate data, as well as external factors such as market trends, economic indicators, and regulatory changes, to create projections of future demand. This information is critical for making informed long-term decisions regarding resource allocation, supplier contracts, and investment in distribution infrastructure.

External signals must also be incorporated into the data-driven model used for demand prediction of critical items. External signals stem from any data sources outside the organization that can provide valuable insights into the factors that impact demand. Incorporating external signals, such as market trends, economic indicators, government policies, social media sentiment, and weather patterns, into the forecasting model can improve the accuracy of demand predictions. External signals such as government mandates requiring everyone to wear masks in public places, and lockdowns or social distancing measures, can significantly impact demand for critical consumables like masks, food, cleaning supplies, and medical equipment; and social media sentiment analysis can also provide insights into potential surges in demand for products like medical supplies, cleaning products, or non-perishable foods.

By incorporating both short-term and long-term decision forecasting methods, along with the external signals, organizations can effectively manage inventory levels for critical products and adapt to changing demand patterns. This approach ensures that resources are available when needed while minimizing excess inventory and associated costs. Ultimately, this proactive strategy helps to create a more resilient and efficient distribution network for critical products.

4.4.2 Inventory Replenishment

Managing the inventory replenishment process for critical consumables is a complex task. Several challenges arise, including increased demand uncertainty, deteriorating supply capacity, fluctuating prices, extended lead times, and the impact of product unavailability on the functioning of facilities. Addressing these challenges, we develop a simulation-optimization-based inventory replenishment algorithm for the primary distribution node, which serves as the main source for inventory distribution to all downstream nodes. This algorithm leverages demand forecast to determine optimal replenishment strategies for both regular and emergency suppliers.

Regular suppliers replenish inventory through a low-cost but slower transportation mode, resulting in longer and variable lead times. The primary distribution node periodically reviews the stock levels and places orders with the regular supplier based on the demand forecast. However, this may result in occasional delays in delivery due to unforeseen circumstances or supply chain disruptions. In these situations, the primary distribution node relies on emergency suppliers that provide expedited shipments through a faster, albeit more expensive, transportation mode. This emergency supplier contribute toward ensuring the availability of critical consumables, even when regular supplier orders face delays. Due to the higher procurement costs and varying shipment frequencies, it is essential to establish separate review periods for regular and emergency orders.

Leveraging both regular and emergency suppliers enables the primary distribution node to maintain adequate inventory levels while minimizing procurement costs and lead times. This approach ensures continuous availability of critical consumables, promoting efficient facility operations during challenging times.

4.4.3 Distribution System Design

The proposed distribution strategy sheds away from the conventional approach in which individual units within a network are solely responsible for procuring critical resources. In the proposed novel approach, individual entities no longer need to place orders for essential resources as long as the number of active users, resource consumption, and inventory are known. This necessitates the conceptualization and implementation of a seamless, quasi-autonomous, demand-driven resource distribution system, incorporating decision-making algorithms and live connections to demand and inventory databases and stakeholders.

4.4.3.1 Targeted T-R Autonomy and Inventory Optimization

In our suggested approach, each node in the network maintains a targeted T-R autonomy, corresponding to T-time R-robust demand coverage. This implies that the strategy aims to have sufficient stock in each node to cover realized demand with at least an R% probability over the next T time periods, For example, target autonomy may be T= 3 days at R= 99%. In a higher-tier functional node, the targeted stock takes into account both the inventory within that specific node and the inventory in each subordinate functional node it serves.

The system triggers a series of delivery tickets across various nodes to periodically adjust inventory levels to reach the T-R autonomy target, given current inventory status and demand predictions. Consequently, most of the time, personnel within the network do not need to reorder resources. The system accommodates special orders in cases of significant staffing level changes or events that drastically reduce on-hand inventory. The T-R targets are regularly updated to adapt to current system state and projections.

While maintaining high inventories at each node may seem like an easy solution to ensuring high availability, it is inefficient and does not encourage careful resource usage during times of supply scarcity and supply/demand uncertainty. Instead, the system and its underlying algorithms manage supply uncertainty and scarcity at the main inventory level, maintain lean inventory at distribution nodes, ensure adequate autonomy without promoting hoarding behavior, and facilitate efficient resource delivery.

4.4.3.2 Distribution Planning, Execution, and Resource Substitution

Distribution planning algorithms optimize lean inventory autonomy levels in smaller and larger units, postponing the dedication of shared resources to maintain high responsiveness to unforeseen changes and minimize the overall network-wide inventory necessary for smooth distribution and continuous availability. Distribution execution algorithms optimize delivery timings across the network, employing smart routing and vehicle/cart loading to minimize overall delivery efforts. These algorithms generate delivery tickets for distributors to replenish units within the network.

We propose the implementation of smart dispensers and lockers as a key part of the distribution strategy. These technologies offer several benefits, including precise consumption monitoring and control, access restrictions per user, and limitations by units and time (Phade et al., 2021) (Zainudin et al, 2022). They allow for splitting stock-keeping units (SKUs) into smaller portions, streamlining distribution and improving consumption monitoring. For example, a box of 100 face masks can be split into individual masks or smaller packs, enabling better resource allocation and more accurate usage tracking, which facilitates distribution and ensures precise consumption monitoring and control. Smart lockers can be customized with security measures like biometric authentication and environmental sensors for optimal storage conditions. Smart lockers also integrate with the larger network, providing inventory level updates and usage pattern notifications.

Handling critical resources involves managing the scarcity of commodities. In addition to rationing techniques that limit the number of items accessible to each user, it is essential to have substitution protocols for scarce products. These protocols allow for the reassignment of resource usage based on product preference and availability, ensuring that the distribution network can continue functioning efficiently even in times of resource scarcity.

4.4.3.3 Physical Internet-Enabled Containers and Autonomous Vehicle Integration

In our distribution strategy, we propose using Physical Internet-enabled modular containers (Montreuil et al., 2015) to store and transport critical products. These containers protect the encapsulated products and enable smart, reliable, and efficient tracking, such as RFID on containers (Jiang et al., 2021). Real-time traceability of containers provides visibility of the location of assets at any given time. For critical products, close tracking of inventory is essential due to the higher risk of pilferage and unauthorized use. Furthermore, the proposed modular containers have composition-decomposition and interlocking properties, which protect the constituents of the container, making it difficult to access compared to a box on a pallet.

During critical and urgent situations, workforce and physical resources supply may decrease due to factors such as work absenteeism or planned capacity reductions to protect labor force and public health. To address this constraint, we propose leveraging a degree of vehicle autonomy. With a strong startup ecosystem in the robotics space (e.g., Starship robots, Nuro, and KiwiBots) and evolving legislation, these technologies present robust opportunities to automate the distribution system with minimal human intervention. This approach may reduce the margin of error, resulting in fast and accurate deliveries and 24/7 availability.

In scenarios such as pandemics, deploying autonomous shuttles can strengthen infection prevention and control by significantly reducing social contact while simultaneously saving time and effort. Combined with Physical Internet-based modular containers, seamless distribution can be achieved using π-totes that can be interconnected with or placed inside sidewalk delivery robots. Fleets of automated delivery robots and drones already provide service worldwide on a small scale, with battery capacity and flight regulations typically restricting the service radius. However, the continuous operational availability of these technologies offers advantages over human-centric operations.

4.4.4 Control Tower

We propose the implementation of advanced shared control towers as a strategic component, providing real-time visibility and fostering collaboration among all stakeholders. The control tower serves as a unified information source, facilitating trust and collaborative efforts across enterprises. Consequently, supply chain participants can achieve objectives, such as cost reduction and service improvement, beyond the capabilities of individual entities. Enhanced supply network visibility and transparency reinforce trust in the system and enable stakeholders to capitalize on numerous benefits. Furthermore, a supply chain informed by timely and accurate data optimizes overall operations and mitigates the risk of disruption.

The proposed control tower design aims to deliver comprehensive end-to-end visibility throughout the supply chain while maintaining a central dashboard displaying key metrics of the overarching system and network. The dashboard assists in identifying and addressing issues while refining decisions. The control tower affords direct insight into inbound and outbound orders at each tier node, along with delivery notifications confirming order receipt. Moreover, it offers real-time intelligence for managing inventory, including insights into imbalances, shortages, and stock-outs. Monitoring supplier lead time and on-time delivery of supplies within the control tower is also essential. Finally, the dashboard facilitates comparison between forecasts and actual consumption, aiding in the ongoing evaluation and improvement of forecasting algorithms.

5 Conclusion

This paper has introduced a definition of societally critical products and has presented a comprehensive conceptual and analytical framework, elaborating on underlying principles, components, and relationships. It has then introduced a conceptual framework for a hyperconnected and autonomous distribution system for these critical products. These frameworks form the foundation for future research, development, and implementation, enabling the exploration of potential benefits, limitations, and opportunities for improvements.

The large-scale adoption of the proposed distribution system for critical products presents several challenges, offering opportunities for future research and innovation. Key areas to explore include technological integration and interoperability, data privacy and security, and regulatory compliance. Potential research directions could involve the development of advanced simulation models to assess the feasibility and performance of transitioning from human-centric to autonomous operations, accounting for the dynamic interplay of human behavior. Additionally, executing further pilot studies to evaluate the proposed system's viability and performance, as well as investigating the system's resilience to both simulated and real-world disruptions, represent significant and relevant research avenues.

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