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Maximizing Supply Chain Resilience: Viability of a Distributed Manufacturing Network Platform Using the Open Knowledge Resilience Framework

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Abstract
This paper introduces the Open Knowledge Resilience Framework (OKRF), a set of seven cooperative data standards, and demonstrates its alignment with the Supply Chain Interoperability Specification (SCIS) Platform. Building upon the Internet of Production Alliance (IoPA) work, this article explores how integrating OKRF and SCIS can enhance production flexibility and efficiency through substitutability and resource repurposing strategies. The OKRF-SCIS integration exhibits the potential to enhance Supply Chain Resilience (SCR) by empowering organizations to adapt to fluctuating demand and availability through adaptability strategies such as supplier/product substitution and resource repurposing. While this study primarily focuses on the conceptual design of OKRF and SCIS, further empirical research is needed to validate its effectiveness. Additionally, investigating the framework's applicability across various industries and contexts would provide valuable insights. The integration of OKRF and SCIS can enable organizations to optimize supply chain operations, enhancing resilience and facilitating adaptation to changing demands through seamless substitutability and resource repurposing. This integration can also reduce transportation costs and increase responsiveness to local demand. Furthermore, it can enhance SCR and promote sustainable, resilient supply chain ecosystems by improving data transparency and resource utilization efficiency. This paper illustrates the potential of OKRF and SCIS in healthcare supply chains.

Keywords Supply chain management · Reconfigurable Manufacturing System · Supply chain resilience · Supply chain resilience framework · Interoperability

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1 Introduction

The COVID-19 pandemic has revealed the vulnerability of contemporary supply chains, prompting a reassessment of conventional supply chain analysis and operations. Supply Chain Resilience (SCR) has emerged as a critical concern for businesses and governments alike, emphasizing the need for a comprehensive and integrated approach that goes beyond disruption response. This entails implementing strategies like supplier diversification, enhancing Supply Chain Transparency and visibility, fostering effective communication and collaboration among stakeholders, and facilitating seamless data interoperability.

To address these challenges, we propose the Open Knowledge Resilience Framework (OKRF), a set of data standards operate through the Supply Chain Interoperability Specification (SCIS) platform. The OKRF builds upon the foundational work of the Internet of Production Alliance (IoPA), which facilitates data interoperability through open standards. IoPA has already established two data standards: Open Know How (OKH) and Open Know Where (OKW). Expanding on IoPA's project, we introduced five new data standards: Open Know Materials (OKM), Open Know Process (OKP), Open Know Transport (OKT), Open Know Contract (OKC), and Open Know Quality (OKQ). Collectively, these seven data standards form the OKRF.

In this project report, we employ a conceptual design approach, drawing upon existing literature and industry practices. Our paper focuses on the alignment between the OKRF and the proposed macro-framework of SCIS, which serves as a distributed manufacturing network platform connecting various facilities, suppliers, and customers. The SCIS plan, an integration of OKRF data standards and SCIS, presents a novel approach to enhancing supply chain resilience. It embraces two primary adaptive strategies: substitutability and repurposing. Substitutability involves the replacement of suppliers or products, while repurposing focuses on the reuse or reconfiguration of existing resources to effectively address market fluctuations or disruptions. Furthermore, the SCIS plan integrates social, economic, and environmental considerations into the supply chain, advocating for ethical and responsible practices. It encourages local sourcing for social sustainability and resource sharing for economic sustainability. The plan optimizes production and logistics to minimize environmental impact and conducts sustainability assessments through trusted third-party organizations, ensuring transparency and credibility. By embracing circular economy principles, the SCIS plan promotes sustainable practices that minimize waste and maximize resource efficiency. Additionally, it offers swift adaptation and essential equipment production during crises by providing free access to open-source models.

SCIS serves as a platform connecting manufacturers, suppliers, and logistics providers to streamline production and distribution. It enables flexible and efficient production by manufacturing products closer to the point of consumption and sharing resources among multiple facilities. These capabilities result in reduced transportation costs, increased responsiveness to local demand, and enhanced supply chain resilience. To illustrate the practical application of the

SCIS plan, we provide an example in healthcare supply chains to effectively respond to disruptions and shortages caused by pandemics or natural disasters.

The paper is structured as follows: Section 2 delves into the theoretical background. Section 3 presents the development methodology and offers an overview of the OKRF data standards and their compliance with the SCIS platform. In Section 4, a practical example of the SCIS plan in the healthcare domain is presented, highlighting its notable benefits. Section 5 serves as the discussion segment, delving into the concept of antifragility within the SCIS plan, elucidating its significance, and also addressing the utility of the OKRF and SCIS platform in both academic and industrial contexts. Finally, Section 6 concludes by summarizing key findings and outlining future research directions.

2 Theoretical Background

In Section 2, we provide the theoretical background for our study. Section 2.1 examines the dimensions of supply chain resilience, including relevant concepts and frameworks. Section 2.2 emphasizes the importance of data interoperability in the SCIS plan, emphasizing its role in achieving visibility and transparency. Lastly, in Section 2.3, we build upon the theoretical insights from previous subsections to present the OKRF-SCIS approach.

2.1 Dimensions of Supply Chain Resilience: Concepts, Frameworks, and the Case of Healthcare Supply Chains

Different studies have defined supply chain resilience (SCR) from different perspectives. Ribeiro and Barbosa [45], in a systematic literature review aiming to identify definitions of supply chain resilience, found no consensus in the literature. The definition of supply chain resilience often centers around its ability to swiftly and effectively bounce back from unexpected disruptions, either by returning to its original state or by transitioning to a more favorable state, thereby gaining a competitive edge. As a result, the level of SCR signifies the capability for both resistance and recovery, which, in turn, shortens the time lag between a disruption and the subsequent recovery [4].

Widely recognized in supply chain management (SCM) is the concept of resilience as a multifaceted capacity, encompassing various elements of risk management and response. As stated by Madni and Jackson [35] and Romero and Stahre [46], resilience involves four phases: anticipation (avoiding), absorption (withstanding), reconfiguration (adapting to), and restoration (recovering from) disruptions, both expected and unexpected. These phases, collectively, constitute the core capabilities of supply chain resilience (SCR). They mirror the diverse stages that a supply chain goes through in response to disruptions, spanning from proactive risk management to the post-disruption recovery and restoration phase [3, 47].

Supply chain resilience (SCR) is a multifaceted concept, reflecting the intricate journey of a supply chain in addressing disruptions. It involves proactive measures, such as preparation (or anticipation), which enable the supply chain to foresee and mitigate potential issues. Moreover, within SCR, there lie responsive capacities like recovery and robustness, enabling the supply chain to efficiently react and restore stability in the presence of disruptions. Adaptability, a central component of SCR, underlines the supply chain's ability to learn, grow, and evolve by analyzing disruption causes and impacts and by innovatively preparing for and responding to future challenges. This holistic approach to resilience ultimately positions the supply chain to achieve a new equilibrium or even a more advantageous state, thereby enhancing its competitive edge.

In response to these evolving priorities, we introduce the Open Knowledge Resilience Framework (OKRF), which consists of a set of data standards operating through the Supply Chain Interoperability Specification (SCIS) Platform. The OKRF aims to establish a Reconfigurable Manufacturing System (RMS), known for its adaptability and flexibility in accommodating changes in product design, production volume, and market demand [29, 44].

Aligned with these new priorities, the SCIS plan harmonizes with established theoretical frameworks such as Reconfigurable Supply Chains (RSCs), Viable Supply Chains (VSCs), and AURA (Active Usage of Resilience Assets). As elaborated in Section 2.3, these frameworks provide valuable insights and strategies for effectively managing disruptions and improving supply chain resilience. This is illustrated in Table 1 (created by the authors).

2.2 Data Interoperability in the SCIS plan

Recent research has highlighted the importance of end-to-end visibility and transparency in achieving supply chain resilience. These aspects enable organizations to comprehend the flow of goods, services, and information throughout the supply chain, facilitating the identification of risks and vulnerabilities and the development of mitigation strategies [13, 14, 23–25, 51]. Nevertheless, the attainment of visibility and transparency hinges on interoperability, a concept denoting the capacity of diverse systems and entities to consistently and accurately exchange and employ data. Absent interoperability, data remains confined within separate systems, impeding the sharing of information [50] and cooperation among organizations.

The IEEE defines interoperability as the "ability of a system or a product to work with other systems or products without special effort on the part of the customer" [20]. In the realm of Logistics and Supply Chain Management (LSCM), supply chain interoperability pertains to the ability of autonomous systems to engage and cooperate efficiently without requiring substantial alterations to their individual configurations or behaviors (Barthe-Delanoë et al. 2014). Interoperability should be considered at physical, organizational, business, and digital levels [42].

Modern LSCM places a strong focus on digital compatibility in response to the continuous digitalization and data-centric evolution in logistics operations and solutions. With multiple companies and stakeholders involved in LSCM across various industries, effective communication and efficiency are crucial. To

Table 1 Frameworks for supply chain performance and resilience

Framework	Authors	Strategies
RSC (Reconfigurable Supply Chain)	Dolgui et al. [12]	The Reconfigurable Supply Chain framework emphasizes the ability of a supply chain to quickly and effectively adapt to changing market conditions, customer demands, and internal capabilities. It focuses on creating a supply chain that is agile and responsive, capable of reconfiguring its structure, processes, and resources to meet evolving requirements. It highlights the importance of modularity, flexibility, and information sharing
VSC (Viable Supply Chain)	Ivanov [26]	The framework of Viable Supply Chain strives to establish a supply chain that is sustainable, resilient, and adaptable. It underscores the necessity of a supply chain that is flexible and dynamic, capable of responding efficiently to alterations and disruptions within the business environment. To enhance the overall viability of the supply chain, collaboration, visibility, and risk management are viewed as crucial components
LCNSC (Low-Certainty-Need Supply Chain)	Ivanov and Dolgui [22]	The Low-Certainty-Need Supply Chain framework addresses scenarios where there is low uncertainty and high demand predictability. It focuses on optimizing the supply chain for efficiency, cost-effectiveness, and reliability. Lean principles, demand forecasting, and efficient inventory management are emphasized to streamline operations and minimize waste
AURA (Active Usage of Resilience Assets)	Ivanov [24]	AURA is a supply chain framework that aims to build resilience through the active utilization of various assets. It emphasizes the identification and management of critical resources, capabilities, and relationships to help the supply chain withstand disruptions and recover quickly. Proactive risk assessment, contingency planning, and robust strategies are promoted to enhance supply chain resilience. It involves actively monitoring, maintaining, and leveraging resilience assets

remain competitive, companies are increasingly adopting digital interoperability to streamline operations and improve efficiency [41].

Data interoperability, a subset of digital interoperability, plays a vital role in enhancing supply chain resilience. Interoperability of information empowers efficient sharing and use of data within the supply chain network, fostering cooperation and the exchange of insights. Placing data interoperability at the forefront allows organizations to enhance their supply chain robustness and readiness for upcoming disturbances.

Effective collaboration and information exchange across divergent systems facilitate comprehensive insight and openness across the entire supply chain. As highlighted by Margi Van Gogh, Director of Supply Chain and Transportation at the World Economic Forum, connected, adaptable, and robust supply systems rely on visibility, traceability, and harmonious interaction [19].

In this document, supply chain data harmonization is described as the aptitude of diverse collaborators, systems, and procedures to seamlessly communicate, share data, and cooperate. Achieving data interoperability requires common standards, protocols, and data formats, as well as appropriate governance mechanisms to ensure secure and reliable data exchange. Common standards, protocols, and data formats ensure consistent data exchange, while governance mechanisms safeguard data security and privacy.

The success of the SCIS ecosystem depends on effective collaboration and communication through data and information exchange. The OKRF serves as a common language and framework for data exchange, enabling efficient coordination among manufacturing nodes in the distributed manufacturing network.

By facilitating the sharing and analysis of data, including designs and capabilities, across the distributed manufacturing network, the OKRF enables seamless information exchange among participants such as suppliers, manufacturers, and distributors. This interoperability enhances the flow of information, improving communication, collaboration, and decision-making. As a result, the OKRF enhances supply chain resilience by enabling quick responses to disruptions and maintaining operational continuity.

Data exchange interoperability encompasses two main types: syntactic and semantic. Syntactic interoperability focuses on technical aspects, ensuring that different systems can exchange data using the same format and communication protocols. Semantic interoperability, on the other hand, enables systems to understand the meaning behind the exchanged data, enabling effective communication and decision-making.

The OKRF's collection of data standards facilitates both structural and meaning-based compatibility, fostering effective interaction and partnership among participants in the supply chain. It provides a common language and framework for data exchange, including standardized formats, protocols, and structures. The OKRF also establishes a shared understanding of data through standardized terms, definitions, and ontologies. This seamless sharing of information improves supply chain efficiency and resilience, as data can be easily understood and utilized across different systems and organizations.

2.3 Enhancing Supply Chain Resilience and Adaptability: The OKRF-SCIS Approach

The OKRF, as a comprehensive set of data standards, plays a crucial role in addressing the different stages of a supply chain's response to disruptions, encompassing proactive risk management, post-disruption recovery, and the restoration phase (see Section 2.1).

During proactive risk management, the OKRF enables companies to anticipate and mitigate disruptions by providing standardized data templates for risk assessment and planning. By having access to consistent and reliable information about materials, processes, contracts, and transport capabilities through the data templates, companies can make informed decisions and execute proactive approaches to mitigate the consequences of potential disruptions.

In the post-disruption recovery phase, the OKRF facilitates rapid supply chain recovery through standardized templates. Companies can quickly identify alternative suppliers, match designs with available manufacturing facilities, and ensure seamless production continuity. The OKRF's data standards promote efficient communication and collaboration among stakeholders, enabling swift response and supply chain reconfiguration.

During the restoration phase, the OKRF aids in reestablishing supply chain stability and resilience. Comprehensive data templates provide accurate information on materials, processes, contract obligations, and transportation capabilities. This empowers informed decision-making, optimal resource allocation, and effective coordination to restore or enhance the supply chain's resilience.

By providing data standards, the OKRF enables seamless information exchange and interoperability, empowering companies to adapt and make informed decisions during disruptions. It enhances the supply chain's ability to anticipate, respond to, and recover from disruptions efficiently. Additionally, the OKRF supports strategic planning and response, enabling companies to quickly recover and improve their robustness. Its data standards facilitate analysis of disruption causes and impacts, leading to proactive measures and increased adaptability. As a result, the supply chain has the potential to bounce back to a superior condition compared to its state before the disturbance, ultimately resulting in a more robust network overall.

The integration of the OKRF and SCIS, known as the "SCIS plan," shares similarities with various frameworks (see Table 1 in Section 2.1). This integration strengthens the foundation of the SCIS plan and incorporates valuable insights and strategies from these frameworks. For example, the Reconfigurable Supply Chain (RSC) framework shares a common goal with the SCIS plan, emphasizing adaptability and reconfiguration to effectively respond to market changes. Both frameworks acknowledge the importance of agility and flexibility in adjusting the supply chain's structure, processes, and resources.

Similarly, the Viable Supply Chain (VSC) framework aligns with the SCIS plan by emphasizing the development of a sustainable and resilient supply chain through collaboration, visibility, and risk management. While the SCIS plan may not have a direct connection to the Low-Certainty-Need Supply Chain (LCNSC) framework, primarily tailored for situations with low uncertainty and high demand predictability, it offers valuable perspectives on handling disruptions and bolstering resilience in various other settings.

The SCIS strategy strongly correlates with the AURA (Active Usage of Resilience Assets) framework, as both share a common goal of fortifying supply chain resilience by actively harnessing essential resources, competencies, and partnerships.

3 The Open Knowledge Resilience Framework (OKRF)

Section 3 focuses on the Open Knowledge Resilience Framework (OKRF) and its various components. It serves to provide a clear understanding of the purpose and structure of the OKRF. The section is divided into the following subsections. In Section 3.1, the methodology for the development of the OKRF-SCIS is explained, highlighting the approach taken to create the framework. Section 3.2 introduces the governing principles of the OKRF, which establish the foundation for its operation. Section 3.3 is about the compliance of the OKRF with the SCIS platform is explained. This subsection highlights how the OKRF aligns with the platform, ensuring seamless integration and compatibility. Section 3.4 offers a design overview of the OKRF, presenting its collection of seven templates. Finally, Section 3.5 delves into the resilience enablers of the OKRF, explaining how these templates contribute to the framework's ability to enhance supply chain resilience.

3.1 Development Methodology

The OKRF is a comprehensive set of data standards that provides a common language and framework for data exchange, enabling supply chain partners to quickly and effectively respond to disruptions, restore operations, and ensure the continuity of supply chain operations. The development of OKRF in conjunction with SCIS follows a model-driven approach that can be divided into three main phases:

1. Problem definition and requirements gathering: In this initial phase, we defined the problem and identified the necessary requirements for the solution. Our team's personal experience in the midst of the health supplies shortages created by the COVID-19 pandemic informed this crucial step.
2. Development: The development of the OKRF and SCIS plan follows a model-driven approach with a focus on creating a comprehensive and flexible framework that could be easily adapted to different supply chain contexts. This phase involves extensive testing and prototyping to ensure that the proposed solution is both effective and feasible.
3. Validation: The final phase of our project is validation, which will involve pilot implementations of OKRF in real-world settings. This step is critical for validating our research results and ensuring that our proposed solution is practical and effective in real-world scenarios. The results of these pilot implementations will be used to further refine and improve the OKRF framework.

3.2 Governing Principles for Templates

The OKRF is built on a set of governing principles that ensure the consistency and quality of the data standards it encompasses. These principles serve as the foundation for all data standards that make up the OKRF and include Modularity, Statelessness, Composability, Templatability, Machine Readability, Openness, and Iterative Development.

1. **Modularity:** Modularity is a fundamental aspect of successful software design, as it greatly influences changeability and evolvability. Its value lies in the ability to accommodate potential changes in a system [10, 52]. In design, modularity encompasses breaking down a system into smaller, self-sufficient components that can be constructed and applied across diverse systems. These units can be easily substituted with similar components or products from alternate sources, minimizing the impact on existing units [31]. In the context of the OKRF, modularity ensures that its data standards can be divided into smaller, independent components. This design approach enables greater flexibility and ease of maintenance, as each component can be reused or updated individually without affecting the rest of the system. By leveraging modularity, the OKRF enhances adaptability and facilitates seamless integration within the supply chain ecosystem.
2. **Statelessness**: Stateless guarantees uniformity in the state of all service instances. In a stateless structural framework, the service operations refrain from retaining any session or state-related data [34]. In the context of the OKRF, it ensures that each interaction with the data standards is treated as a standalone transaction, without relying on the previous state or information. This allows for greater flexibility and scalability, as the data standards can be easily used in a variety of different applications.
3. **Composability:** Composability reflects the extent to which an object can be formed by amalgamating various components, elements, or constituents [6]. In the context of the OKRF, it refers to the ability of the OKRF's data standards to be combined or integrated with other standards to create more complex systems. Composability ensures that existing components can be reused and repurposed in new and innovative ways, leading to the creation of more versatile and efficient systems.
4. **Templatability**: The Templatability approach refers to the ability to define common elements or components once in a parent template and reuse them in multiple child templates. In the context of the OKRF, it allows for the inheritance of parent properties in manifests and the definition of templates using YAML resources while still allowing for fine-grained distinctions between child types. This means that common elements can be defined once in a parent template and reused in multiple child templates.
5. **Machine Readability:** Machine Readability relates to the ability of computer systems or software to comprehend and manipulate data or information presented in a format that machines can readily interpret. In the context of the OKRF, this entails ensuring that all properties of the data standards are designed to be machine-readable. By adopting this approach, it becomes possible to develop

advanced functionalities and platforms that build upon these standardized elements, facilitating seamless integration and interoperability.

6. **Openness**: Engaging in open scientific methodologies presents several benefits, such as easing the replication and expansion of studies, increasing the accessibility of data for theory development and meta-analysis, and cultivating avenues for peer assessment and cooperation [39]. Within the scope of the OKRF, these practices necessitate that the data standards be publicly accessible with an appropriate license and conform to the principles of open standards. The core values of open standards involve partnership, clarity, established procedures, equal accessibility, market support, and rights, all contributing to an all-encompassing and impartial approach to data exchange.
7. **Iterative Development**: The OKRF framework is designed to be a dynamic and evolving entity, constantly improving over time to meet the needs of the industry. The Iterative Development approach is characterized by the ongoing iteration of design, testing, and implementation, with the goal of continuously delivering increased value to its users and stakeholders.

Together, these governing principles of the OKRF have a pivotal function in upholding the uniformity and quality of the data standards within the framework and provide a flexible and scalable foundation for the development of new and innovative applications.

3.3 Integrating OKRF and SCIS

In regards to the integration between OKRF and SCIS, there are seven main elements to consider: data interoperability, integration plan, accessibility, scalability, customization, robustness, reliability, and functionality overlap. Next, we will delve deeper into each of these components.

1. **Data interoperability:** Modularity, Composability, Machine Readability and Openness are the principles of the OKRF that allow for data interoperability.
2. **Integration plan:** The principles of Modularity, Composability, and Machine Readability in the OKRF allow for an integration plan with the SCIS platform.
3. **Accessibility:** The principle of Openness in the OKRF allows for Accessibility.
4. **Scalability:** The principle of Statelessness and Modularity in the OKRF allows for Scalability.
5. **Customization:** Modularity, Templatability, and Composability are the principles of the OKRF that allow for customization.
6. **Robustness and reliability:** Modularity and Templatability are the principles of the OKRF that allow for robustness and reliability.
7. **Functionality overlap:** Templatability is the principle of the OKRF that ensures that the functions provided by OKRF and SCIS do not overlap or conflict with each other.

3.4 Design Overview and Proposed Templates

The Internet of Production Alliance ("IoP Alliance") initiated the development of data standards by the working groups of the IoP Alliance. The implementation of open data standards has a significant positive impact on manufacturers, suppliers, logistics companies, and other stakeholders in the production industry, as it allows for more accurate and consistent data exchange. By promoting open data standards, the IoPA envisions a decentralized and collaborative future of production where knowledge is shared and accessible to all. This type of collaborative environment enables organizations to work together more effectively, resulting in more efficient and sustainable production processes.

Here are the data standards as currently published [21]:

- Open Know How (OKH), published in 2019, represents an open data framework for disseminating online hardware designs and documentation, explaining the process of creating something.
- Open Know Where (OKW), published in 2020, outlines a mapping guideline aimed at recording and disseminating data concerning the global positioning of manufacturing facilities and capabilities.

We have forked IoP Alliance's project to extend it, resulting in the creation of five new data standards, hereafter referred to as "templates": Open Know Materials (OKM), Open Know Process (OKP), Open Know Transport (OKT), and Open Know Contract (OKC).

The collection of seven templates that make up the OKRF is presented in Fig. 1 (created by the authors):

The OKRF is a comprehensive set of data standards that provides a common language and framework for data exchange, facilitating the rapid and efficient response

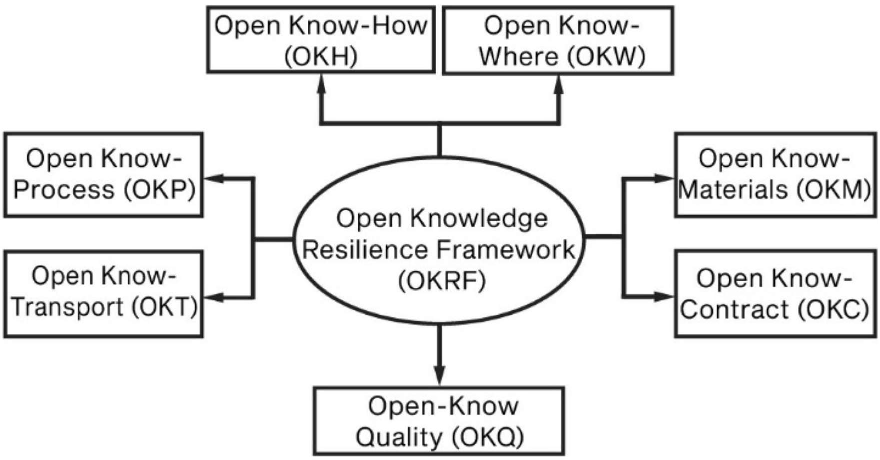

Fig. 1 Open Knowledge Resilience Framework (OKRF)

to disturbances, recovery of operations, and the uninterrupted flow of supply chain activities among partners.

Next, we will briefly outline each of the seven templates that make up the OKRF. The OHK template has been selected for a longer, more detailed explanation, as it will be used for demonstration purposes.

3.4.1 Open Know How (OKH)

The OKH data standard ensures the consistency and quality of products in the supply chain. It provides clear and detailed instructions, in the form of OKH schemas, for the manufacture of items. These schemas act as “recipes” and allow for easy replication of products, reducing the chance of human error and promoting efficiency and accuracy.

With the use of OKH data standards, anyone with the necessary tools and materials can produce the object, contributing to the overall success of the supply chain. The OKH schemas belong to a catalog within a design library. Table 1 illustrates the data entry process. This process involves entering information about design assets into the database to create a centralized repository, commonly referred to as a catalog.

A catalog is a centralized repository that provides data management, search, and metadata capabilities. The purpose is to provide information about the data, making it easier to find, understand, and utilize it effectively. The metadata (data about data) within the catalog helps to improve data governance and management. It provides information about the data stored in the repository, including characteristics, content, and structure, allowing for improved version control, license management and data analytics capabilities.

When a buyer selects an item from the catalog, the related OKH schema is automatically sent to all appropriate members of the distributed manufacturing network. This process ensures that all necessary information is shared, streamlining production and reducing the chance of human error.

The OKH data standard is a critical element of the OKRF architecture, ensuring consistency and quality of products in the supply chain while supporting the substitution adaptation strategy (see Section 3.5.4.1). This design approach enables the replacement of components identified as suitable substitutes in the OKH template, ensuring that the system can maintain production even in the face of unexpected disruptions.

The use of the OKH schema in conjunction with the SCIS platform establishes a distributed manufacturing network capable of quickly responding to changes in demand. The centralized repository of design assets provided by the SCIS platform allows for agile deployment, making it especially useful for small and medium-sized businesses lacking the resources to respond to disruptions effectively. With the SCIS platform, these businesses can connect to more extensive supply networks and quickly adapt to shifts in demand or supply. The recipients of the OKH schema may be makers or craftspeople who utilize the schemas to manufacture products and support the supply chain.

In practice, the OKH template relies on links to external documents. Figures 2 and 3 (both created by the authors) present a breakdown of an Open Know How

Metadata about the *manifest* document itself (when it was created, who it was written by and the language it is in, including translation information if needed).	date-created: 2000-01-01 date-updated: 2000-01-01 manifest-author: name: "" affiliation: "" email: "" manifest-language: "" documentation-language: "" manifest-is-translation: title: "" manifest: URL web: URL lang: "" documentation-is-translation: title: "" manifest: URL web: URL lang: ""
Top-level information about the design repository including keywords, contributors, contact information and whether the design has been *actually made* and/or *replicated.*	title: “” description: "" intended-use: "" keywords: [""] project-link: URL health-safety-notice: "" contact: name: "" affiliation: "" email: "" social: - platform: "" user-handle: "" contributors: - name: "" affiliation: "" email: "" image: URL version: "" development-stage: ""
	made: false made-independently: false
Conformance to standards, including industry, international safety standards (ISO, ASTM, IEC), or other jurisdictional regulatory requirements.	standards-used: - standard-title: "" publisher: "" reference: "" certification: - certifier: "" date-awarded: 2000-01-01 link: URL
Ancestry or modification history of the design repository.	derivative-of: title: "" manifest: URL web: URL variant-of: title: "" manifest: URL web: URL sub: title: "" manifest: URL web: URL

Fig. 2 A breakdown of an Open Know How file: Part 1

License information describes the ways the design can be used: share-alike, non-commercial, commercial are common properties of licenses.	license:
	  hardware: ""
	  documentation: ""
	  software: ""
	
	licensor:
	  name: ""
	  affiliation: ""
	  email: ""

Links and location to download design repository via the internet.
 	
Schematics are engineering drawings.
	documentation-home: URL
	archive-download: URL
	design-files:
	  - path: URL
	    title: ""
	
	software:
	  - path: URL

Bill of materials is effectively the ingredients and tools list.
 	
Making instructions is a recipe for production. Tool settings would be options on tools (oven temperature, drill speed, etc).
 	
Manufacturing files include gcode, CAM, 3D printer .stp files, etc
 	
Risk assessment is most likely an FMEA (failure modes and effects analysis) of the product.
 	
Maintenance instructions describe how to take care of the product to ensure the desired lifespan. It must also, to be effective, describe common repair operations.
 	
Disposal instructions describe afterlife, reusability of components, recyclability of components, or how to properly store systems at end-of-life.
	title: ""
	
	schematics:
	  - path: URL
	    title: ""
	
	bom: URL
	tool-list: URL
	
	making-instructions:
	  - path: URL
	    title: ""
	
	tool-settings:
	  - path: URL
	    title: ""
	
	manufacturing-files:
	  - path: URL
	    title: ""
	
	risk-assessment:
	  - path: URL
	    title: ""
	
	quality-instructions:
	  - path: URL
	    title: ""
	
	operating-instructions:
	  - path: URL
	    title: ""
	
	maintenance-instructions:
	  - path: URL
	    title: ""
	
	disposal-instructions:
	  - path: URL
	    title: ""

Fig. 3 A breakdown of an Open Know How file: Part 2

file. In future work, we will introduce the Open Know Interface (OKI) concept, which will define how an OKH can communicate with other OKH-defined parts or machines, enabling greater composability.

The provided breakdown is a representation of the metadata and information included in an Open Know How (OKH) file, which is a component of the OKH data standard. Here is a brief explanation of the different sections:

- **Metadata about the manifest document itself**: This section includes information about the creation date, update date, authorship, and language of the manifest document. It also allows for translation information if needed.
- **Top-level information about the design repository**: This section provides details about the design, including its title, description, intended use, keywords, project link, health and safety notice, and contact information. It also specifies whether the design has been made or replicated.
- **Standards and certifications**: This section describes whether the design conforms to any industry or regulatory standards. It includes information about the specific standards used, the publisher, and references to certification, if applicable.
- **Derivative and variant designs**: This section indicates if the repository is based on or modified from a prior design. It includes references to the original design, whether it is a derivative or a variant.
- **License information**: This section describes the licensing terms of the design, including how it can be used (share-alike, non-commercial, commercial). It specifies the licensing details for hardware, documentation, and software.
- **Links and location to download design repository**: This section provides the necessary links and locations to access the design repository and its associated files, including schematics, bill of materials (BOM), making instructions, manufacturing files, risk assessment, maintenance instructions, disposal instructions, and more.

  The provided URLs represent the paths to access these files or documents related to the design. For example, the schematics section provides URLs to access the engineering drawings, while the manufacturing files section offers links to download files such as gcode, CAM, or 3D printer .stp files. The remaining sections provide links to various instructions and documents associated with the design.

3.4.2 Open Know Where (OKW)

The Open Know Where (OKW) is the second template developed by the IoPA and was designed to complement the Open Know How (OKH). The OKW initiative promotes accessibility of information about the location of manufacturing facilities and capabilities worldwide, making it easier to match and route OKH designs to the best-suited manufacturer. The OKW helps to ensure that the right design is sent to the right facility for production.

The information gathered in the OKW template encompasses the manufacturing, warehousing, and transportation capabilities of individual facilities; it can include details such as tool inventory, material stockpiles, and ISO certifications.

The specification is intended for adoption by entities that collect or share data about manufacturing, such as platforms, governments, NGOs, aid agencies, mapping communities, makers, and online hobby groups.

The OKW data standard is a critical component of the OKRF architecture, supporting the repurposing adaptation strategy (see Section 3.5.4.2). By offering information regarding the location of manufacturing facilities and competencies worldwide, this design approach enables manufacturers to quickly and efficiently repurpose manufacturing resources to meet changing demands.

3.4.3 Open Know Process (OKP)

The OKP template outlines the necessary tests and procedures for manufacturing a product according to a specific template, as outlined in an Open Know How (OKH) manifest. It establishes the processes used to test, validate, and verify that the end product meets all necessary standards to ensure high quality. By defining these processes, the OKP ensures that the entire manufacturing process is thorough and compliant with the required standards.

3.4.4 Open Know Material (OKM)

The Open Know Material (OKM) template plays a crucial role in the manufacturing process by providing essential information about the materials used in production. By defining the requirements, properties, and composition of materials, the OKM helps bridge the gap between the Open Know How (OKH) and Open Know Where (OKW) templates. With access to this information, manufacturers can quickly determine the suitability of materials for their needs, helping to improve the efficiency and reliability of the manufacturing process. In addition, by ensuring proper material selection and quality judgment, the OKM helps to ensure a higher-quality end product. The comprehensive information provided by the OKM is indispensable for the achievement of manufacturing success within a supply chain ecosystem.

In a manufacturing process, several materials with similar quality can often be used. Rather than directly including each material's properties in the OKH document, it is more efficient to include references to a series of well-defined materials in the OKM document. This approach allows for better management of the materials used, ensuring that only the materials with the necessary properties and quality are used in the manufacturing process. By having a clear and concise OKM, manufacturers can make informed decisions about material selection and improve the overall efficiency and quality of the manufacturing process.

The OKM supports sustainable practices such as reverse logistics, promoting a low-waste circular economy by facilitating reuse, recycling, and decommissioning. This promotes environmental sustainability. The OKM is likely to be referenced in future OKHs and may replace the Material class in OKWs, making it an increasingly important document in the OKRF.

3.4.5 Open Know Transport (OKT)

The Open Know Transport (OKT) template gathers information about carrier entities' logistics, equipment, and capability, creating a comprehensive profile. This information helps determine a carrier's suitability for a given task, streamlining the transportation process and, ultimately, strengthening the supply chain network. OKT is flexible and can accommodate carriers of various sizes and forms, from established shipping companies to volunteer groups. With the OKT template, we can ensure that the transportation leg of the supply chain network is as robust as possible, ready to step up, and aid in times of crisis.

The Open Know Where (OKW) and Open Know Transport (OKT) templates complement each other, both playing critical roles in reinforcing the supply chain network. The OKW helps manufacturers of all sizes to step up and produce needed goods in the event of a supply chain network failure, ensuring that essential goods and materials reach their intended recipients. On the other hand, the OKT template plays a crucial role in supporting the delivery leg of the supply chain network. It allows companies, small businesses, other groups, and even individuals to aid in the delivery of needed goods when negative factors, such as transportation issues or unforeseen events, may delay their arrival.

The OKT template can help prevent failures in the supply chain network by connecting carriers with those in need of aid who lack proper transportation. One instance where OKT can be incredibly useful is in the delivery of personal protective equipment (PPE) from a manufacturer to a hospital in need. The manufacturer can search for a carrier profile with the necessary capacity and willingness to deliver the PPE, ensuring timely arrival and proper safety measures. Additionally, OKT can serve as a reference in an OKC agreement, specifying the transportation action required to fulfill a part of the agreement.

3.4.6 Open Know Contract (OKC)

The OKC template streamlines the contract process within the OKRF, representing agreements between parties. The OKC outlines the obligations for the production of specific outputs or outcomes, such as an object specified in an Open Know How (OKH), at a facility represented by an Open Know Where (OKW), and delivery to the final destination via a carrier represented by an Open Know Transport (OKT).

The OKC enables the use of various forms of contracts within the OKRF, including verbal agreements, physically signed documents, email exchanges, or blockchain records verified by a third party and digital signatures. This flexibility makes it possible for parties to choose the most suitable method for their agreement.

3.4.7 Open Knowledge Quality Test (OKQ)

An Open Knowledge Quality Test (OKQ) gathers standardized methods for evaluating the quality of other templates within the Open Knowledge Resilience Framework (OKRF). The OKQ assesses the quality of the templates within the OKRF, evaluating the accuracy, completeness, and relevancy of information contained in each template, as well as verifying that all parties involved in the supply chain network are following established standards and procedures.

The OKQ is designed to make the testing regime and quality assurance of produced items easily discoverable and verifiable. This information is essential for consumers and stakeholders to trust the authenticity and quality of the products and services, promoting a culture of transparency and trust.

3.5 OKRF Resilience Enablers

The OKRF is a comprehensive supply chain resilience framework designed to create a Reconfigurable Manufacturing System (RMS). The OKRF offers key enablers of Supply Chain Resilience (SCR) that work in unison to create a flexible and adaptive manufacturing network that can withstand and recover from disruptions while still achieving business objectives and delivering high-quality products to customers. The five key enablers of SCR are as follows: (1) agility, (2) transparency, (3) collaboration, (4) adaptability, (6) flexibility and (5) sustainability. These enablers provide a holistic approach to enhancing SCR and ensure a more robust and sustainable manufacturing network.

3.5.1 Agility

In stable supply chain networks with steady demand, the overriding parameter to optimize is cost. Companies must carefully balance the cost of their supply chain operations while meeting customer demands and maintaining profitability. However, in an acute emergency, the situation changes drastically. The overriding parameters to optimize become the speed of delivery and rapid response to urgent production demands. In these situations, companies must respond rapidly and effectively to changing circumstances to minimize disruptions and maintain business continuity.

Supply Chain Agility (SCA) represents an organizational strategic capability geared towards swiftly perceiving and addressing both internal and external uncertainties through the effective harmonization of supply chain partnerships [16]. This concept underscores the paramount significance of robust relationship integration within supply chain ecosystems. Such integration serves as a critical bulwark against disruptions and ensures the punctual and efficient delivery of products to customers.

Agility strategies can generally be categorized as proactive, reactive, or a combination of both. Proactive enablers serve as preemptive measures and risk mitigators, enabling the anticipation of potential opportunities or threats. On the other hand, reactive enablers function as defensive mechanisms, allowing the supply chain to respond to events once they have already transpired [2].

In the OKRF and SCIS platform, SCA is approached using a mixed methods approach of proactive and reactive responsiveness to balance preparedness and flexibility. Proactive strategies involve anticipating and preparing for changes, such as adjusting production schedules or shifting sourcing strategies. On the other hand, reactive strategies include responding quickly and effectively to unexpected changes, such as rerouting shipments to avoid disruptions. The OKRF combines proactive and reactive strategies to optimize the supply chain and make it more capable of responding to changing market conditions and disruptions.

This SCA approach applied to the SCIS plan reflects the importance of strong relationship integration between the manufacturing nodes in the supply chain to respond rapidly to uncertainties in a changing environment. The result is a supply chain that is better equipped to remain flexible and competitive in a constantly changing environment, meeting customer demands and overcoming challenges in the marketplace.

3.5.2 Transparency

Supply Chain Transparency (SCT) is crucial to building resilience and trust in business relationships. It involves being aware of and sharing information about every step of the supply chain, both within the organization and with external parties. Moreover, SCT mandates that all participants possess information that balances negotiation power among participants, resulting in an increased awareness of product provenance [5, 32]. As SCT improves, companies can strengthen partnerships, enhance their reputation, and increase consumer trust. Research has shown that consumers are willing to pay a premium, ranging from 2 to 10%, for products with greater supply chain transparency [30].

SCT can be achieved through a combination of practices, including the following [38]:

- Visibility pertains to an organization's capacity to collect and arrange data concerning its supply chain operations, primarily for internal purposes.
- Traceability encompasses the diverse procedures and systems needed to improve information synchronization.
- Disclosure is the act of divulging organizational data to both internal and external stakeholders.
- Openness represents a broader organizational orientation towards promoting transparency and proactive disclosure.

The OKRF and SCIS platform enable full visibility and traceability. This means that everyone using the SCIS platform will have access to complete and accurate information about every stage of supply chain operations, from raw materials to finished products. The SCIS plan recognizes that enabling full visibility is crucial for achieving discoverability, which is essential for efficient and effective supply chain network operations.

Discoverability involves the ability to identify products that can be made using Open Known How (OKHs) and manufactured within the supply network due to Open Known Where (OKWs). Full visibility is needed throughout the supply chain to achieve this, allowing businesses and manufacturers to understand the products and materials available to them, as well as the production capabilities of their partners and suppliers.

For example, each manufactured object in the OKRF must provide sufficient information about its origin, enabling the discovery of information such as assembly instructions, material components, testing protocols, repair instructions, reuse limits, and recycling techniques within products and processes. By making this information easily accessible, the OKRF enables organizations to maintain the maintainability, reusability, recyclability, and adaptivity of supplies within their supply chains. This level of transparency ensures that organizations can make informed decisions and take proactive measures to maintain the continuity and success of their operations, contributing to Supply Chain Resilience (SCR).

The OKRF and SCIS platform support full openness and disclosure by allowing organizations to share information about their supply chain operations with internal and external stakeholders, including suppliers, customers, and governments.

It should also be observed that in the OKRF, transparency is a key factor in ensuring the sustainability, efficiency, and adaptability of supply chain resources. The ability to track and understand the journey of products and materials, as well as the conditions under which they are produced, is essential for driving positive change and meeting sustainability goals.

The integration of visibility, traceability, openness, and disclosure is key to promoting accountability and building trust in the supply chain network. The OKRF is dedicated to promoting transparency and trust in the SCIS distributed manufacturing network platform. With the goal of establishing a transparent ecosystem, OKRF ensures that the reliability of manufactured items is based on their transparency and testability, rather than solely on the reputation of the manufacturer or author. This approach enhances the overall trustworthiness of the platform and its products, helping to foster a more secure and reliable environment for all participants.

3.5.3 Collaboration

In Supply Chain Management (SCM), collaboration entails a cooperative endeavor where multiple independent firms collaborate closely to strategize and execute supply chain operations for mutual advantage. This collaborative approach enables them to reap more significant benefits compared to individual, isolated efforts [49].

Summarizing the literature, Cao and Zhang [11] provide a comprehensive definition of Supply Chain Collaboration (SCC), which encompasses seven interconnected elements. These dimensions, including information exchange, objective alignment, decision synchronization, incentive harmonization, resource sharing, effective collaborative communication, and joint knowledge creation, are intricately linked. Their interrelation can potentially yield benefits such as cost reduction, accelerated response times, optimized resource utilization, and enhanced innovation.

The first three elements emphasize the importance of effective coordination and communication among supply chain partners. The subsequent four dimensions underscore the collaborative nature of SCC and its potential to yield comprehensive improvements in supply chain performance.

SCIS and OKRF work together to facilitate Supply Chain Collaboration (SCC) by supporting each of the seven interconnecting components identified in the literature [11]. The OKRF aims to foster cooperation among supply chain collaborators by facilitating the exchange of information via standardized data protocols. This supports the key component [48, 49] of Supply Chain Collaboration

(SCC), ***information sharing***. By providing a common language for data exchange, the OKRF allows supply chain partners to readily access and utilize each other's resources. This facilitates the sharing of essential information regarding designs, requirements, and capabilities. As a result, supply chain partners can collaborate as if they were part of a unified enterprise, leveraging each other's strengths to create a more robust and efficient supply chain.

The SCIS platform then helps to facilitate the use of this information by providing a centralized and easily accessible repository of information, which supports ***goal congruence*** and ***decision synchronization***. SCIS supports ***goal congruence*** by creating a shared understanding of objectives and outcomes. In addition, the SCIS platform enables ***decision synchronization*** by providing real-time access to data and information, allowing supply chain partners to collaborate and make informed decisions.

The OKRF ***aligns incentives*** by establishing a clear and transparent set of data standards for supply chain operations, so all parties have access to the same data and can work together to optimize benefits for the entire supply chain. In addition, ***resource sharing*** is facilitated by the OKRF data standards and SCIS platform, which allow for the sharing of resources and capabilities between supply chain members. This improves the ability to leverage assets and capabilities, leading to more effective use of resources.

The SCIS platform provides an environment for ***collaborative communication*** by enabling the exchange of information and messages among supply chain participants, empowering them to tap into and harness each other's resources, thereby reaping the benefits they offer. This improves the quality of communication, supporting ***joint knowledge creation***, enabling members of the supply chain to share and build upon each other's knowledge and experiences, promoting a culture of continuous learning and improvement.

In summary, the combination of SCIS and OKRF enhances the seven interconnecting components of Supply Chain Collaboration (SCC), leading to improved supply chain performance focusing on responsiveness to customer needs. Supply Chain Collaboration (SCC) benefits are crucial for building a resilient supply chain equipped to handle changes and overcome challenges, resulting in reduced costs, leveraged resources, increased flexibility, and fostering innovation.

3.5.4 Adaptability

Supply Chain Adaptability (SCA) refers to the capacity of a supply chain system to adjust and modify its structure and processes in response to external changes and disruptions. This may involve reallocating production to alternative locations, modifying sourcing techniques, or altering production schedules. SCA is a crucial aspect of supply chain resilience as it helps to minimize risks and ensure ongoing supply chain operations, even in the face of unpredictable events [24, 25].

The OKRF data standards promote SCA through the application of the principles of *modularity* and *composability*. These principles allow for the complex supply chain system to be broken down into smaller, independent components that can be rearranged and combined to form new systems. The ability to quickly rearrange and adapt the supply chain enables it to respond effectively to challenges, such as changes in consumer demand or disruptions in the supply of critical materials.

The concept of *modularity* ensures that parts can be substituted by parts made in different ways or by different parties, without significant degradation of performance or function. The concept of *composability* expands on this, allowing for parts to be reused and repurposed across multiple applications.

Next, we will delve into the practical application of supply chain adaptation strategies, focusing specifically on substitution and repurposing as applied by the OKRF to increase supply chain resilience.

3.5.4.1 Substitution Adaptation Strategy The substitution adaptation strategy is supported by the OKRF architecture primarily through the OKH template, which provides the necessary information for the manufacture of products, including detailed instructions for the manufacturing process. This information can be used to assess alternative products and processes and determine their suitability for substitution. The modular design approach enables the replacement of components identified as suitable substitutes in the OKH template, ensuring that the system can maintain production even in the face of unexpected disruptions.

The use of a systematic and data-driven approach enables a thorough evaluation of alternatives, ensuring that the best possible substitute is identified. This approach provides a more accurate and reliable way of assessing alternatives, which can improve the flexibility and resilience of the distributed manufacturing network.

In addition to the OKH template, the substitution adaptation strategy is also possible through the other six templates used in the OKRF, as follows:

1. Open Know Where (OKW) template provides information about the location of manufacturing facilities and capabilities, making it easier to match and route OKH designs to the best-suited manufacturer. This information can be used to identify alternative suppliers and determine their ability to produce the required product or process.
2. Open Know Process (OKP) template outlines the necessary tests and procedures for manufacturing a product and validating its quality. This information can be used to assess the quality of alternative products and processes and ensure that they meet the necessary standards.
3. Open Know Material (OKM) template provides essential information about the materials used in production, including their requirements, properties, and composition. This information can be used to assess alternative materials and determine their suitability for use in the manufacturing process.
4. Open Know Transport (OKT) template provides information about the logistics, equipment, and capability of carrier entities. This information can be used to determine the suitability of alternative carriers for transportation.
5. Open Know Contract (OKC) template streamlines the contract process within the OKRF, representing agreements between parties. This information can be used to negotiate contracts with alternative suppliers and carriers.

6. Open Knowledge Quality Test (OKQ) template gathers standardized methods for evaluating the quality of other templates within the OKRF. This information can be used to evaluate the quality of alternative products and processes and ensure that they meet the necessary standards.

In summary, the OKH template, along with the other six data standards used in the OKRF, enables a comprehensive and flexible approach to the substitution adaptation strategy. The OKRF templates allow for the seamless replacement of products, processes, contracts, and materials, allowing for a smooth transition without any disruptions to the overall functioning of the supply chain.

3.5.4.2 Repurposing Adaptation Strategy The repurposing adaptation strategy is supported by the OKRF architecture primarily through the OKW template, which provides information about the location of manufacturing facilities and capabilities worldwide. By utilizing this information, manufacturers can quickly and efficiently repurpose manufacturing resources to meet changing demands.

The composable design approach provides manufacturers with the ability to quickly repurpose resources and build new systems with different functionality, utilizing existing resources in new and innovative ways, reducing the need for costly new investments. This approach is particularly effective in situations where supply chain disruptions occur and manufacturers need to quickly adapt to new market conditions.

The use of a systematic and data-driven approach provides manufacturers with the ability to accurately assess potential alternatives for repurposing and determine the most efficient and effective use of existing resources. This approach involves analyzing data about the manufacturing system, including the location and capabilities of manufacturing facilities and the availability of raw materials, to utilize existing resources in new and innovative ways.

In addition to the OKW template, the repurposing adaptation strategy is also possible through the other six templates used in the OKRF, as follows:

1. Open Know How (OKH) template provides clear and detailed instructions for the manufacture of items, which can be easily adapted to new products or processes with minimal effort. This allows for the repurposing of existing manufacturing resources in response to changing market conditions or disruptions.
2. Open Know Process (OKP) template outlines the necessary tests and procedures for manufacturing a product according to a specific template and establishes the processes used to test, validate, and verify that the end product meets all necessary standards. This information can be used to quickly and efficiently adapt manufacturing processes to new products or changes in market conditions.
3. Open Know Material (OKM) template provides essential information about the materials used in production, including requirements, properties, and composition. This information can be used to quickly and efficiently repurpose existing resources in response to changes in materials or supply chain disruptions.

4. Open Know Transport (OKT) template gathers information about carrier entities' logistics, equipment, and capability, creating a comprehensive profile. This information can be used to quickly and efficiently repurpose transportation resources in response to changing market conditions or disruptions.
5. Open Know Contract (OKC) template streamlines the contract process within the OKRF, representing agreements between parties. This standard helps to ensure that contracts can be quickly and easily adapted in response to changes in market conditions or disruptions.
6. Open Knowledge Quality Test (OKQ) template gathers standardized methods for evaluating the quality of other templates within the OKRF. This helps to ensure that any repurposed resources meet the necessary standards for quality and safety.

In summary, the OKRF data standards enable the successful implementation of the repurposing adaptation strategy. They provide the necessary information to quickly and efficiently repurpose existing resources in response to changing market conditions or disruptions.

3.5.4.3 Building Supply Chain Transparency: The Role of Repurposing and Substitutability Strategies The use of repurposing and substitutability strategies, as applied by the OKRF, require a high level of Supply Chain Transparency (SCT). This transparency can be achieved through a combination of practices, including visibility, traceability, disclosure, and openness.

Visibility is essential to the success of repurposing and substitutability strategies. The OKRF provides a systematic and data-driven approach to assess potential alternatives for repurposing and substitution, utilizing detailed information about the manufacturing system to determine the most efficient and effective use of existing resources.

Traceability plays a crucial role in enhancing the OKRF's adaptability strategies related to repurposing and substitutability. It offers a transparent and comprehensive perspective on the manufacturing process and the flow of products and materials across the supply chain. This data is essential for recognizing potential avenues for repurposing and substitution, enabling manufacturers to make informed choices and swiftly respond to evolving market conditions or disruptions.

Disclosure is essential for the OKRF's adaptability strategies of repurposing and substitutability because it enables transparency and accountability in the supply chain. By sharing organizational information with internal and external stakeholders, manufacturers can build trust and improve collaboration, which is crucial for identifying potential opportunities for repurposing and substitution. This information exchange ensures that all parties have a clear understanding of the manufacturing process and supply chain activities leading to more effective decision-making. The disclosure also builds trust and fosters better communication between supply chain partners, enabling more effective collaboration during disruption.

Openness is essential for the OKRF's adaptability strategies of repurposing and substitutability because it promotes a culture of transparency and proactive disclosure throughout the supply chain. This approach promotes trust and accountability, which are essential for achieving transparency in the supply chain and implementing the adaptability strategies of repurposing and substitutability. By being open and transparent, manufacturers can work with stakeholders to identify potential opportunities for repurposing and substitution, which can help to improve the flexibility and resilience of the supply chain.

By enhancing SCT, the OKRF allows organizations to identify opportunities for repurposing and substitution and collaborate with their supply chain partners to adapt to changing market conditions and supply chain disruptions. This strategy enables organizations to sustain their operations and fulfill their obligations to customers while minimizing their environmental and social footprint. Moreover, partnering and collaborating with supply chain counterparts can foster streamlined and more impactful decision-making, ultimately leading to enhanced results for all stakeholders.

3.5.5 Flexibility

Supply Chain Flexibility (SCF), as per Fayezi et al. [16], is the operational competence enabling organizations to swiftly adapt both internally and with key partners, addressing internal and external uncertainties through seamless supply chain integration. It embodies a supply chain's ability to promptly align with market demands, ensuring smooth product and service flow [8].

In the literature, there are diverse perspectives, but it is widely accepted that Supply Chain Flexibility (SCF), as highlighted by Liu et al. [33], involves both internal and external dimensions. Internally, SCF focuses on the manufacturing adaptability of the central company, covering areas like modification flexibility (MOD), product mix flexibility (MIX), new product introduction flexibility (NEW), and production volume flexibility (VOL). Externally, SCF includes supplier flexibility (SUP), logistical flexibility (LOG), and supply network flexibility (NET).

The OKRF provides a comprehensive framework that enhances Supply Chain Flexibility (SCF) by applying substitutability and repurposing adaptive strategies. The OKRF offers internal and external dimensions of SCF, ensuring that the distributed manufacturing network can maintain production and respond effectively to any changes or disruptions.

Regarding the internal aspect of Supply Chain Flexibility (SCF), the OKRF expedites product modifications (modification flexibility), accommodates the production of diverse products within the same planning period (product mix flexibility), seamlessly integrates new products into production (new product introduction flexibility), and adjusts manufacturing volume (volume flexibility). Turning to the external dimension of SCF, the combination of OKRF and SCIS enables suppliers to swiftly adapt to changing customer demands (supplier flexibility), efficiently manages product reception and delivery as supply sources and customer requirements evolve (logistics flexibility), and simplifies the adaptation of supply chain partners in response to shifts in the business environment (supply network flexibility).

3.5.6 Sustainability

Supply Chain Sustainability (SCS) pertains to the strategy of incorporating economic, ecological, and societal considerations into the formulation and administration of supply chains. Organizations voluntarily undertake this initiative to attain sustainability and optimize the procurement, manufacturing, and distribution of their products or services efficiently [1, 37]. The SCS plan aims to meet stakeholder expectations while simultaneously improving the immediate and future profitability, competitiveness, and resilience of businesses.

In this section, we introduce the triple bottom line approach to sustainability and how it is being applied through the OKRF and SCIS platforms.

3.5.6.1 Sustainability as a Triple Bottom Line Approach Sustainability is a crucial factor in building resilience in supply chains. The term "sustainable-resilient" describes the interdependent relationship between these two concepts. Sustainable-resilient supply chains are able to withstand and recover from disturbances while also ensuring long-term viability.

Companies now prioritize the long-term well-being of their supply chains, with sustainability playing a crucial role in achieving this goal. A better grasp of supply chain sustainability results in enhanced resilience, risk reduction, efficiency, cost-effectiveness, improved reputation, and heightened customer loyalty [15, 18, 27, 28, 49].

Sustainability is no longer solely focused on environmental concerns. The sustainability debate nowadays encompasses three dimensions: environmental, social, and economic bottom lines [7]. Similarly, the term Supply Chain Sustainability (SCS) uses the term sustainability as a triple bottom line approach: "environmental sustainability," "social sustainability," and "economic sustainability." By considering these factors, organizations can improve their relationships with suppliers and customers, increase employee engagement, and build a more resilient and sustainable future.

3.5.6.2 Triple Bottom Line of Sustainability: A Look into the OKRF and SCIS Platform The OKRF and SCIS platform support sustainability in a comprehensive and integrated manner, balancing social, economic, and environmental considerations to promote long-term sustainability in the supply chain.

(a) Social Sustainability Perspective

In the social sustainability perspective, the OKRF and SCIS platform enable more ethical and responsible supply chain practices by fostering transparency and traceability of products, materials, and practices. This enables buyers to ensure that they are ethically and responsibly sourced, resulting in better working conditions and fair labor practices, promoting the well-being of workers and communities. Furthermore, by promoting local sourcing, the SCIS plan supports local economies and creates jobs, thereby contributing to the overall well-being of communities.

(b) Economic Sustainability Perspective

The OKRF and SCIS platform support economic sustainability by promoting a circular economy. Initially, the 3R principles of *reduction*, *reuse*, and *recycling* were the dominant methods to promote a circular economy. However, with the increasing awareness of sustainable innovation, the 6R approach has become relevant. The 6R approach adds the concepts of *recovery*, *redesign*, and *remanufacture* to the traditional 3R principles, providing a more comprehensive approach to a circular economy [17]. The SCIS plan's support of the 6R approach promotes sustainability by enabling organizations to implement reduction, reuse, and recycling strategies, as well as recover, redesign, and remanufacture processes. By facilitating transparency and traceability of resources, the OKRF and SCIS platform enable organizations to better understand the flow of goods, services, and information in the supply chain network. This increased visibility leads to improved decision-making and better resource management, ultimately reducing waste and increasing efficiency. Further, the OKRF and SCIS platform help organizations to identify opportunities for collaboration and resource sharing, which can lead to increased efficiency and cost savings. This supports the circular economy by reducing the need for virgin resources and promoting the reuse of existing resources. Finally, by enabling organizations to source materials and products locally, the OKRF and SCIS platform support local economies and reduce the environmental impact of transportation.

(c) Environmental Sustainability Perspective

In the environmental sustainability perspective, the OKRF and SCIS platform support sustainability by enabling a more environmentally conscious and responsible supply chain. The SCIS platform facilitates the optimization of production and logistics, reducing transportation costs and increasing responsiveness to local demand, which can result in a reduction of greenhouse gas emissions and more sustainable use of resources. The sustainability assessment of the OKRF is a critical process that helps to determine the environmental impact and sustainability of OKRF's materials, products, and operations. To ensure impartiality and accuracy, third-party organizations will be responsible for conducting sustainability assessments of products, materials, and practices in the OKRF. Having a third-party organization conduct the assessment increases transparency and credibility, as the results of the assessment are not influenced by internal biases or interests. This fosters trust among stakeholders and underscores a firm commitment to sustainability and environmental responsibility.

4 Healthcare Supply Chain: An Illustrative Example

The objective of Section 4 is to examine the application of the SCIS plan in the healthcare supply chain sector. It begins by discussing the challenges faced by healthcare supply chains during the COVID-19 pandemic and how the OKRF and SCIS platform can be leveraged to address these issues (Section 4.1). Subsequently, Section 4.2 provides a comprehensive understanding of the key concepts of the SCIS platform and visually represents the interactions among different network participants through a basic scenario. Section 4.3 further enhances understanding by presenting a real-world example of the SCIS platform in action, demonstrating the potential benefits of its implementation through a narrative scenario.

4.1 Healthcare Supply Chains and COVID-19 Challenges

Healthcare supply chains face challenges including fragmentation, lack of information exchange, and COVID-19's profound impact. The pandemic exacerbated pre-existing issues, revealing vulnerabilities in supply and demand, workforce deficits, and supply chain disruptions (SCDs). Key factors contributing to delayed responses during the crisis include bottlenecks at ports, worker shortages, export restrictions, panic-driven hoarding, cost-focused strategies, overreliance on a few manufacturers, offshore production, insufficient transparency, and lack of coordination among agencies and institutions [36]. Addressing these challenges post-COVID-19 is essential for enhancing healthcare supply chain resilience. These challenges fall into four categories: Lack of Supply Chain Resilience (SCR), Lack of Supply Chain Transparency (SCT), Just-in-Time (JIT) manufacturing, and Integration and Interoperability challenges.

With regard to the lack of SCR challenge, OKRF and SCIS can help build more resilient supply chains by enabling quick adaptation to changes in demand, availability, or other factors. The two supply chain adaptation mechanisms of substitutability and repurposing allow for quick adaptation to changes in market conditions or disruptions. This results in the continuity of operations and minimizes risk exposure in the supply chain.

In terms of the lack of SCT challenge, OKRF and SCIS can provide end-to-end visibility and transparency, allowing organizations to understand the flow of goods, services, and information across the entire supply chain. This increased visibility helps organizations to identify opportunities for reducing waste and improving the efficiency of their supply chains, leading to cost savings and increased profitability.

Regarding the JIT manufacturing challenge, OKRF and SCIS can help organizations to source materials and products locally, reducing the environmental impact of transportation. This supports the principles of the circular economy by enabling organizations to recover, redesign, and remanufacture products, materials, and services, extending the life of resources and reducing the need for new materials.

Integration and Interoperability challenges can be addressed through the OKRF, as it facilitates data interoperability, ensuring that data generated by various actors in the distributed manufacturing network can be easily shared, analyzed, and utilized by all participants.

Finally, the implementation of OKRF and SCIS can support sustainability in healthcare supply chains by promoting the principles of the circular economy and reducing the environmental impact of transportation. By enabling organizations to source materials and products locally, OKRF and SCIS support local economies and reduce the need for virgin resources, promoting the reuse of existing resources.

4.2 Key Concepts of the SCIS Platform

As explained in Sections 3 and 4 of this paper, the OKRF enables the development of a Reconfigurable Manufacturing System (RMS) through the SCIS distributed manufacturing network platform. The SCIS platform connects various manufacturing facilities, suppliers, and customers in a decentralized manner, promoting coordination in production, logistics, and distribution. The key concepts of the SCIS platform include the following:

- Buyers are individuals or organizations that require products that can be supplied through the platform.
- Sellers are individuals or organizations that offer goods or services in exchange for payment.
- Manufacturers are individuals or organizations that have the ability to manufacture products listed in the catalog using designs from the design library.
- Suppliers are producers of raw materials or components used in the manufacturing process.
- Transporter is an individual or organization responsible for moving products from one place to another.
- Warehouser is a person or organization that operates a storage facility.
- Catalog is a collection of items that can be ordered and purchased (or obtained for free) through the distributed manufacturing network.
- Design Library is a pre-existing repository of designs for products that can be manufactured.
- Platform is the main component of the distributed manufacturing network, connecting various players and facilitating coordination of production, logistics, and distribution.

Next, Fig. 4 (created by the authors) showcases the seamless interactions and processes involved in the SCIS platform, providing a comprehensive visual representation of the distributed manufacturing network.

Here, we present a comprehensive explanation of the entire process outlined in Fig. 4, starting from a buyer's selection of a product from the catalog to the final step of the delivery.

The buyer (1) first accesses the catalog (2), where they can choose from a collection of items that can be ordered and purchased through the network. The engine (3), which is the Reconfigurable Manufacturing System (RMS) enabled by the OKRF, ensures that the product design is efficiently processed and manufactured. The fulfillment service (4) and contract service (5) work together to ensure that the product is produced and delivered to the buyer in the most convenient and efficient way possible, with secure and transparent agreements facilitated by the OKC template. The state tracking system (6) monitors the fulfillment plan, keeping track of the goods and their status throughout the supply chain, improving transparency and accountability. Finally, the transporter (7) delivers the product to the final destination, the patient (8) in this scenario.

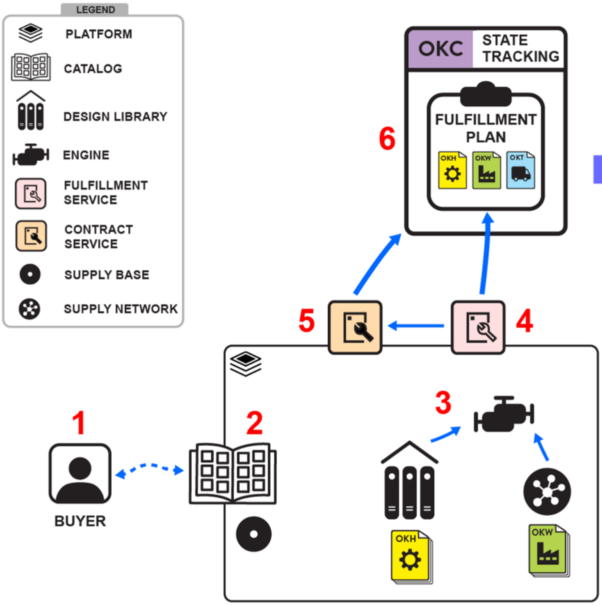

Fig. 4 Process flow in the SCIS Platform: from buyer selection to product delivery

4.3 A Narrative Scenario

This section provides a narrative scenario that showcases how a SCIS-compliant platform could have been leveraged to respond to the COVID-19 pandemic if it had been available in 2020. This scenario serves to demonstrate the potential benefits and practical uses of the platform in an easily understandable and relatable manner.

1. Bob is a small business owner who operates a medical store in a remote and rural area. As the COVID-19 pandemic begins to spread in March 2020, Bob becomes worried about the future of his business. He realizes that there is a growing demand for personal protective equipment (PPE), but he quickly realizes that the supply chain is overwhelmed and getting PPE products is difficult.
2. Bob hears about the SCIS platform, which offers a way for small businesses like his to connect with suppliers and manufacturers in a decentralized manner, overcoming the challenges posed by traditional supply chains. He decides to explore these options further and join the network, hoping to secure a steady supply of PPE for his store.

The SCIS platform offers a flexible solution to customers' needs by providing three distinct options for product fulfillment. If the product is in stock, it can be purchased immediately, ensuring quick and convenient access. If the product is not in stock but can be manufactured, the platform has the capability to enable production, ensuring that the customer can still receive the desired product. Lastly, if the product is not available in stock or cannot be produced, the platform has the ability to meet the customer's needs through substitution or repurposing adaptation strategies, providing a tailored solution to the customer's unique needs.

Next, we go into further detail on each of these three scenarios, showcasing the versatility and flexibility of the SCIS platform in meeting customer demands.

(a) First case: Product in stock:

1. Product availability: The platform identifies at least one supplier in the OKW with a *ready-made product* that matches the buyer's criteria and selection from the catalog.
2. Request for a quote: The customer generates a request for a quote and an open fulfillment request.
3. Supplier response: The supplier generates a quote in response to the customer's request.
4. Purchase agreement: If the price and product meet the buyer's criteria, the purchase is completed.
5. Quick access: Once the purchase agreement is reached, the product is shipped to the buyer for quick and convenient access.

   Overall, the first scenario highlights the capability of the SCIS platform in providing immediate access to the customer's desired product when it is in stock.

(b) Second case: Product not in stock but can be manufactured:

1. Production capability: The platform identifies at least one manufacturer in the OKW with the *ability to produce* the requested product. The manufacturer provides information on the cost of production, lead time, capacity, and delivery criteria/cost.
2. Request for a quote: The customer generates a request for a quote and an open fulfillment request.
3. Manufacturer response: The manufacturer generates a quote detailing the cost of production, lead time, capacity, and delivery criteria/cost.
4. Purchasing process: If the customer agrees to the quote, the purchasing process will proceed, and the product will be manufactured as per the manufacturer's lead time.
5. Delivery: Once the product is manufactured, it will be delivered to the customer as per the delivery criteria/cost mentioned in the quote.

   The second scenario showcases the flexibility of the platform in enabling production when the product is not in stock, ensuring that the customer can still receive the desired product. The platform also provides transparency and clear communication between the customer and the manufacturer, ensuring that the customer is informed about the lead time and delivery details.

(c) Third case: Product not available in stock or cannot be produced:

1. Open request: No OKW indicates the ability to supply or manufacture the requested product in the OKH. The customer generates an open request indicating the order fulfillment need.
2. Adaptation proposal: A manufacturer identifies the *ability to adapt* to the customer's demand and proposes a quote detailing the cost of production, lead time, capacity, and delivery criteria/cost.
   - Active product: The product remains active for a specified period of time.
   - Renewal request: If the product remains unfulfilled, the system requests a renewal from the buyer.
   - Product removal: If the renewal is not received, the product will be removed from the system.
3. Purchasing process: Once the customer accepts the quote, the purchasing process will proceed.
4. Delivery: Upon successful delivery and confirmation from the supplier/manufacturer, relevant OKWs in the system are updated.

   The third case showcases the platform's ability to adapt to the customer's demand through substitution or repurposing strategies to provide an effective solution to meeting customer demands, even when the product is not readily available.

The narrative scenario shows the potential of the OKRF and SCIS platform in enhancing supply chain resilience in the healthcare industry. The three hypothetical cases showcased the adaptability and flexibility of the SCIS plan in meeting customer demands, whether by providing quick access to in-stock products, enabling local production of out-of-stock products, or offering substitution and repurposing options when needed.

The COVID-19 pandemic has exposed the vulnerability of our current supply chain systems, with the shortage of essential items such as PPE having devastating consequences for those in need. If the SCIS platform had been in place during the pandemic, it could have made a significant difference in the response to the crisis. The platform would have provided a valuable resource for small business owners like Bob to quickly shift their operations and produce essential items like PPE, contributing to a more efficient and resilient response.

The SCIS plan would have given small manufacturers access to open-source models that are free and publicly available, enabling them to pivot their operations quickly and easily. The addition of small makerspaces to the network would have created a decentralized support system, which would have leveled the playing field and allowed the supply chain to quickly adapt to disruptions and market changes.

This hypothetical scenario underscores the potential of the SCIS platform in creating a more robust and flexible supply chain network in the healthcare industry. By enabling quick adaptation to market changes through substitutability and repurposing, the SCIS plan can help prevent shortages of critical medical supplies and equipment, such as personal protective equipment (PPE), ventilators, and medication. This will ultimately ensure that healthcare professionals have the necessary tools and equipment to provide timely and effective care to patients, potentially saving lives.

5 Discussion

Contemporary discourse, as highlighted by Brandon-Jones et al. [9] and Pettit et al. [43], traditionally views supply chain resilience as the capacity to "bounce back" post-disruption. However, recent perspectives, such as those of Nikookar et al. [40], propose redefining resilience as antifragility, where supply chains do not just recover but improve in the face of adversity. This reorientation underscores not only financial resilience but also social and environmental gains, offering a more holistic approach to supply chain management.

Integrating OKRF and SCIS creates a distributed manufacturing network that exemplifies antifragility. This network, dynamic in nature, evolves to meet the challenges of unforeseen events, demonstrating significant potential in crisis situations like supply chain disruptions. The SCIS platform's ability to identify alternative supply sources and integrate with local production capabilities, such as makerspaces, highlights its role in fostering a resilient and adaptive supply chain.

The effective management of supply chains, particularly in healthcare, is crucial for ensuring the availability of essential items like PPE, ventilators, and medications. The integration of OKRF and SCIS enhances supply chain visibility and sustainability, enabling rapid adaptation to fluctuating demands and ensuring timely delivery of critical medical supplies. As more objects and manufacturers join the system, its effectiveness will grow exponentially, resulting in a positive net effect. Anyone in the system can use the templates to collaborate and contribute to the development of a flexible and interoperable supply chain network capable of providing critical components during times of disruption. This potential for significant improvement in supply chain management underlines the necessity of empirical research to further understand and validate these advancements.

Empirical studies are thus needed to validate the real-world applicability and effectiveness of the OKRF and SCIS platform. Future research should encompass diverse industry case studies, scalability assessments, comparative analyses, and both quantitative and qualitative approaches. This research should also investigate the broader social and environmental benefits of adopting an antifragile approach in supply chains, ensuring that the theoretical benefits translate into tangible improvements in supply chain resilience and efficiency.

The OKRF and SCIS platform potentially offer substantial benefits in both academic and industrial contexts. In academic settings, OKRF and SCIS promise to enrich supply chain management and logistics curricula, offering practical frameworks for research and theoretical model development. In the industrial sector, the OKRF and SCIS are poised to enhance supply chain operations through their compatibility with existing systems, facilitating easy integration and adoption, particularly for small and medium-sized enterprises. The open-source nature and modular design the OKRF and SCIS frameworks make them accessible and cost-effective. Industries reliant on supply chains stand to benefit from improved operational agility, enhanced collaboration, and the ability to swiftly respond to market changes.

In concluding our discussion, it is important to observe that the advancement and refinement of the SCIS plan significantly rely on the integration of several state-of-the-art technologies. These technologies, though not yet integrated into the project, are inherently compatible with the SCIS plan and have the potential to improve the system's resilience and adaptability. Their future integration represents a strategic shift toward creating a more advanced, efficient, and secure supply chain management system. Central to these advancements is the Internet of Things (IoT), which is posited as a transformative tool for achieving real-time visibility within supply chain networks. Theoretically, the deployment of IoT sensors across the supply chain could facilitate the collection of critical data points such as temperature and geographical location, thereby enabling a more dynamic and responsive operational framework. In particular, the hypothetical application of IoT in the pharmaceutical sector could ensure the maintenance of optimal conditions for temperature-sensitive medications during transportation, thereby mitigating the risk of spoilage. Additionally, the conceptual integration of RFID (radio-frequency identification) alongside IoT for asset tracking is anticipated to considerably diminish losses due to theft and optimize inventory management.

Blockchain technology is another area of interest, valued for its capacity to bolster transparency and foster trust within the supply chain. The envisaged application of blockchain in the SCIS plan could facilitate the establishment of an uninterrupted chain of custody for goods, effectively countering counterfeiting and enhancing stakeholder trust. Additionally, the prospective integration of robotic process automation (RPA), enhanced by artificial intelligence (AI), offers the possibility of automating repetitive and rule-based tasks within the supply chain. This level of automation could lead to more streamlined processes in areas such as order processing and inventory management. Predictive analytics, driven by machine learning algorithms, emerges as another significant field for future investigation. This advanced technology could equip the SCIS platform with the capability to foresee and strategically manage potential supply chain disruptions. Lastly, the increasing digitization of supply chains brings to the fore the theoretical need for robust cybersecurity measures within the SCIS platform. This entails a detailed analysis of potential cybersecurity strategies, including the implementation of encryption protocols, access controls, intrusion detection systems, and regular security evaluations.

6 Conclusions

This paper provided an overview of the OKRF data standards and its compliance with the SCIS specification. We have showcased the application of the OKRF and SCIS in the healthcare industry, illustrating how they facilitate the creation of robust and flexible supply chain networks, ultimately helping healthcare professionals deliver high-quality care and save lives. The three hypothetical cases in our narrative scenario underscore the adaptability and efficiency of the SCIS plan in providing quick and convenient access to critical medical supplies and equipment.

Beyond healthcare, the implementation of the OKRF data standards and SCIS specification holds immense potential in various other sectors. The distributed manufacturing network platform, underpinned by these standards, offers a powerful solution for enhancing supply chain resilience across industries. This is particularly beneficial for small and medium-sized manufacturers, enabling them to quickly and efficiently pivot operations in response to crises. By leveraging free, open-source models, manufacturers can adaptively respond to market demands and supply chain disruptions, not only in healthcare but in other critical sectors as well.

The antifragile nature of the SCIS plan makes the distributed supply chain network more adaptive and less prone to collapse in the face of unexpected events, creating a resilient system that can thrive in the face of adversity. As more manufacturers and objects are integrated into the system, the SCIS platform's effectiveness is set to grow exponentially, generating a positive net effect for all participants. The platform's templates can be utilized to promote collaboration and develop a nimble and interoperable supply chain network capable of providing critical components during times of supply chain shortages and disruptions. This solution has the potential to generate resilience against other threats beyond the COVID-19 pandemic and other widespread catastrophes that carry the specter of global societal collapse, creating a brighter future for all.

The OKRF and the SCIS platform have made substantial progress, thanks to the unwavering commitment of a dedicated volunteer community. Their invaluable contributions have been pivotal in propelling the project forward. To further advance these open-source initiatives, HELPFUL Engineering, a non-profit organization dedicated to providing open-source solutions for global challenges, extends an invitation to developers, designers, and testers interested in collaborating on these projects. For more information and access to the project's GitHub repository, please visit our volunteering community [https://helpfulengineering.org/volunteer/].

To propel the OKRF and the SCIS platform into the pilot and commercialization phase, a strategic roadmap is imperative. Critical steps include the undertaking of pilot initiatives and comprehensive case studies across diverse industry sectors. These endeavors will serve the dual purpose of substantiating the effectiveness of the frameworks and garnering the interest of prospective stakeholders. Continuous engagement with the community and active solicitation of feedback will be instrumental in facilitating iterative enhancements.

Furthermore, the invaluable partnership with the Internet of Production Alliance (IoP Alliance), which played a pivotal role in establishing the OKRF's foundation, stands as a strategic asset that warrants prominent recognition. Looking ahead, it is essential to leverage these existing strengths by exploring potential avenues for securing funding. These may include grants, private investments, or collaborative ventures with academic and industrial institutions. Equally important is the need to ensure the scalability, adaptability, regulatory compliance, and alignment with industry standards to ensure their long-term viability and relevance.

For those seeking a deeper understanding of the mathematical underpinnings of SCIS, we recommend reviewing the document titled "A Preliminary Mathematical Description of SCIS," authored by Robert L. Read and Sarah Abowitz. This document offers a preliminary exploration of the mathematical aspects of SCIS and outlines ongoing efforts to implement a practical SCIS framework in Python. Here are the relevant links:

- Document "A Preliminary Mathematical Description of SCIS": https://helpfulengineering.github.io/OKF-SCIS/supportive-math/MathematicalDescriptionofSupplyChainInteroper.html
- Python code repositories: Project Data Platform and Library https://github.com/helpfulengineering/project-data-platform
- https://github.com/helpfulengineering/library

Annex

A comprehensive list of abbreviations can be found in Table 2, while Table 3 provides a summary of key concepts used in this paper.

Table 2 List of abbreviations

Abbreviation	Meaning
AURA	Active Usage of Resilience Assets
HCSC	Healthcare Supply Chain
HSCM	Healthcare Supply Chain Management
IoP Alliance	Internet of Production Alliance
JIT	Just-in-Time
LCNSC	Low-Certainty-Need Supply Chain
LSCM	Logistics and Supply Chain Management
LOG	Logistics Flexibility
MOD	Modification Flexibility
MIX	Mix Flexibility
NEW	New Product Flexibility
NET	Supply Network Flexibility
OKC	Open Known Contract
OKH	Open Known How
OKM	Open Known Material
OKP	Open Known Product
OKQ	Open Know Quality
OKQT	Open Known Quality template
OKRF	Open Knowledge Repurposing Framework
OKT	Open Known Transport
OKW	Open Known Where
RMS	Reconfigurable Manufacturing System
RSC	Reconfigurable Supply Chain
SCA	Supply Chain Agility
SCC	Supply Chain Collaboration
SCD	Supply Chain Disruption
SCF	Supply Chain Flexibility
SCIS	Supply Chain Information Sharing
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
SCS	Supply Chain Sustainability
SCT	Supply Chain Transparency
SSC	Sustainable Supply Chain
SUP	Supplier Flexibility
SCR	Supply Chain Resilience
VOL	Volume Flexibility
VSC	Viable Supply Chain

Table 3 Key concepts

Key concepts	Definitions
Antifragility	A system that thrives in the face of disorder and uncertainty, gaining from challenges rather than just recovering from them
Data interoperability	Seamless communication and exchange of data between partners, systems, and processes to promote collaboration and information sharing
Digital interoperability	Focus on achieving compatibility and integration in digital and data-driven logistics systems and services
Interoperability	The ability of a system or product to work with others without requiring special effort from the customer
Internet of Production Alliance (IoPA)	An organization promoting the integration of digital technologies and data standards in the production industry to enhance interoperability, collaboration, and innovation in manufacturing
OKH (Open Know How)	A part of the Open Know How data standard that contains metadata and file information, including design details, standards, licenses, derivatives, and download links
OKW (Open Know Where)	A complement to OKH that provides location information about manufacturing facilities worldwide, facilitating matching and routing of OKH designs and enabling resource repurposing
OKP (Open Know Process)	A template outlining tests and procedures for manufacturing a product based on an OKH manifest, ensuring thorough and compliant manufacturing processes
OKM (Open Know Material)	A template providing essential information about materials used in production, including requirements, properties, and composition, bridging the gap between OKH and OKW templates
OKT (Open Know Transport)	A template gathering logistics information about carrier entities, including equipment and capability, to enhance the transportation leg of the supply chain network
OKC (Open Know Contract)	A template streamlining the contract process within the OKRF, representing agreements between parties involved in production, facility representation, and transportation
OKQ (Open Knowledge Quality Test)	A standardized method for evaluating template quality within the OKRF, assessing accuracy, completeness, relevancy, and adherence to standards and procedures
OKRF (Open Knowledge Resilience Framework)	Comprehensive data standards enabling efficient coordination and exchange among manufacturing nodes, enhancing supply chain resilience
Reconfigurable Manufacturing System (RMS)	An easily adjustable system that responds quickly to changes in product design, production volume, and market demand

Table 3 (continued)

Key concepts	Definitions
Supply Chain Interoperability Specification (SCIS)	A distributed manufacturing network platform connecting various facilities, suppliers, and customers
SCIS plan	Integration of OKRF and SCIS to build more resilient supply chains by enabling quick adaptation to changes in demand, availability, or other factors
Supply Chain Adaptability (SCA)	The capacity of a supply chain system to adjust and modify its structure and processes in response to external changes and disruptions
Supply Chain Agility (SCA)	The strategic ability of organizations to rapidly sense and respond to internal and external uncertainties by effectively integrating supply chain relationships
Supply Chain Transparency (SCT)	Involves being aware of and sharing information about every step of the supply chain, both within the organization and with external parties
Supply Chain Collaboration (SCC)	The integration of seven interconnecting components: information sharing, goal congruence, decision synchronization, incentive alignment, resource sharing, collaborative communication, and joint knowledge creation
Supply Chain Flexibility (SCF)	An operational ability that enables organizations to change efficiently internally and/or across their key partners in response to internal and external uncertainties through effective supply chain relationship integration
Supply Chain Sustainability (SCS)	The approach of integrating economic, environmental, and social factors into the design and management of supply chains

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Consent to Participate Not applicable.

Consent for Publication Not applicable.

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