

Digital Technologies in Cold Chain Pharmaceutical Supply Chain: A Systematic Literature Review

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Abstract

The cold chain pharmaceutical supply chain (CCPSC) plays a crucial role in maintaining the safety and integrity of temperature-sensitive pharmaceuticals such as vaccines and drugs. With growing emphasis on temperature control in the healthcare industry, digital technologies are being widely adopted in CCPSC due to their ability to enhance real-time monitoring, improve traceability, and increase transparency across the supply chain. This study aims to identify major digital technologies in the field of CCPSC and to identify trends and gaps of digital technology application in the identified literature. A systematic literature review was conducted using PRISMA guidelines to identify relevant articles, which were further analyzed to determine whether they presented implementable frameworks. These frameworks were then examined to understand the technologies used and their application across five functional areas: manufacturing, storage & inventory management, distribution, transportation, and monitoring & control. Technologies such as blockchain, IoT, RFID, and smart contracts were found to be widely used. The study also identified that digital technologies are predominantly used in monitoring & control, in stark contrast to manufacturing. By mapping technologies to specific functions, this study offers insights for academics and decision-makers and lays the groundwork for future research.

Keywords

Cold chain, pharmaceutical supply chain, digital technologies, PRISMA

1. Introduction

The pharmaceutical supply chain (PSC) plays a crucial role in the healthcare system by safely and efficiently managing pharmaceutical products through their entire lifecycle, from manufacturing to administration to patients. It involves an interconnected network of systems that involve production, storage and delivery of pharmaceutical products to the right people at the right time. The stakeholders of this supply chain include, but not limited to, pharmaceutical companies, distributors, drug manufacturers, healthcare facilities and pharmacies (Shruthi & Poornima, 2024).

The CCPSC is a specialized PSC that deals with temperature-sensitive pharmaceutical products such as vaccines and drugs that require strict temperature maintenance throughout its lifecycle. Typically, the temperature range for these pharmaceuticals is between 4° Celsius to 8° Celsius, but the exact temperature can vary based on the specific product (Hulea et al., 2018). This means that any change in environmental conditions, like temperature or humidity, can cause degradation of the product, making it ineffective or even dangerous. Thus, maintaining consistent temperature throughout the lifecycle of such temperature-sensitive pharmaceutical products is imperative not only to avoid financial loss, but more importantly, to protect patients from serious health risks. Given the critical nature of this supply chain and the vulnerability of the end users (patients), the stakeholders are held with a higher level of accountability to ensure the safety, integrity, quality and availability of pharmaceutical products. Attention to this field has increased in recent years, following the COVID-19 pandemic, when vulnerability in CCPSC were exposed due to the world being unprepared for such an event (Lam et al., 2023).

Digital technologies are being widely used to enhance CCPSC, by enhancing traceability, reliability and transparency of the process. Various digital technologies such as IoT and RFID have been used in CCPSC for a number of years. There are other novel digital technologies such as blockchain, digital twin and smart contracts that are gaining momentum in various fields and are being adopted by CCPSC stakeholders (Rinaldi et al., 2025; Roman et al., 2025). With several technologies being used in different functional areas with different levels of operational effectiveness, it becomes essential to systematically analyze the applications of these digital technologies to CCPSC processes, to determine the most widely used technologies, as well as the underserved areas of CCPSC.

1.1 Objectives

This study aims to systematically analyze the existing literature in the field of CCPSC, in order to:

- (1) identify the most widely used digital technologies in the field, and
- (2) examine how these technologies are applied across the different functional areas of CCPSC (such as manufacturing, storage & inventory management, transportation, distribution, and monitoring & control) to identify key trends and gaps in literature.

By doing so, the study intends to establish a foundation for future research that can guide decision-makers in adopting appropriate digital technologies within their organizations.

2. Literature Review

Kumru et al. (2014) state that maintaining the temperature of pharmaceutical products such as vaccines and medicines is critical in ensuring their safety and viability. These products require a temperature-controlled environment right from when they are manufactured to when they are administered to the patient. Any change in temperature, either higher or lower than the recommended temperature, causes spoilage and reduction in effectiveness. This results in wastage of products, causing financial strain on both manufacturers and distributors. More importantly, it disrupts healthcare services and ultimately affects patients who need these vaccines and medicines in potent condition for the success of their treatment. Thus, it is important to maintain the temperature of the pharmaceutical products in all stages of the CCPSC. Based on review of CCPSC literature, (see: Campos & Villa, 2018; Montoya M., et al., 2021) CCPSC has been broadly classified into five key functional areas as shown in Table 1.

Table 1. Definition of functional areas of CCPSC

Functional areas of CCPSC	Definition	References
Manufacturing (M)	This function involves the manufacturing of pharmaceutical products that require strict maintenance of temperature to preserve their integrity.	Campos & Villa (2018)
Storage & Inventory Management (SIM)	This function involves storage of temperature-sensitive pharmaceutical products and management of inventory resulting in efficient use of storage space and ability to keep track of stocks and expiry dates of the products.	Jossy et al. (2024)

Functional areas of CCPSC	Definition	References
Distribution (D)	This function involves the logistics decisions and activities that result in the distribution of these temperature-sensitive pharmaceuticals through the supply chain, to warehouses, hospitals, and other end users.	Campos & Villa (2018); Lam et al. (2023)
Transportation (T)	This function involves the physical movement of temperature sensitive pharmaceutical products from one point to another, given the risk associated with variations in environmental conditions and transportation uncertainties.	Campos & Villa (2018)
Monitoring & Control (MC)	Serving as an overarching functional area, this function involves continuous monitoring, real-time tracking and regulatory compliance of temperature-sensitive pharmaceuticals through all the above functional areas.	Potdar et al. (2009)

The digitalization of CCPSC has led to rapid advancements in this field, along with a fast-growing interest among academics and decision makers to understand and apply these digital technologies to various functional areas of CCPSC. Digital technologies have been proven to enhance our ability to monitor environmental conditions of temperature-sensitive pharmaceuticals, while improving our risk capabilities, supply chain resilience and product traceability across the supply chain, which would otherwise require constant human intervention (Cai et al., 2023; Lam et al., 2023). Several digital technologies have been adopted to enhance the CCPSC functionality and efficiency. Based on the review of the literature conducted, Table 2 identifies the most commonly used digital technologies in CCPSC.

Table 2. Definition of digital technologies

Digital Technology	Definition	References
Blockchain Technology (BCT)	A type of DLT that records transactions as blocks and cryptographically links them as a chain of events, resulting in an immutable record of transactions.	Boubeta-Puig et al. (2021)
Cloud Computing (CC)	Provides large scale, centralized computing capabilities and data storage capacity for long term data usage.	C. Yang et al. (2023)
Complex Event Processing (CEP)	A software system that analyzes events and provides real-time data for decision making.	Boubeta-Puig et al. (2021)
Digital Sensor (DS)	A physical device that converts physical attributes such as temperature and humidity into digital signals.	D'Uva et al. (2021)
Digital Twin (DT)	Dynamic digital replica of a physical system that receives real-time data from the physical system and used to predict changes in the actual system.	Lam et al. (2023)
Digital Wireless Sensors (DWS)	A digital sensor that can transmit the digital signal to the processing unit wirelessly.	D'Uva et al. (2021)
Distributed Ledger Technology (DLT)	A decentralized system where multiple nodes share a distributed ledger that records and synchronizes transactions of all nodes.	Vergine et al. (2023)
Edge Computing (EC)	Provides the ability to process data locally rather than in the cloud, for situations that need increased speed of response compared to cloud computing.	C. Yang et al. (2023)

Digital Technology	Definition	References
Global Positioning Devices (GPS)	Satellite based tracking device that provides accurate position and time information of an object.	Mohsin, & Yellampalli (2017)
Internet of Things (IoT)	A network of physical objects that can communicate with each other and share data.	Gannavaram V et al. (2021)
Internet of Everything (IoE)	An evolution of the concept of IoT, where devices are connected with people, processes and data to achieve a higher level of interconnectivity and data sharing.	C. Yang et al. (2023)
IoT Edge Devices (IoT-E)	IoT devices that collect and process data locally rather than in the cloud, thus reducing latency for real-time decision making.	H. Yang et al. (2023)
Machine Learning (ML)	A type of artificial intelligence technology that learns and adapts based on existing data.	Nechifor et al. (2014)
Radio Frequency Identification (RFID)	A technology that uses radio frequency signals to identify and track objects.	FanJun Li & ZhaoJiong Chen (2011)
Sensor Network (SN)	A network of sensors that collect information and transmit it to a central processing unit.	Schoen & Streit-Juotsa (2015)
Smart Containers (SCT)	Advanced storage units that monitor temperature conditions inside them and digitize the results.	Kamenivskyy et al. (2022)
Smart Contracts (SMT)	A software that automatically executes contracts when conditions are met, without the need for external intervention.	Hosseini Bamakan et al. (2021)

3. Review Methodology and Article Selection

A Systematic Literature Review (SLR) was conducted using Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. The PRISMA approach is used due to its transparency, robust methodology and its wide acceptance in academic research (Page et al., 2021), particularly in the field of supply chain management (see: Kabir et al., 2024; Lopes et al., 2024; Sultana et al., 2024). Using the PRISMA technique, peer-reviewed research articles were collected using carefully selected key words that closely match the area of our research. This resulted in a total of 164 articles. Further filtration was necessary to find articles that addressed the objectives of this study.

To achieve the objectives of this study, each article was selected with the following questions in mind:

1. Is this article specific to the field of CCPSC?
2. Does this article address the application of at least one digital technology in the context of CCPSC?
3. Does this article provide an implementable framework for the application of one or more digital technologies to enhance CCPSC?

Independent variable – CCPSC context: This variable indicates if the article is in the context of CCPSC. This includes any discussion of CCPSC including vaccines, medicines, etc. that need to be maintained at cold or freezing temperatures.

Dependent variable - Digital technologies: This variable indicated if the article discussed application of any digital technology in the context of CCPSC improvement. This includes any digital technologies such as blockchain, IoT, RFID, machine learning, cloud computing, etc.

3.1 Selection of Database

Three databases, namely Web of Science (WoS), Science Direct (SD) and IEEE Xplore (IEEE), were accessed for the purpose of this study. This selection was based on considerations such as the credibility of databases and the availability of institutional access

3.2 Selection of search terms

The search terms for this study were selected carefully to ensure both broad coverage as well as relevance to the field of study. Thus, core search terms such as ‘cold chain,’ ‘supply chain,’ ‘pharmaceutical,’ and ‘vaccine’ were used ensure we get articles in the right domain. An exhaustive list of approximately 20 digital technology terms were used to broaden the scope of technology inclusion. Some search terms include ‘blockchain,’ ‘digital twin,’ ‘RFID,’ ‘cloud computing,’ and ‘artificial intelligence.’

3.3 Article selection process

A total of 164 articles were obtained across the three databases. Inclusion and exclusion criteria were used to filter these articles for this study.

3.3.1 Inclusion and exclusion criteria

Inclusion criteria: Only peer-reviewed articles in the English language, accessible through WoS, SD and IEEE were included. Additionally, only articles that discuss CCPSC and discuss at least one digital technology in the context of CCPSC were considered for the purposes of this study.

Exclusion criteria: Duplicate and inaccessible articles were excluded. Further, those articles that do not specifically mention CCPSC and at least one digital technology in the context of CCPSC were excluded from this study.

3.3.2 Filtration process

Duplicate and non-English articles exclusion: A handful of articles were identified as duplicates between the three databases and were removed, along with a few articles that were not in the English language. This resulted in 143 peer-reviewed articles.

Inaccessible articles exclusion: Of the 143 articles that remained, 6 were not accessible due to institutional permissions. Hence 137 articles remained for further review.

Relevance to area of study: Each of the 137 articles were carefully reviewed to extract data with respect to relevance to the topic of our study. For this purpose, articles that did not mention CCPSC and ones that did not mention any digital technologies were excluded. This resulted in a total of 87 articles that were relevant to the topic of this study.

Final articles selected for study: The 87 articles were further reviewed to identify those proposing implementable frameworks for applying digital technologies to address issues in the CCPSC. This resulted in a final selection of 48 articles. The graphical representation of the article selection process is shown in Figure 1.

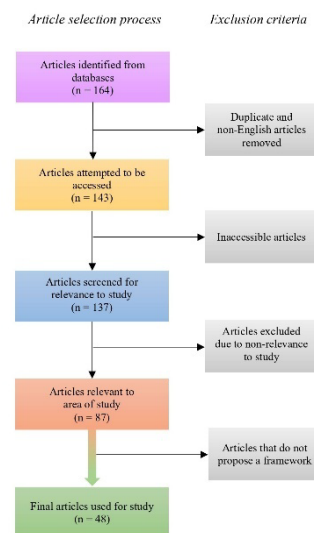


Figure 1. PRISMA flowchart

5. Results and Discussion

From the selected 48 articles, it was observed that there was an increase in the number of research papers published in recent years, which is shown in Figure 2. The graph shows an increasing interest in the specific domain of this study, especially since 2021. The spike in the number of articles in 2021 could be attributed to the COVID-19 pandemic, during which the supply chain issues of the world became much more evident, drawing attention to academic research as well as industrial improvement in this area.

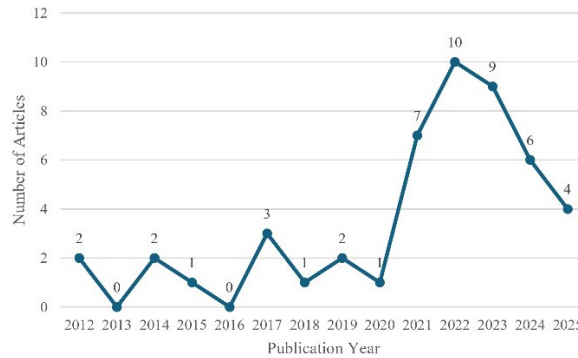


Figure 2. Articles published by year

The 48 articles that were selected for this study were reviewed meticulously to identify what specific digital technologies were used in the framework and what functions of the CCPSC does the framework address. Each article was found to have multiple digital technologies applied to multiple areas of the CCPSC. For the purpose of this study, we have only considered major digital technologies used in each proposed framework. To identify the functional areas of the digital technology application, the framework was considered as a whole and was further investigated to identify the functional areas. The results of our review are presented as in Table 3.

Table 3. Digital technologies used in the functional areas of CCPSC

Reviewed article	Digital technologies used															Functional areas							
	B C T	C C	C E P	D L T	D S	D T	D W S	E C	G P S	I o T	I o E	I o T E	M L	R F I D	S C T	S M C	S N	M	S I M	T	D	M C	
Kamenivskyy et al. (2022)	✓														✓	✓	✓		✓	✓	✓	✓	
Al Sadawi & Ndiaye (2022)	✓															✓			✓	✓	✓	✓	✓
Rehman et al.(2023)	✓			✓												✓			✓			✓	✓
Lam et al. (2023)						✓				✓									✓	✓	✓	✓	✓
Monteleone et al., (2017)										✓				✓					✓	✓	✓	✓	✓
Mamoon & Shah (2023)	✓									✓						✓			✓			✓	✓
Kim et al., (2012)														✓			✓		✓	✓	✓	✓	✓
Wan & Huang (2023)	✓									✓					✓				✓	✓	✓	✓	✓
Nechifor et al. (2014)				✓									✓							✓		✓	✓
D’Uva et al. (2021)							✓							✓					✓	✓	✓	✓	✓
H. Yang et al. (2023)	✓										✓								✓	✓	✓	✓	✓
Sharmila et al. (2022)	✓									✓				✓		✓			✓	✓	✓	✓	✓
Cao et al. (2022)	✓									✓									✓	✓	✓	✓	✓
Musamih et al. (2021)	✓									✓						✓	✓		✓		✓	✓	✓
Boubeta-Puig et al. (2021)	✓		✓														✓			✓		✓	✓
Ramkumar et al. (2024)	✓	✓								✓									✓	✓	✓	✓	✓
Qin et al. (2021)										✓									✓	✓	✓	✓	✓
C. Yang et al. (2023)	✓	✓						✓			✓								✓		✓	✓	✓
Fournier & Skarbovsky (2019)	✓		✓																✓	✓	✓	✓	✓
Lankipalle et al. (2025)	✓												✓			✓			✓	✓	✓	✓	✓

Reviewed article	Digital technologies used																Functional areas					
	BCT	CC	CEP	DLT	DS	DT	DWS	EC	GPS	IoT	IoE	IoTE	ML	RFID	SCT	SMC	SN	M	MI	T	D	MC
M et al., (2024)	✓									✓						✓		✓	✓	✓		✓
Panigrahi et al. (2024)										✓								✓	✓	✓	✓	✓
Mohsin, & Yellampalli (2017)									✓	✓							✓	✓	✓	✓	✓	✓
Shaji et al. (2023)										✓								✓	✓			✓
Sarkar et al. (2022)										✓								✓	✓			✓
Awasthi et al. (2025)										✓								✓	✓			✓
B.Gopinath et al. (2025)	✓									✓								✓	✓			✓
Vergine et al. (2023)				✓						✓								✓	✓	✓	✓	✓
Romeiro et al. (2021)							✓	✓										✓				✓
Bouazzi et al. (2025)									✓	✓				✓				✓	✓			✓
Dos Santos et al. (2015)														✓				✓	✓			✓
Hulea et al. (2018)				✓						✓								✓	✓	✓	✓	✓
Bapatla et al. (2022)	✓									✓								✓	✓			✓
Nechifor, Petrescu, et al. (2014)			✓							✓								✓				✓
Anand et al. (2022)	✓									✓				✓				✓	✓	✓	✓	✓
Prakash et al. (2012)					✓									✓				✓	✓	✓	✓	✓
Bengiovanni et al. (2020)										✓								✓	✓	✓	✓	✓
Shruthi & Poornima (2024)	✓									✓						✓		✓	✓	✓	✓	✓
Vargis et al. (2022)	✓									✓						✓		✓	✓	✓	✓	✓
Zhou & Chakrabartty (2017)	✓									✓						✓		✓	✓	✓	✓	✓
Xie et al. (2019)					✓									✓				✓	✓			✓
Josy et al. (2024)					✓									✓				✓				✓
T & Sarvagya (2022)					✓					✓				✓				✓				✓
Rehan et al. (2023)	✓									✓								✓		✓	✓	✓
Meghla et al. (2021)	✓												✓					✓	✓	✓	✓	✓
Amarasinghe G et al. (2022)	✓									✓			✓			✓		✓				✓
Amaya et al. (2021)										✓									✓			✓
Verma et al. (2024)	✓															✓		✓		✓	✓	✓

The results of the study were further analyzed graphically to identify major technologies in the field of CCPSC, trends within functional areas and which specific technologies, if any, were most used in a specific functional area of the CCPSC.

5.1 Heatmap of digital technologies in each functional area

A heatmap was used to depict the trends of digital technologies across the five functional areas identified in this study as shown in Figure 3.

Frequency by Functional Areas: It can be seen from the heatmap that the monitoring & control function is well-represented by the use of digital technologies. This is because monitoring & control function is valued as the overarching functional area that is applied across the other functions, making it a significant function for temperature-sensitive pharmaceuticals. It can also be seen that the manufacturing function has the lowest use of digital technology, making it an underserved function.

Frequency by Digital Technology: It can be observed from the heatmap that IoT and BCT appeared most frequently across the proposed frameworks, followed by RFID and SMC. This shows a widespread use of these four technologies, as well as the ability of these technologies to work seamlessly with other digital and physical technologies, resulting in an extensive adoption into the proposed frameworks.

IoT is a well-adaptable, versatile technology that integrates seamlessly with other digital technologies and physical systems and is commonly embedded with legacy systems. IoT devices can monitor products in real-time and send alerts based on changing environmental conditions. RFID, while often integrated within IoT frameworks, also

functions effectively as a stand-alone solution. It plays a critical role in enhancing product traceability, inventory accuracy, and real-time visibility across the supply chain.

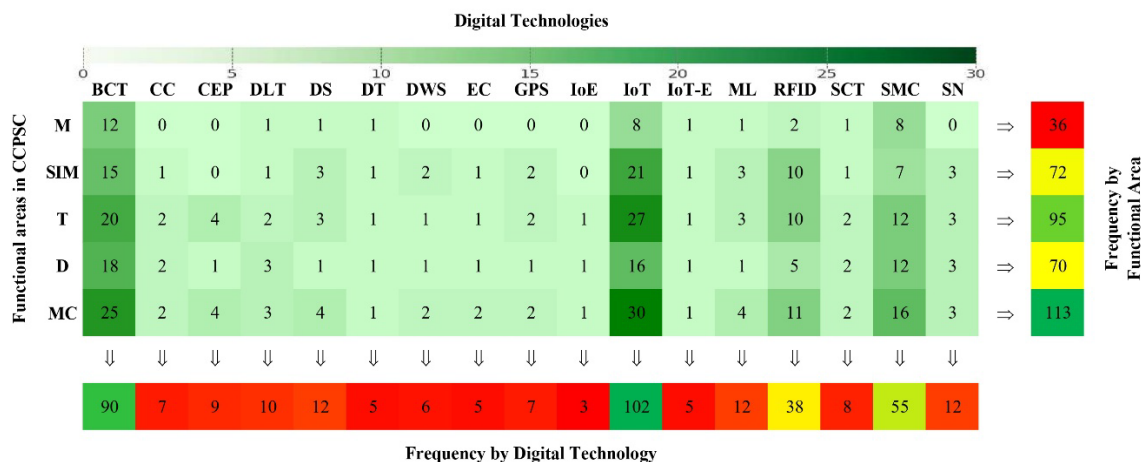


Figure 3. Heatmap showing frequency of digital technologies across functional areas of CCPSC

Although BCT is a relatively novel technology, its widespread adoption in CCPSC frameworks shows its ability to integrate with other technologies. Its ability to create immutable records has proven to be valuable in terms of enhanced traceability, privacy and regulatory compliance. The advancements in BCT have paved way for SMC, which provides powerful automation by self-executing contracts without human intervention.

Technologies such as DT, IoE and IoT-E were found only once in the reviewed frameworks. Keeping in mind that all three technologies are emerging niche technologies, further analysis is required to understand if this limited presence in proposed frameworks is due to the novelty of these technologies or other implementation challenges in CCPSC.

6. Conclusion

This study set out to systematically analyze the identified literature for the use of digital technologies in various functional areas of CCPSC, and to identify key trends and gaps in the academic literature. This systematic literature review was conducted using PRISMA guidelines, resulting in 48 articles that proposed frameworks addressing digital technology applications in CCPSC.

In alignment with the study’s objectives, these articles were reviewed to identify the major digital technologies used in each functional area and to identify key trends and gaps in literature. The results highlighted four major technologies, blockchain, IoT, RFID, and smart contracts, which were the most frequently occurring across the reviewed frameworks. Additionally, the results also showed a wide-spread application of digital technologies in the monitoring & control area, highlighting its significance as an overarching area across the other functions, and minimal application of digital technologies in the manufacturing area. Other newly emerging technologies were also identified, emphasizing the need for further research.

These findings present a unique facet for research in the field of CCPSC, by providing a comprehensive view of digital technologies in this field and a function-wise mapping of the technologies. This structured analysis not only fills the gaps in existing literature but also serves as a strong foundation for future research in this field. The results of future research in this area would guide decision-makers, academics and industry practitioners when adopting digital technologies. It will enable data-driven understanding of the technologies with respect to each functional area, further amplifying our ability to create a practical, implementable framework with best practices in the field.

6.1 Limitations

The following are the limitations of the study:

- This study identified only the major digital technologies in each framework that was reviewed. However, most frameworks used several other secondary digital technologies which were not captured. Identifying

these secondary digital technologies could potentially alter the frequencies of digital technologies in CCPSC research.

- Each framework that was considered was taken as a whole and every digital technology in the framework was mapped equally to all functional areas addressed in the framework, instead of mapping individual digital technologies to each of the functional areas. The latter type of mapping could offer a clearer picture of how specific technologies are tied to particular functional areas, which goes beyond the scope of this study.

6.2 Future directions

The limitations identified above can present opportunities for future research:

- A much more detailed analysis of digital technologies, including supporting or secondary technologies, can be carried out. This would provide a more complete picture of the technological landscape in CCPSC frameworks.
- A detailed mapping of individual digital technologies to specific functional areas within each framework can be performed, rather than assuming equal application across all functions. This type of detailed mapping could strengthen the accuracy of the findings and provide clearer insights into how technologies are being used.
- Additionally, each framework can be analyzed to identify the challenges and benefits associated with the adoption of specific digital technologies. This would not only support the development of practical recommendations for decision-makers but also help propose a framework that reflects best practices in academic research while aligning with industry needs. It would further allow for a deeper understanding of the implications of using multiple technologies together in the CCPSC.

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Biographies

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