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Conceptualizing the digital thread for smart manufacturing: a systematic literature review

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Abstract

Business operations and supporting data analysis initiatives are impeded by the silos of data present within departments, systems, and business units. Consequently, the ability of managers and engineers to harness data for operational management and informed decision-making is curtailed. The rapid advancements in technology have revolutionized various aspects of product development, manufacturing, operations, and end-of-life treatment. One such transformative concept, the digital thread, has emerged as an important paradigm. It orchestrates the integration of information and data along the entire product lifecycle, spanning from initial design and engineering through production, maintenance, use, and eventual end of life. While the digital thread has garnered increasing attention within both the research community and industrial enterprises, there remains a notable lack of standardization concerning its utilization and applications. This comprehensive literature review aims to explore the role of the digital thread in manufacturing within the context of the product lifecycle. As a result, this review synthesizes insights into the technologies, roles, and functions of the digital thread throughout the product lifecycle. Furthermore, it proposes a structured framework designed to impart a standardized perspective of the digital thread's relevance within the manufacturing product lifecycle. Ultimately, this framework is poised to serve as a guiding resource for practitioners and researchers in designing and implementing digital threads.

Keywords Digital Thread · Manufacturing · Product lifecycle · Data connectivity · Data traceability · Decision making

Introduction

Global manufacturers are actively spearheading initiatives aimed at achieving digital transformation, recognizing the imperative to reshape their business operations to maintain a competitive edge. Against the backdrop of the prevailing global trend towards digitalizing manufacturing systems, there has been a pronounced emphasis on the generation and exploitation of Big Data for driving advanced analytics, encompassing Machine Learning (ML) and Artificial Intelligence (AI) applications, for informed decision-making. This increasing emphasis on data-driven analytics has motivated manufacturing companies to increasingly adopt the 'digital thread' architecture. The heightened interest in the digital thread within the industrial domain can be attributed to a notable discrepancy between the perceived value of data and the tangible value realized. This disparity arises from the inherent challenges of data accessibility and sharing across diverse departments, stakeholders, the enterprise as a whole, and throughout the extended supply chain (Dertien & Hastings, 2021). While the amount of data that is being generated from the industrial sectors' products, humans, and processes is constantly increasing, the management of this manufacturing data keeps growing in complexity to the point where interoperability is a major concern (Hedberg et al., 2020). At the same time data created by manufacturing systems is growing at an exponential rate in the modern manufacturing industry, and data-driven manufacturing is viewed as a prerequisite for smart manufacturing (Tao et al., 2018). As a result, data is increasingly becoming a critical enabler for improving manufacturing competitiveness, and businesses are beginning to appreciate the strategic relevance of data (Tao et al., 2018). This led companies to have an increased interest in the digital thread

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as an enabler for simple and universal data access architecture along the product lifecycle. Eskue (2023) utilized a metaphor to highlight the relevance of a digital thread for the product, proposing a pilot and a co-pilot scenario. The pilot would feel confident flying with their co-pilot knowing that they passed specific certifications, but more knowledge about the co-pilot's life, health, and history would allow for better flight planning, risk calculations, and decision-making. This metaphor effectively represents the use of data and information for the product's digital thread, which enables informed decision-making for manufacturing, including AI utilization. Tracing back to the origin of the digital thread, it appeared first in 2010 within the Aerospace industry (Cohen, 2010) and has been described as follows.

> *"The digital thread goes from conceptual design through detail design and into manufacturing and MRO. That same digital thread that starts with design engineers is used for the entire life-cycle of the airplane. The database is completely digital"* (Cohen, 2010).

Since 2010 there has been a growing interest in digital threads in different fields of research and industrial applications, accordingly, its concept, technologies, and architecture have evolved. Simultaneously, as the digital thread was introduced other Industry 4.0 concepts, most notably the Digital Twin (DT), have also emerged (Negri et al., 2017). They received more attention from researchers and industry practitioners due to their heightened significance. This led to a lack of collaboration and dispersion within the research community. Consequently, when engaging in discussions regarding the digital thread, noticeable inconsistencies arose in defining the concept and articulating its precise implementation strategies. The absence of a standardized framework led to varying interpretations and approaches to digital thread adoption, thereby impeding the clarity and uniformity necessary for its widespread understanding and application. Previous literature reviews on digital threads have been few and performed focusing on a specific implementation use case. For example; Bonnard et al. (2019) have performed a state of the art study of digital threads within Additive Manufacturing (AM) applications where the authors concluded with recommendations on formats to use for AM data models to enable digital threads. On the other hand, Eskue (2023) performed a review on digital thread for composite aerospace components, and discussed the critical gaps and benefits of the digital thread for aerospace applications. Also within the aerospace industry, West and Pyster (2015) have discussed the digital thread for combat aircraft acquisition, and while this article is a special feature without a strict literature review methodology, it presents an interesting discussion on the challenges for digital thread. As the digital thread has been researched within varying applications there is a need for a review of the research efforts carried out across all applications and use cases within manufacturing to synthesize and consolidate a vision for the digital thread that can be further researched and implemented from a standardized understanding. A recent literature review by Daase et al. (2023) compares between the digital thread and DT in Industry 4.0 context and reviews the technologies available for digital thread implementation, without a specific focus on a use case implementation. However, as mentioned by the authors their review has been confined to ScienceDirect database and they have not considered open-source implementations. Additionally, there are no literature reviews that address the digital thread from a product lifecycle perspective. To address these gaps, a systematic literature review is performed and presents an integrated understanding of the definition, roles, functions, and technologies of the digital thread in the product lifecycle of the manufacturing industry. This review provides insights for researchers and practitioners, enabling them to discern the appropriateness of employing the digital thread as a solution for their specific use cases. Moreover, it offers the opportunity to gain a comprehensive grasp of the requisite infrastructure necessary for the meticulous planning and execution of digital thread. The article presents a systematic literature review of the digital thread, in the form of a bibliometric analysis and a systematic content analysis, reviewed from a manufacturing product lifecycle perspective. Furthermore, as a result of the reviewed articles a framework for the digital thread within the product lifecycle is proposed.

The remainder of this paper is organized as follows. Section 2 presents the objectives of the current paper. Section 3 outlines the methodology followed for the literature review. Section 4 presents the Bibliometric Analysis results. Section 5 presents the Systematic Content Analysis results. Section 6 discusses the review results and introduces the proposed framework for the digital thread in the product lifecycle. Finally, Sect. 7 concludes the article.

Objective

This literature review aims to facilitate a comprehensive understanding of the prevailing research areas and trends associated with the digital thread in the manufacturing industry. Additionally, this review seeks to explore and elucidate the multifaceted aspects, encompassing definitions, technologies, functions, and roles of the digital thread from a product lifecycle perspective tailored to manufacturing operations. A pivotal goal of this work is to formulate and present a structured framework that offers industrial practitioners and researchers a standardized reference point for comprehending the intricacies of the product lifecycle digital thread. This framework not only serves to guide future research collaboration opportunities but also endeavors to establish a unified and standardized perspective on the digital thread for its effective implementation within an industrial context.

Methodology

A systematic review has been conducted to identify and critically analyze the relevant research articles, this methodology has been chosen to extract useful information from scientific databases and present them in a manner directly useful for researchers and practitioners. Systematic literature review has been a widely acceptable methodology for the methodical, transparent, and reproducible synthesis of research findings (Snyder, 2019). Accordingly, the methodology proposed by Tranfield et al. (2003) has been adopted within this article, which focuses on conducting reviews for evidence based management knowledge (Goltsos et al., 2019). This methodology outlines five steps for conducting the review, namely (i) identification of research; (ii) selection of studies; (iii) quality assessment; (iv) data extraction and monitoring progress; and (v) data synthesis. Figure 1 displays the workflow followed for the planning and development of the review.

Identification of research and selection of studies

A keyword search was conducted on Scopus and Web of Science (WOS) databases as they together cover a wide range of publications in the fields of engineering, science, and technology. In line with this study's focus, the following search string was used on both databases to extract all articles that mention the digital thread within manufacturing context. This search is updated to April 2023.

> TITLE-ABS-KEY ("digital thread*" AND ("manufacturing" OR "operation*" OR "production")).

A total of 334 articles were obtained from both databases, i.e. 227 from Scopus and 107 from WOS. The first exclusion criteria applied was the selection of articles written in the English language only to ensure ease of readability for all authors, which led to the exclusion of nine articles. The second exclusion criteria excluded all articles that were not journal articles or conference papers (such as review articles and book chapters) which led to the exclusion of 23 papers. After the removal of duplicate articles resulting from both databases, 196 research papers were ready for the quality assessment and data extraction phase.

Quality assessment and data extraction

The authors implemented the following exclusion criteria to rectify type II errors, i.e. articles that have been included in the sample papers that should have been excluded (Goltsos et al., 2019). This was done by reading the title, abstract, and keywords, as well as a scan of the contents of the articles.

- *Fourth* exclusion criteria: Articles that are not focused on manufacturing or production activities;
- *Fifth* exclusion criteria: Articles with no access rights for the authors to read;
- *Sixth* exclusion criteria: Review papers, posters, or white papers;
- *Seventh* exclusion criteria: Articles that mention the digital thread in the abstract and keywords only, and never in the main text.

The resulting 80 articles will be used for conducting the *Bibliometric analysis*. In order to synthesize the definitions, technologies, and role of the digital thread within the product lifecycle, a further exclusion criterion has been applied which resulted in 27 articles for the *Systematic content analysis*.

- *Eighth* exclusion criteria: Articles that did not provide a detailed discussion of the framework, architecture, or implementation of the digital thread within the methodology or discussion sections.

Data synthesis

As mentioned previously, two methodologies have been used for the review of the articles: a Bibliometric analysis and a Systematic content Analysis.

80 articles have been used for conducting a *Bibliometric analysis* to provide statistical analysis of literature articles and gauge the impact and advancement of a research area over time (Jamwal et al., 2022). Five types of analysis have been conducted: (i) Year-wise publication trends; (ii) Year-wise citation structure; (iii) Source structure analysis; (iv) Keywords and research areas analysis; and (v) Author analysis.

For the Year-wise publication trends, Year-wise citation structure, and Source structure analysis the Average Citation per Paper (ACP) has been calculated for each year to present a better understanding of the impact of the articles. The ACP presents the impacts of individual papers within each

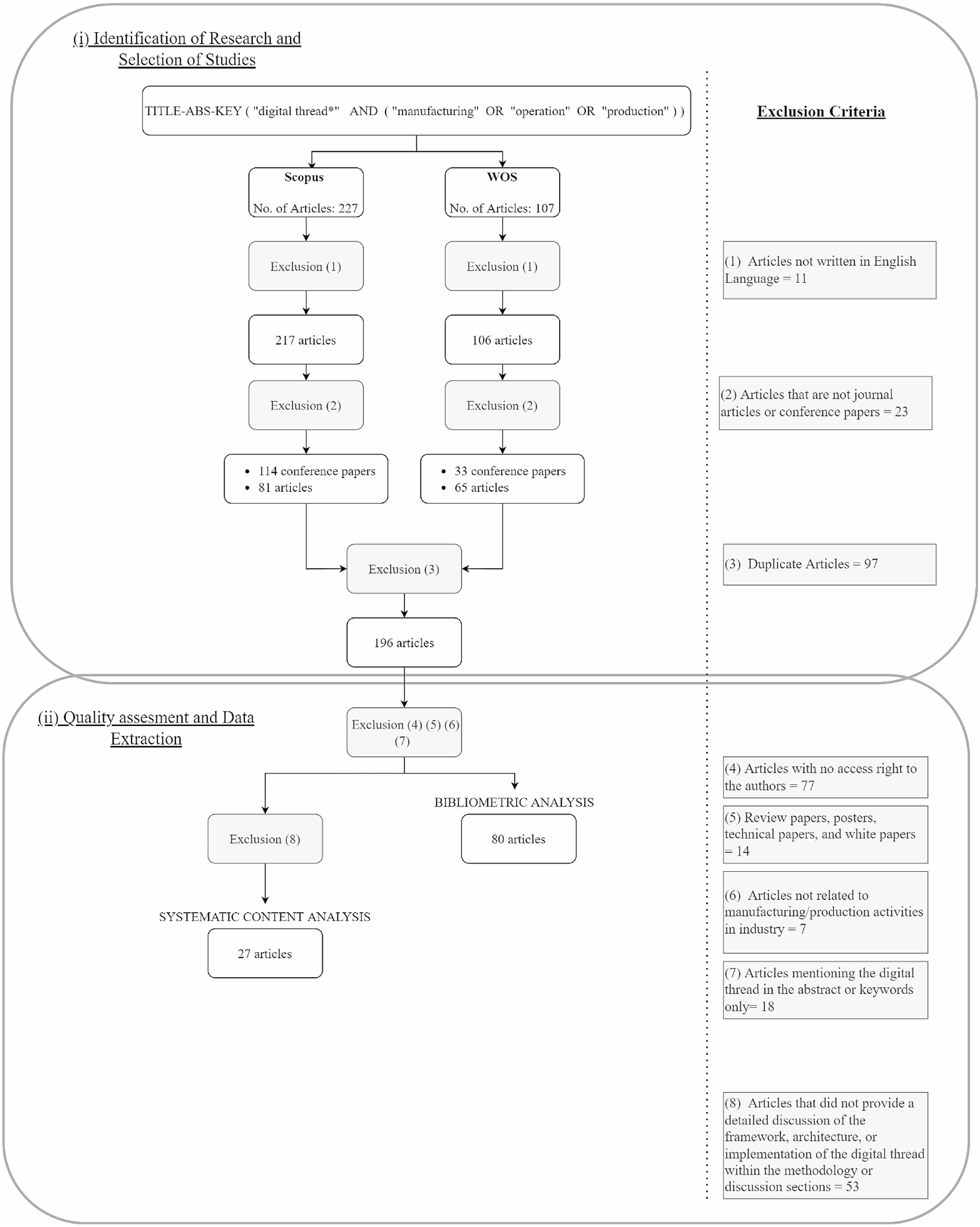


Fig. 1 Literature review methodology

year normalized and has been calculated using the following formula (Jamwal et al., 2022):

$$ACP = \frac{Total\, citations\, per\, year}{Total\, no.\, of\, published\, articles\, per\, year} \tag{1}$$

The open-source software VOSviewer has been used for the 'keywords and research areas' study, as well as the author study by performing a co-occurrence and co-authorship analysis respectively. Thesaurus files have been created for both the keyword analysis and the author analysis to avoid duplication of terms, such as 'IOT' and 'Internet of things'.

For the *Systematic Content Analysis*, the authors filtered further the articles to extract the papers that discussed in detail the design and implementation of the digital thread within the methodology or discussion section. This allowed the selection of papers that provide a clear understanding of the role and structure of the digital thread within their contributed work, and resulted in 27 papers with differing strengths to literature.

Bibliometric analysis

Publication trends

The Year-wise publication trends are displayed in Table 1. The first cited article providing a clear definition of the digital thread for manufacturing was in 2013 by Nassar and Reutzel (2013) for additive manufacturing. Throughout the next ten years, 80 articles focusing on digital threads have been published in total, with a gradual increase in the trend of published articles each year as seen in Fig. 2. A closer analysis of the type of papers published each year reveals an interesting trend in the number of conference papers versus the number of journal articles. A total of 24 conference papers and 56 journal articles have been published. As can be seen from Fig. 2 the increase in the number of published journal articles has a steeper rate of increase than the number of conference papers, indicating the high impact of digital thread research.

Citation structure

The structure of the citations of articles focusing on the use of the digital thread is presented from 2013 to 2023 in Table 1 for 80 articles. The table records the total number of citations for each year, where the highest number of citations can be seen in 2018 with 285 total citations, followed by 2020 with 280 total citations. However, the ACP has been calculated for each year to present a better understanding of the impact of the articles using Eq. (1) presented in Sect. 3.3.

Papers published in 2016 prove to be the most influential with an ACP of 69.3, which means on average the papers published in 2016 have been cited 69 times. Table 1 also shows that two (Hedberg et al., 2016; Steuben et al., 2016) out of the four published articles in 2016 have been cited equal to, or more than, 100 times. Following 2016, the papers published in 2013 and 2015 have the second highest ACP with one cited paper in 2013 and four cited papers in 2015.

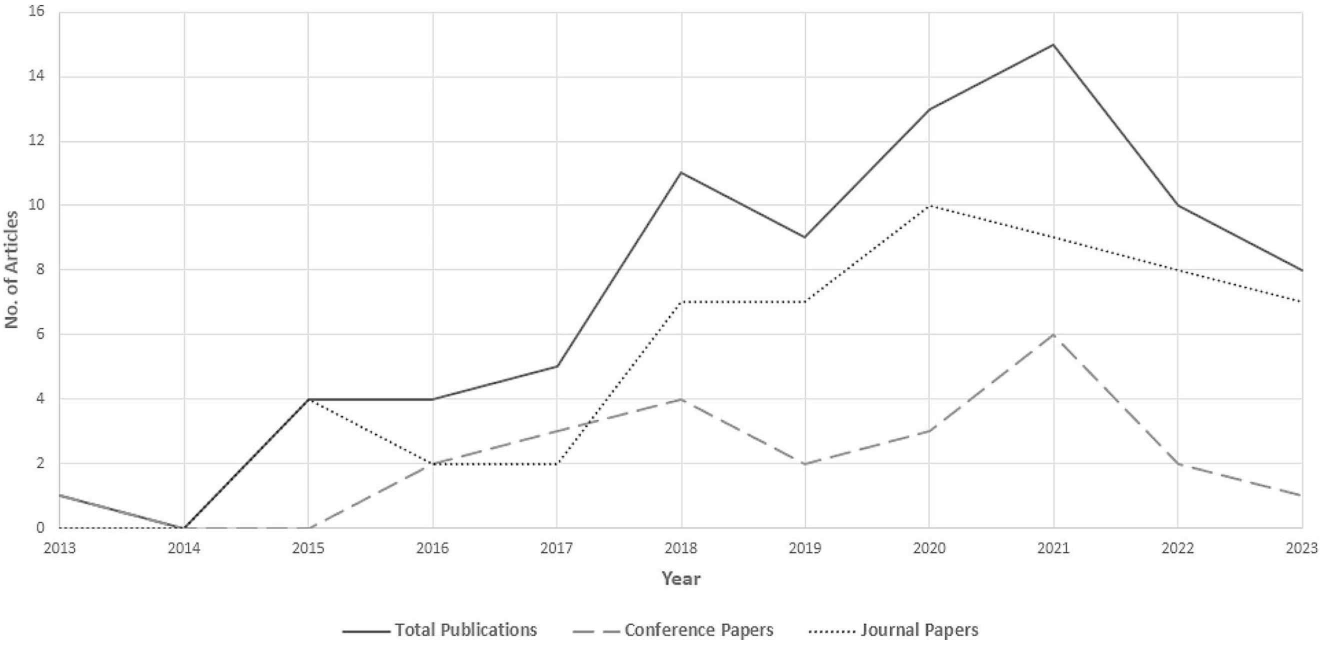


Fig. 2 Year-wise publication trend graph

Table 1 Year-wise publication and citation structure

Year	Year-wise Analysis of Publication Structure			Year-wise Analysis of Citation Structure						
	Total No. of publications	No. Of Conference papers	No. Of Journal papers	Total Citations	No. Of publications cited	ACP*	No. of publications cited at least N times			
							$N=100$	$N=50$	$N=25$	$N=1$
2013	1	1	0	46	1	46	0	0	1	0
2014	0	0	0	0	0	0				
2015	4	0	4	186	4	46.5	1	1	0	2
2016	4	2	2	277	4	69.25	2	0	0	2
2017	5	3	2	142	5	28.4	0	1	1	3
2018	11	4	7	285	11	25.9	0	1	4	6
2019	9	2	7	221	9	24.6	0	0	4	5
2020	13	3	10	280	13	21.5	0	2	3	8
2021	15	6	9	210	13	16.2	0	2	0	11
2022	10	2	8	51	8	6.4	0	0	0	8
2023	8	1	7	7	8	0.9	0	0	0	1

*Represents the number of times the paper has been cited on average

Table 2 Source structure

Source	No. of published articles	Subject Areas	Total Citations	ACP
Journals				
Journal of Manufacturing Systems	6	Computer Science; Engineering	125	24.80
Advanced Engineering Informatics	5	Computer Science	100	20
Journal of Computing and Information Science in Engineering	4	Computer science; Engineering	159	39.75
International Journal of Computer Integrated Manufacturing	3	Computer Science; Engineering	79	26.33
Applied Sciences (Switzerland)	2	Chemical Engineering; Computer Science; Engineering; Material Science; Physics and Astronomy	93	46.5
International Journal of Advanced Manufacturing Technology	2	Computer Science; Engineering	37	18.5
Journal of Mechanical Design	2	Computer Science; Engineering	25	12.5
Conferences	No. of published articles	Subject Areas	Total Citations	ACP
AIAA SciTech Forum	3	Aerospace	24	8
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	2	Computer Science; Engineering	65	32.5
Procedia CIRP	2	Production Engineering	9	4.5

Considering that no papers were published in 2014 directly addressing the use of digital thread, the articles published in 2013 and 2015 introduce the digital thread and provide the base upon which the scientific and empirical contributions are being built, hence their high influence. This is also due to the fact that research on digital threads has not been receiving a great deal of attention from scientific communities, where other buzzwords, such as ‘Digital Twin’, have been more active. Therefore, researchers rely on early scientific contributions to structure the understanding and guide the work related to digital thread.

Sources structure

56 sources have been identified for the 80 articles based on the data set. 20 are conference proceedings and 36 are journal articles. The leading journals are Journal of Manufacturing Systems with six published articles and Advanced Engineering Informatics with five published articles, followed by the Journal of Computing and Information Science in Engineering with four articles, International Journal of Computer Integrated Manufacturing with three articles, and two articles published in each of Applied Sciences (Switzerland), International Journal of Advanced Manufacturing Technology, and Journal of Mechanical Design. As can be seen from Table 2, articles published in Applied Sciences (Switzerland) has the highest ACP followed by Journal of Computing and Information Science in Engineering.

Research on digital thread has been mainly addressed from a computer science perspective as the integration of data and information from various sources (such as design software, production systems, testing and quality control tools, and maintenance and support systems) is necessary for the digital thread. Advanced technologies like IoT, cloud computing, big data analytics, and AI/ML are frequently needed for this integration. As a result, the development and implementation of the digital thread depends heavily on computer science and associated disciplines like software engineering and data science. However, in addition to mechanical engineering, materials science, industrial engineering, and business management, other academic disciplines may also be involved in the study and use of the digital thread.

Analysis of keywords and areas of research

A total of 160 keywords were obtained from the dataset and used to highlight research hotspots and trends within the digital thread related literature. A co-occurrence analysis was carried out and the results are displayed in Table 3 with the most used keywords and the number of their occurrences. 'Digital Thread' is the most used keyword with 38 occurrences, followed by 'Digital Twin' with 18 occurrences, 'additive manufacturing' and 'manufacturing' with eleven occurrences. They provide insight into the nature of use of digital thread in literature and the most common applications digital thread serves.

The keyword *'Digital Twin'* appeared first in 2019 within the found article set, and the articles within this category provide an idea on how the digital thread could be used to support the creation and implementation of different kinds of DT. Zhang and Zhu (2019) proposed a framework of DT driven product smart manufacturing system for manufacturing aero-engine blades, where the digital thread is responsible for remote control of the production flow and operation, as well as providing seamless integration of the DT throughout the whole lifecycle of the product. Cogswell et al. (2022) discussed the 'component DT', providing a clear use of the digital thread i.e. storing in a secured way the manufacturing and environmental history and managing the flow of material data between the physical and the virtual systems. While 'Digital Twin' as a keyword appeared first in 2019 within the current data set, the use of digital thread with DT has been first discussed in 2017 in two companion papers (Kobryn et al., 2017; Zweber et al., 2017) in the area of Digital Engineering. They provided a study on the use of various tools, including DT and digital thread, during the course of the various stages of a U.S. Department of Defense program's system development lifecycle.

Table 3 Author analysis

No. of articles published within the analyzed sample	Authors
4	bao, jingsong; hedberg, thomas
3	bonnard, renan; feng, shaw c.; monnier, Laetitia; singh, victor; willcox, karen e.; witherell, paul
2	adhikari, anku; alvares, alberto j.; bachelor, gray; barbau, raphael; barnard feeney, a.; bernstein, william z.; bi, fengyang; brecher, Christian; brusa, eugenio; chang, daofang; chen, chun-hsien; cheng, c.-t.; danjou, Christophe; deng, q.; eynard, benoit; ferretto, davide; fey, marcel; flügge, wilko; franke, m.; gao, yinping; hascoët, jean-yves; huang, ziqi; iliopoulos, athanasios p.; jagusch, Konrad; jericho, David; ke, yinglin; kim, duck bong; kobryn, p.; kolonay, r.; kwon, soonjo; lejardi, e.s.; li, shi; lim, h.; lipman, robert michopoulos, john g.; miletic, m.; mitschke, andreas; mognol, pascal; niu, xiaojing; pang, t.y.; pelaez restrepo, j.d.; qin, shengfeng; rial, r.m.; schleich, Benjamin; sender, jan steuben, john c.; thoben, k.-d.; tuegel, e.; wang, junliang; wang, qing; wang, shilong; winslett, Marianne; xu, chuqiao; xu, zhenyu; yang, bo; yasin, a.; yu, cijun; zhang, jie zhang, qiang; zheng, shouguo; zhong, ray; zweber, j.

'Additive manufacturing' was used as a keyword, within the analyzed data set, first in 2015 by Kim et al. (2015) who developed a workflow for information needs in order to speed up the AM information flow during product creation. In their work the digital thread has been defined as the 'information and information path' for a single part produced using AM, with a specific focus on the digital relationships present within the transformation of design-to-product stage. Bonnard et al. (2019) emphasized the need present within the manufacturing industry for a worldwide, consistent, and generic paradigm for managing digital thread data, as well as the importance of establishing a digital thread for successful AM projects. Hence, in order to develop a full and high-performance digital thread for AM, they presented a unified and generic Hierarchical Object Oriented Model (HOOM), which offers a general data structure. Similar to the case of the keyword 'Digital Twin', the keyword 'Additive manufacturing' appeared first in 2015, however, the first article discussing digital thread for AM was by Nassar and Reutzel (2013) which interestingly was also the first appearance of digital thread in literature.

The keyword *'Manufacturing'* with eleven occurrences comprises advanced manufacturing, cognitive manufacturing, computer integrated manufacturing, digital manufacturing, and hybrid manufacturing. While the previously presented articles discussed the digital thread as a part of, or serving, another technology, articles within these group discuss the digital thread as a main proposal or solution for manufacturing related applications. Adhikari et al. (2016) propose the digital thread-as-a-service that offers a logically consolidated point of reference for interpreting and evaluating a manufactured product's complete life history, from design to production, logistics, use, and maintenance. The digital thread-as-a-service supplier has been proposed to also offer analytics capabilities, account and key management tools, encryption services, metadata management tools, and guarantees against tampering. In an article by Yang et al. (2022) an approach for proactive and reactive service composition (PRSC) for cloud manufacturing is developed using digital thread. The main role of the digital thread, as presented by Yang et al. (2022) is to control and regulate the unpredictability and randomness of real-time information in cloud manufacturing to ensure stability and consistency of data structures and interaction mechanisms in various activities, phases, and organizations.

The relationships between the various keywords can be seen in Fig. 3. The figure shows the four research area clusters, notably: (i) Cluster 1 – Research area focusing on the use of digital threads for additive manufacturing and it includes the keywords 3d printing, additive manufacturing, cad/cam, and step nc; (ii) Cluster 2 – Research area focusing on the use of digital thread for DT applications, and it includes the keywords digital shadow, digital twin, smart manufacturing; (iii) Cluster 3 – Research area focusing on the use of digital threads for data modeling throughout the product lifecycle, and it includes the keywords big data, cyber-physical, data, data modeling, industry 4.0, internet of things, product lifecycle; (iv) Cluster 4 – Research area focusing on the use of digital thread for simulation and model based applications in the aerospace industry, and it includes the keywords aerospace/aircraft, design, manufacturing, model based, simulation, uncertainties.

Authors analysis

The author analysis provides insight into the influential authors in the field. By examining the publication history and citation impact of individual authors, key contributors to the field can be identified to gain a better understanding of the scientific landscape. 80 articles were used for the analysis which provided a total of 279 authors. The following authors were found to be the most influential: (i) Hedberg Thomas, from National Institute of Standards and Technology, Gaithersburg, United States. He has an h-index equal to 15 with four articles related to digital thread within the analyzed papers. (ii) Bao Jinsong, from Donghua University, Shanghai, China. He has an h-index equal to 3 with four articles published related to digital thread within the analyzed sample of papers. Table 4 shows the full list of authors with 2 or more papers within the analyzed 80 articles. Figure 4 shows the spread of the connections between authors, as a result of the co-authorship analysis performed. From the figure it is apparent that there is a lack of interactions and collaborations between the various research groups working on the digital thread.

Systematic content analysis

A total of 27 articles were reviewed systematically to analyze and report on the definitions given for the digital thread, the technologies employed, and the digital thread's role in the product lifecycle. The results of this analysis are presented in Table 5. The articles reviewed either proposed an architecture or framework for the digital thread (shown as 'Th' in the 'Implementation' column), implemented the digital thread in an industrial setting (shown as 'I' in the 'Implementation' column), or tested it in a laboratory or experimental setting (shown as 'Lab/E' in the 'Implementation' column). Additionally, Table 5 displays whether the reviewed articles are journal or conference articles (shown in the 'Type' column), the field of implementation of the

keyword	occurrences
digital thread	33
digital twin	18
additive manufacturing	11
manufacturing	11
internet of things	7
model based	6
data	5
design	5
industry 4.0	5
product lifecycle	5
smart manufacturing	5

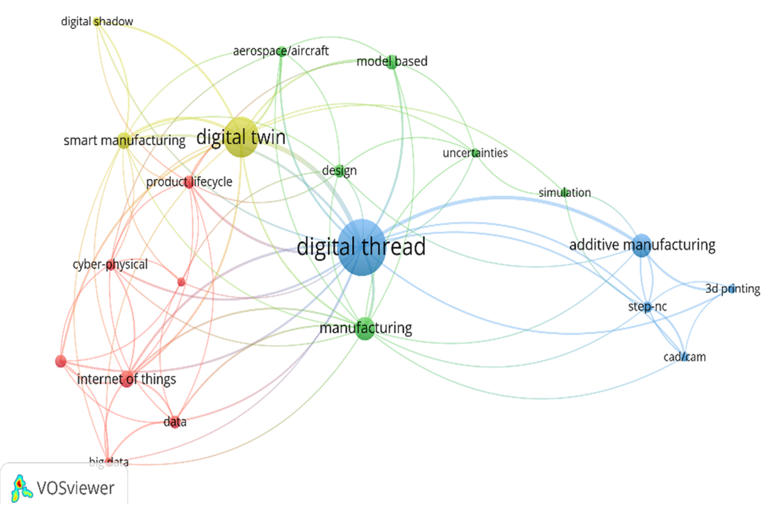


Fig. 3 Keywords relationships and cluster map

Table 4 Results of the systematic content review

Field	Article	Type	Implementation	Technologies			Lifecycle Phase		
				Data Types	Data Transfer / Storage	Data Mapping / Linking	BoL	MoL	EoL
Aeronautical /Aerospace	(Gharbi et al., 2017)	C	Th				x		
	(Kinard, 2018)	C	I	Design data; Engineering data;	N/A	Ad-hoc solutions	x		
	(Zhang & Zhu, 2019)	J	Lab/E	Process data; Quality data	PLM (Teamcenter software)	N/A	x		
	(Singh & Willcox, 2018).	C	Lab/E	Design data; Operation data; Production data	N/A	mathermatical model	x	x	
Aeronautical /Aerospace - DT support	(Zhang et al., 2022)	J	Lab/E	Product features; Process parameters; Equipment operation states.	MySQL	directed graphs	x		
AM	(Kim et al., 2017)	J	Th				x		
	(Nassar & Reutzel, 2013)	C	Th						
	(Bonnard et al., 2018)	J	Lab/E	Design data; Process data	N/A	SPAIM	x		
	(Bonnard et al., 2019)	J	Lab/E	Design data; Process data	N/A	SPAIM	x		
	(Bonham et al., 2020)	J	Lab/E	User data; Production data; Environmental data	PLM	Ad-hoc code (python)	x	x	
Manufacturing Process	(Helu et al., 2017)	J	I	Design data; Process data; Production data; Quality data	web interfaces; APIs	N/A	x		
	(Kwon et al., 2020)	J	Lab/E	Design data; Quality data	N/A	Ontologies (Protégé); KG	x		
	(Hedberg et al., 2020).	J	Lab/E	Design data, Process data; Quality data	Rest APIs; database (Neo4j)	Ad-hoc solution (Syndeia)	x		
	(Wang et al., 2020)	J	Lab/E	Production data; Process data	N/A	graph structure	x		
	(Pang et al., 2021).	J	Th				x	x	
	(David et al., 2021)	C	Lab/E	Process data; Design data	Rest API; web server; Siemens NXOpen API	ontology (Protégé)	x		
	(Singh & Willcox, 2021)	J	Th				x	x	
	(Cogswell et al., 2022)	J	Th				x	x	
	(Liu et al., 2023)	J	Lab/E	Process data; Quality data	platform	Ad-hoc code	x		
	(Paramatmuni & Cogswell, 2023)	J	Th						
	(Yang et al., 2022)	J	I	User data; Production data;	Cloud platform	Ad-hoc code		x	
	(David et al., 2023)	C	Lab/E	Design data; Process data	Siemens NXOpen API	N/A	x		

Table 4 (continued)

Field	Article	Type	Implementation	Technologies			Lifecycle Phase		
				Data Types	Data Transfer / Storage	Data Mapping / Linking	BoL	MoL	EoL
Manufacturing Process - CM	(Deng et al., 2021)	C	I	Circular protocols; Process data	web application	ontology			x
Manufacturing Process - DT support	(Gao et al., 2022)	J	Lab/E	Production data; Simulation data; Process data	N/A	ontology; KG		x	
	(Niu & Qin, 2021)	J	Lab/E	User data; Operation data; Service data; Simulation data	web based platform (Django); MangoDB; SQLite3	N/A		x	
	(Jiang et al., 2023)	J	Lab/E	Design data; User data; Production data	Cloud; API	N/A	x		
	(Huang et al., 2023)	J	I	Process data; Design data	N/A	Ad-hoc code	x		

Legend:

DT = Digital Twin; AM = Additive Manufacturing; CM = Circular Manufacturing

J = Journal paper; C = Conference paper

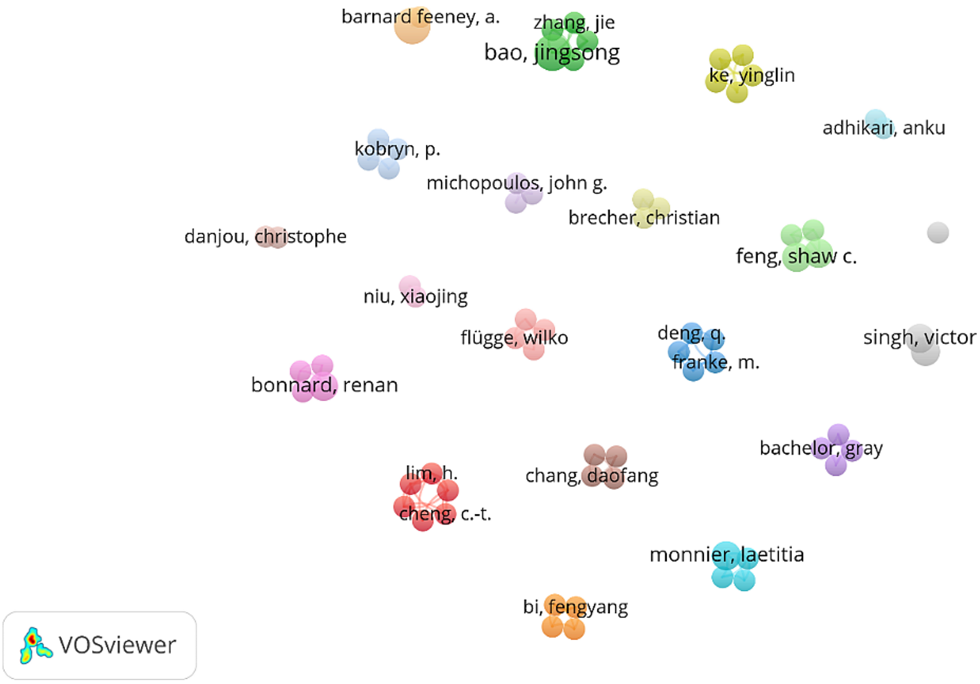
Th = Theoretical discussion; I = Industrial application; Lab/E = Lab or Experimental application

PLM = Product Lifecycle Management software; N/A = Not available or not specified by the authors

SPAIM = STEP-NC Platform for Advanced and Intelligent Manufacturing; KG = Knowledge Graphs

BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life

Fig. 4 Co-authorship graph



digital thread (shown in the 'Field' column), the technologies used (shown in the 'Technologies' column), and the lifecycle phase in which the digital thread was implemented, i.e within the Beginning of Life (BoL), Middle of Life (MoL), or End of Life (EoL) (shown in the 'Lifecycle Phase' column). These articles provide a strong foundation for understanding the research efforts and use of digital thread in manufacturing.

The articles in this table are grouped by the field of study of the digital thread, as its application and focus can vary

Table 5 Digital thread definitions from literature

Reference	Digital Thread Definition	Definition Terminology	Scope	Purpose
(Helu et al., 2017)	The digital thread links disparate systems across the product lifecycle and throughout the supply chain. It enables the collection, transmission, and sharing of data and information between systems across the product lifecycle quickly, reliably, and safely. [referencing: (Hedberg et al., 2017)]	-	Product lifecycle	Collection; transmission; and sharing of data and information
(Singh & Willcox, 2018)	Digital Thread introduces the idea of linking information generated from all stages of the product lifecycle (e.g., early concept, design, manufacturing, operation, post-life, and retirement) through a data-driven architecture of shared resources (e.g., sensor output, computational tools, methods, and processes) for realtime and long-term decision making.	Data driven architecture	Product lifecycle	linking information
(Kinard, 2018)	[.] defines it as the creation, use, and reuse of the 3-D models by engineering and downstream functions, including manufacturing and sustainment.	-	-	creation, use, and reuse of the 3-D models
(Bonnard et al., 2018)	a set of interconnected manufacturing process, end to end: from scan or design to analysis and simulation, through build planning and fabrication, to end use of the part, all connected in a series of feedback and feed-forward loops[referencing: (Kim et al., 2015)]	Interconnected processes	Manufacturing process	-
(Zhang & Zhu, 2019)	It is build based on modeling and simulation tools. And it is also data flow and information flow throughout the product life cycle, from product design, process, manufacturing to utilization, and maintenance. [referencing: (Kraft, 2016)]	Modelling and simulation tools; data and information flow	Product Lifecycle	-
(Kwon et al., 2020)	The digital thread can be defined as the ensemble of data that enables the combination of MBD, manufacturing, and inspection. [referencing: (Hedberg et al., 2016, 2017)]	Data	Design and Manufacturing	Linking of MBD, manufacturing, and inspection.
(Hedberg et al., 2020)	The digital thread is an integrated information flow that connects all the phases of the product lifecycle using accepted authoritative data sources (e.g., requirements, system architecture, technical data package (TDP), three-dimension (3D) CAD models). [referencing: (Hedberg et al., 2016; Kraft, 2016; Wardhani & Xu, 2016)]	Integrated information flow	Product Lifecycle	Linking of data
(Bonham et al., 2020)	Digital thread refers to the communication framework that allows a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed perspectives from each party or stakeholder. This thread also is a prerequisite to trace back the settings and conditions used throughout the design and build phase.[referencing: (Kim et al., 2015)]	Communication Framework	Product Lifecycle	Linking of data; Provides integrate view of data to all stakeholders
(Niu & Qin, 2021)	Digital thread can create access channels to diverse but interrelated data sets so that the upstream and downstream is consistent and available to all users involved in a product lifecycle. It can maintain data associativity and traceability in a smart manufacturing process.	-	Product Lifecycle	Linking of data; Provides integrate view of data to all stakeholders
(Deng et al., 2021)	Used same definition as Hedberg et al. (2020)	Integrated information flow	Product Lifecycle	Linking of data
(David et al., 2021)	The digital thread, in essence, is a framework that helps integrate product lifecycle data to streamline processes along all lifecycle stages.	Framework	Product Lifecycle	Linking of data
(Yang et al., 2022)	A digital thread is a data-driven architecture that links together information generated across the product lifecycle to support real-time analysis and dynamic decision-making. It allows data from all involved and distributed manufacturing systems in the thread to be captured, stored, transferred and shared for real-time and long-term decision-making. [referencing: (Bachelor et al., 2020; Hedberg et al., 2017; Singh & Willcox, 2018)]	Architecture	Product Lifecycle	Linking; collecting; storing; transfering of data
(Zhang et al., 2022)	Digital threads are designed to establish a technical process through advanced modeling and simulation tools, providing the ability to access and analyze data at all stages of the system life cycle.	-	Product Lifecycle	Provides integrate view of data to all stakeholders

Table 5 (continued)

Reference	Digital Thread Definition	Definition Terminology	Scope	Purpose
(Gao et al., 2022)	The digital thread is the core technology to process data from different sources and complete the transmission and flow, aiming at realizing the connection and interaction among modules in the digital twin-enabled scheduling framework.	Technology	Digital Twin	Collect data from different sources; Transmission of data
(Liu et al., 2023)	Manufacturing digital thread takes a model-based approach to describe both each step as well as the connectivity and interoperability of manufacturing processes, both digital and physical	-	Manufacturing Process	Linking; interoperability
(Jiang et al., 2023)	Digital thread is a scalable, configurable, and componentized communication framework in enterprise level, covering all aspects of digit twin system. Possessing integrated views across different levels, multiple scales, and multi-view models, digital thread drives the survival activities of DT systematically with a unified model, thereby providing decision makers with support.	Communication Framework	Digital Twin	Provides integrate view of data to all stakeholders
(Huang et al., 2023)	The digital thread is another key enabler for modeling the DTs of manufacturing processes, since it links disparate systems product lifecycle and enables the connection, unification, and orchestration of heterogeneous data throughout the entire manufacturing process [referencing: (Helu et al., 2018)].	-	Digital Twin	Linking of data; Provides integrate view of data to all stakeholders

depending on the context. Some papers focused on the digital thread in the Aeronautical and Aerospace field, where it is seen as a seamless flow of digital information across various stages of an aircraft's lifecycle, from design and manufacturing to maintenance, operation, and retirement. Specifically, they looked at the digital thread for aircraft and aerospace equipment manufacturing (Gharbi et al., 2017; Kinard, 2018; Singh & Willcox, 2018; Zhang & Zhu, 2019). In the context of AM, the digital thread is studied as a seamless integration of digital information and data throughout the entire AM process, including design, simulation, material selection, printing, post-processing, inspection, and validation. The AM-related articles focused on the file formats used for creating the digital thread and explored how standard and machine-independent formats can be utilized (Bonham et al., 2020; Bonnard et al., 2018, 2019; Kim et al., 2017; Nassar & Reutzel, 2013). Other articles examined the digital thread from a manufacturing process perspective without focusing on a specific industry (Cogswell et al., 2022; Pang et al., 2021; Paramatmuni & Cogswell, 2023; Singh & Willcox, 2021), but instead applied the digital thread in a specific use case (David et al., 2021, 2023; Hedberg et al., 2020; Helu et al., 2017; Kwon et al., 2020; Liu et al., 2023; Wang et al., 2020; Yang et al., 2022). The digital thread as a support tool for DT has been studied in several articles within the manufacturing process (Gao et al., 2022; Huang et al., 2023; Jiang et al., 2023; Niu & Qin, 2021) and aeronautical / aerospace applications (Zhang et al., 2022). One article studied the use of digital threads for circular manufacturing (CM) implementation within the manufacturing process applications (Deng et al., 2021).

The following subsections present a deeper analysis into the available definitions of the digital thread, the implemented technologies, and the role within the product lifecycle. To obtain a comprehensive understanding of the technologies and definition of the digital thread, a thorough review of articles that have successfully implemented it (identified by 'I' and 'Lab/E') was conducted in Sect. 5.1 and 5.2. These articles offer valuable insights on the digital thread implemented for the specific use case. On the other hand, all articles were considered for Sect. 5.3, which discusses the roles of the digital thread in the product lifecycle.

Definition of digital thread

As research about the digital thread within manufacturing has been evolving, so have the definitions given by the various authors. Presented in Table 5 are these definitions, systematically arranged based on the respective years of publication. An examination of these definitions has been conducted with the aim of achieving a standardized comprehension of the digital thread concept. This analysis is undertaken through three key dimensions: 'Definition Terminology,' which elucidates the linguistic aspects of the definitions; the 'Scope' of the digital thread, which expands on its intended application scope; and the 'Purpose' underlying the adoption and application of the digital thread concept.

Starting with the terminologies used to describe the digital thread, there are significant variances in how people address it, as can be seen from the 'Definition Terminology' column. The different terminologies used to describe the digital thread are:

- *Technology*: Gao et al. (2022) defines the digital thread as the core technology for enabling DTs;

- *Interconnected Processes*: Bonnard et al. (2018) refers to the interconnected process of AM as the digital thread;
- *Modelling and Simulation tools*: Zhang and Zhu (2019) describe the digital thread to be made up of modelling and simulation tools;
- *A Framework / An Architecture*: Other authors view the digital thread from a wider lens and define it as a framework (Bonham et al., 2020; David et al., 2021; Jiang et al., 2023) or an architecture (Yang et al., 2022) that is data-driven and connects systems that are otherwise in silos;
- *Data and Integrated Information*: A few authors referred to it as the data (Kwon et al., 2020) or the integrated information flow (Deng et al., 2021; Hedberg et al., 2020; Zhang & Zhu, 2019) that is collected and stored when a single part or product is manufactured.

These terminological variations cause difficulties when addressing practical implementations of the digital thread and determining what can, and cannot, be termed a digital thread. While the terminologies used to describe the digital thread varies, there is a consensus on the scope of application and purpose of the digital thread within the analyzed definitions. The majority of the articles define the digital thread within the scope of the product lifecycle, i.e. it accompanies the product, process, or asset along its full lifecycle (BoL, MoL, and EoL) (Bonham et al., 2020; David et al., 2021; Deng et al., 2021; Hedberg et al., 2020; Helu et al., 2017; Niu & Qin, 2021; Yang et al., 2022; Zhang & Zhu, 2019). A few articled centered their definitions around the manufacturing process (Bonnard et al., 2018; Kwon et al., 2020) and DT (Gao et al., 2022; Huang et al., 2023; Jiang et al., 2023). Within the manufacturing process the digital thread has been defined as connecting the various manufacturing processes such as design, product, and inspection, while the definitions centered around the DT describe the digital thread as a main enabler to the DT. These scopes of the definitions are not contradictory. In fact, a product lifecycle scope seems to be the most comprehensive, as theoretically a digital thread addressing the whole product lifecycle would include the manufacturing process data and can be used an a main enabler to DTs.

The purposes of the digital thread, detailed in the ‘Purpose’ column, can be summarized as:

- Linking of data and information to provide an integrate view to all stakeholder (Bonham et al., 2020; David et al., 2021; Deng et al., 2021; Hedberg et al., 2020; Huang et al., 2023; Jiang et al., 2023; Kwon et al., 2020; Niu & Qin, 2021; Yang et al., 2022; Zhang et al., 2022).
- Collection and Storage of data and information to allow sharing and transmission (Gao et al., 2022; Helu et al., 2017; Yang et al., 2022).

Technologies and supporting infrastructure for digital thread

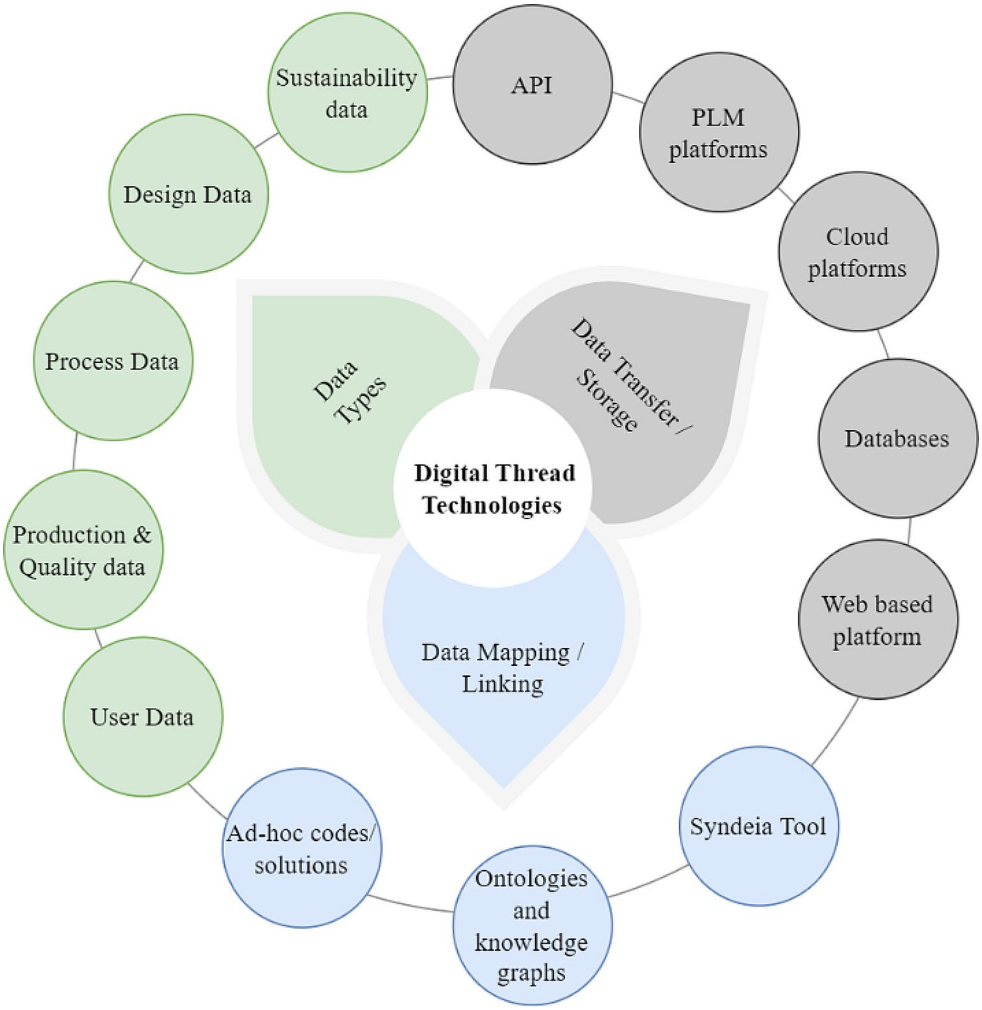
The ‘Technologies’ column in Table 5 lists the various technologies employed. As inferred from Sect. 5.1, the digital thread is primarily utilized for two main purposes: linking data to create a comprehensive information model, and collecting, storing, and sharing data with multiple stakeholders. Accordingly, the technologies employed to implement the digital thread have been classified under three categories: data types, data storage/transfer, and data mapping technologies. This review reports on 20 articles that have implemented the digital thread in either an industrial or laboratory setting. Section 5.2.1, 5.2.2, and 5.2.3 below outline the technologies used in detail. Figure 5 presents a summary of the reviewed technologies.

Data types

The data types column encompasses a spectrum of distinct data types, each bearing unique attributes and relevance within the digital thread framework. Within the digital thread literature, authors focused more on highlighting the types of data encapsulated within the digital thread, rather than the technologies used for gathering the data. The predominant focus of the examined articles pertains to the exploration of the digital thread within the context of BoL. Consequently, it is noteworthy that certain data types are the most frequently encapsulated data types within the digital thread implementations of the extant literature. Notably:

- *Design data*: Design data refers to the design models of the product produced by designers and engineers within the design stage. (Bonnard et al., 2018, 2019; David et al., 2021, 2023; Hedberg et al., 2020; Helu et al., 2017; Huang et al., 2023; Jiang et al., 2023; Kinard, 2018; Kwon et al., 2020; Singh & Willcox, 2018)
- *Process data*: Process data refers to the data about the flow of the manufacturing process such as the process model and work instructions (Bonnard et al., 2018, 2019; David et al., 2021, 2023; Gao et al., 2022; Hedberg et al., 2020; Helu et al., 2018; Huang et al., 2023; Liu et al., 2023; Wang et al., 2020; Zhang et al., 2022; Zhang & Zhu, 2019).
- *Production data*: Production data encompasses information pertaining to the manufacturing processes themselves. This includes data related to the production line’s

Fig. 5 Digital thread technologies



efficiency, output rates, downtime, resource utilization, and any variables directly impacting the manufacturing process. These data mostly gathered using sensors and IOT devices. (Bonham et al., 2020; Gao et al., 2022; Helu et al., 2017; Jiang et al., 2023; Singh & Willcox, 2018; Wang et al., 2020; Yang et al., 2022),

- *Quality data*: Quality data refers to the evaluation and assessment of product quality at different stages of production and includes data about quality metrics and inspection results (Hedberg et al., 2020; Helu et al., 2017; Kwon et al., 2020; Liu et al., 2023; Zhang & Zhu, 2019),

Articles addressing the MoL phase have utilized user data gathered through web applications. User data involves information associated with user interactions and preferences, often relevant in consumer-oriented products, facilitating product customization (Bonham et al., 2020; Jiang et al., 2023; Niu & Qin, 2021; Yang et al., 2022). Simulation data has been used by authors who have utilized the digital thread for the connection between different DT models or between the connection between the physical and the virtual space of DTs (Gao et al., 2022; Niu & Qin, 2021). Furthermore, data related to sustainability such as Environmental data about the CO2 production levels of certain design choices (Bonham et al., 2020) and Circularity protocols data (Deng et al., 2021) have also been used.

Data transfer / storage technologies

Data sharing involves the exchange of data between different departments, participants, and systems along the product lifecycle to break down information silos and allow for more informed decision-making. It involves allowing accessibility of data from various systems to different stakeholders, as well as providing data storage. For implementing digital threads authors have used a variety of data transfer and storage technologies. Within the context of the BoL, i.e. product development and manufacturing, product lifecycle management (PLM) software has been used to maintain the digital thread by providing a centralized platform for managing and integrating product-related information, processes, and collaboration across various departments and stages of the product lifecycle (Bonham et al., 2020; Zhang & Zhu, 2019). Specifically, Teamcenter software of Siemens was used by Zhang and Zhu (2019) as a part of the digital thread in order to transfer design models to the engineering team for manufacturing process sequencing, and has been described as a cutting-edge, a collaborating, and a flexible solution for product life cycle management (PLM) that uses a digital thread to innovate industrial processes. Cloud platforms have been used as data storage solutions as well as for the deployment of data and information models that make up the digital thread (Jiang et al., 2023; Yang et al., 2022). Data management and database solutions used within the analyzed articles are MangoDB (Niu & Qin, 2021), SQLite (Niu & Qin, 2021), Neo4j (Hedberg et al., 2020), and MySQL (Zhang et al., 2022). The use of ad-hoc web-based platforms has been demonstrated in enabling the digital thread in various articles where stakeholders outside of the boundaries of the company are involved in the digital thread, such as in the MoL and EoL stage. They act as a centralized and easily accessible space for stakeholders across different locations to collaborate on product development and operations. They have been used to implement the digital thread for two applications:

1. To provide a collaborative environment for stakeholders in managing the flow of digital information throughout the product lifecycle (Deng et al., 2021; Niu & Qin, 2021). Niu and Qin (2021) used a web-based platform to create a personalized profile for each client to be able to request specific maintenance tasks and connect the request with crowdsourced service providers. Deng et al. (2021) used web-based applications to create a 'digital thread design tool' that provides a model editor as a service in manufacturing companies to allow the stepwise application and realization of activities that could be used for extending the useful life of capital items. Django, which is an open-source Python-based framework, was used by Niu and Qin (2021) for the implementation of the web platform.
2. Providing accessibility to the data from the data repositories (David et al., 2021, 2023; Hedberg et al., 2020; Helu et al., 2018) using Application Programming Interface (API) such as REST APIs (Hedberg et al., 2020) and NXOpen API (David et al., 2023).

Data mapping / linking technologies

Data linking entails finding references to the same real-world entities across many data sources and connecting them. Data mapping, on the other hand, concentrates on describing how data elements in various sources match and may be altered or merged. Both concepts play important roles in the digital thread and are used to translate system definition models that exchange descriptive data, interconnected analytical models that share performance and property data about the system (Stevens, 2020), and create a uniform product model for storing data to ensure consistency (Jagusch et al., 2021). The technologies used for data mapping and linking within the analyzed articles are a mixture of ad-hoc codes, ad-hoc solutions, and mapping/linking tools. The use of ad-hoc codes utilizing diverse coding languages has been demonstrated for data mapping and linking (Bonham et al., 2020; Huang et al., 2023; Liu et al., 2023; Yang et al., 2022). Bonham et al. (2020) used a python-based code to connect user requirements and automatically update a CAD file for customized manufacturing using AM, while semantic networks and tree structures have also been used by other authors (Huang et al., 2023; Liu et al., 2023). Ad-hoc solutions developed specifically for the intended use case include a mathematical model developed by Singh and Willcox (2018) that addresses product design by connecting data and information from manufacturing, design, product conditions, and operating specifications for each product to be used back for the design of future product lifecycles. While, for AM applications, the STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) has been used, which is a STEP-NC manufacturing platform provided by the Ecole Centrale de Nantes/France, and has been used for the implementation and validation of the AM STEP-NC data model (Bonnard et al., 2018, 2019). Hedberg et al. (2020) demonstrated the use of 'Syndeia tool' for digital thread implementation. Syndeia has been described as a platform for model-based engineering on digital threads that federates models and data from many ecosystems of modeling and simulation tools, enterprise applications, and data repositories (https://intercax.com/products/syndeia/).

Moreover, approaches in information representation and knowledge management have been used to model relationships in the manufacturing process and related product data, such as directed graphs (Zhang et al., 2022), knowledge graphs (Gao et al., 2022; Kwon et al., 2020), and ontologies (David et al., 2021; Deng et al., 2021; Gao et al., 2022; Kwon et al., 2020). Protégé has been used for creating and representing the ontology models (David et al., 2021; Kwon et al., 2020).

Supporting infrastructure

Ensuring interoperability, traceability, and secure stakeholder collaboration as functions of the digital thread is vital (Cogswell et al., 2022; Hedberg et al., 2020; Huang et al., 2023). Accordingly, the successful implementation of the digital thread goes beyond just technology; it involves several supporting infrastructures made up of architectures, standards, business practices, and tools. This section demonstrates the needed infrastructure discussed in the analyzed articles that supported digital thread implementations.

Interoperability is the capability of integration and communication of smart manufacturing parts and services both inside and outside the manufacturing facility using a smooth exchange of information with syntax and semantics that are comprehensible by all of the disparate systems involved (Zeid et al., 2019). Interoperability in smart manufacturing can be represented as horizontal and vertical integration. Horizontal integration is the interoperability of products or services operating in the same level of the value chain, such as smart automation devices, cloud services, cloud platforms, and businesses (Zeid et al., 2019), while vertical integration is interoperability between different levels of the value chain such as between production software, shop-floor departments, tasks carried out by various pieces of equipment, various shop-floor systems, to name a few (Bourreau & Kraemer, 2022; Zeid et al., 2019). When enterprise-wide interoperability is successfully implemented, manufacturing activities become more effective and seamless, cutting costs while boosting productivity and product quality (Zeid et al., 2019). An example of how interoperability has been supported by the digital thread is demonstrated by Wang et al. (2020). The authors developed an architecture where the digital thread is a main component of the Platform-as-a-service (PaaS) layer and is responsible for connecting all resource units and their data from various sources. This creates standardization of the metadata from industrial tools, hence providing interoperability between industrial applications. Due to the importance of interoperability in smart manufacturing, the digital thread needs to be designed using methodologies and tools that permit seamless integration and communication across many systems and processes, regardless of their source or what technological platform is used. Different components of the digital thread are required to operate as one entity enabling the exchange and access of data across different systems. From the analyzed articles, the following are the tools authors used to enable interoperability within digital threads:

- *Microservices*: Microservices are the service-oriented architecture's second generation. By breaking down complex systems into independent services with a specialized skillset, a strong emphasis is placed on the creation of software that is maintainable and scalable (Wunck, 2019). The transformation of legacy IT systems for industrial operations to a microservice architecture is an essential stage for platform-based manufacturing which offers many advantages for smart manufacturing, and specifically for Small and Medium Size Enterprises (SMEs) (Wunck, 2019). Accordingly, Wang et al. (2020) proposed the disassembling of a monolithic application into micro-services as the main enabler for the interoperability of different modules of enterprise information systems. By encapsulating many communication protocols into proxy microservice components, the microservice design promotes interoperability. This paves the way for open and dynamic ecosystems by making it simple to change or add new system components (Vresk & Čavrak, 2016). The digital thread provides a strong base foundation for microservices by the connection and standardization of the metadata provided through the industrial IT systems.
- *Manufacturing Data Standards*: International manufacturing standards have been used by authors to represent lifecycle data and build a unified knowledge base. Kwon et al. (2020) used a number of standards such as G-code, STEP AP242, QIF, and MTConnect to build a digital thread that combines as-designed and as-inspected data. MTConnect and QIF were also used to combine the machine data and quality data by Hedberg et al. (2020) using a graph-based approach to create a digital thread that links and traces data throughout the product lifecycle.

Traceability in manufacturing is a wide term that refers to the method of identifying an object or work item and retrieving any data, or information, about it at any point in its lifecycle. This means that at any given point in time, it is possible to identify the source of a particular piece of data, as well as any transformations or manipulations that it has undergone. Digital threads capture and integrate data from various systems with different sources and allow visibility to different stakeholders throughout the value chain, hence traceability allows for complete visibility and accountability throughout the entire lifecycle of a product or process. Within AM applications traceability has been a focal reason for developing digital threads, where Bonham et al. (2020) highlighted that the involvement of multiple stakeholders in the AM process renders traceability and data accessibility a decisive function, as eventually an error in the product development will occur and traceability will allow the isolation and tracking of the source of this error. Moreover, the importance of traceability within the manufacturing process has been recognized by Hedberg et al. (2020) who argue that high-quality manufacturing is made possible by seamless traceability across the product lifecycle, which also promotes trusted enterprise knowledge reuse, and accordingly developed a 'standards-based, linked-data approach' for the digital thread.

To enable the traceability of data within the digital thread authors used the following tools:

- *Unique identifiers*: Assigning a unique numeric or alphanumeric string to entities allows for the identification and traceability of the data relating to a product/process within the digital thread (Bonham et al., 2020; Cogswell et al., 2022; Hedberg et al., 2020; Huang et al., 2023; Niu & Qin, 2021).
- *Knowledge Management System*: Knowledge management may be described as the set of actions that enable businesses to create, store, distribute, and use knowledge (Gunasekaran & Ngai, 2007). The foundation for quick problem traceability is the establishment of an expert system and knowledge database (Zhang et al., 2022). A knowledge management system assists manufacturing companies in effectively managing and utilizing their knowledge assets. It makes it simpler to obtain the information needed, whenever it is needed, by centralizing and standardizing information.

Product and process data is often generated or used by multiple stakeholders along the product lifecycle to produce knowledge or drive decisions. Identifying the stakeholders involved along the created digital thread is important, particularly considering the sensitivity and willingness of stakeholders to share certain kinds of data or information. This is especially prevalent in activities related to sustainability within the manufacturing operations or circular manufacturing activities where strong collaborations and data sharing are important between different organizations outside the boundaries of the manufacturing company, as well as outside the boundaries of the country of operations in certain cases. A number of authors discussed the importance of stakeholder involvement within the digital thread, starting with AM applications where new stakeholders are constantly being involved in the AM digital flow, and collaboration between stakeholders of different phases of the AM process is needed. Accordingly, Bonham et al. (2020) demonstrated the use of a single collaborative Product Lifecycle Management (PLM) platform for facilitating collaboration activities and separating the data processing from the information stored in the PLM. Within Circular Economy strategies Deng et al. (2021) argued that they involve various systems and stakeholders that influence greatly the lifecycle of the product. The authors addressed the needed cross-collaboration by creating a digital thread that will allow transparent information flow in order to have a holistic view of life extension activities and decisions, for all stakeholders. Additionally, within maintenance applications Niu and Qin (2021) demonstrated the use of a web-based user interface and PLM to enable manufacturing servitization and crowdsourcing of service providers based on the customer's requests. Due to the increased connectivity and integration that the digital thread provides to manufacturing data, security is a predominant concern. The high volume of sensitive data being stored and transmitted through digital threads can create vulnerabilities that increase the risk of cyber-attacks and malicious activities. Moreover, the involvement of several stakeholders in the management and use of the digital thread necessitates the need for specialized access rights, hence companies will need to go beyond traditional security measures and redefine the way they approach security. Bonham et al. (2020) addressed access restrictions for different users so that each stakeholder may take the authorized information, process it using its own specific programs, and enter it into the PLM database. As parties involved in downstream processes cannot alter the data generated upstream, this guarantees the use of the most recent data at each stage of the physical process. Niu and Qin (2021) integrated blockchain technology into their developed platform to ensure system security, transparency, and sustainability. Integrating security measures in digital thread needs a multi-faceted outlook with both organizational and technical approaches. The following are key supporting infrastructure presented in the analyzed literature for addressing security in digital thread:

- Training of employees/stakeholders on security best practices for IT safety and crime to ensure that all involved stakeholders with access to the data on the digital thread understand the security risks involved and take the needed precautions.
- Policies for maintaining security: Determining the appropriate user access and developing the user's identity and access management protocol (IAM) is crucial for environments with multi-stakeholder access like digital thread (Bonham et al., 2020).
- Technology to enable security control and access rights to allow the stakeholders to access only the data they are allowed to access and edit, such as blockchain (Kinard, 2018; Niu & Qin, 2021).

The roles of digital thread in product lifecycle

To understand the roles of the digital thread in improving business operations, the articles have been analyzed from a lifecycle perspective. In manufacturing companies, the stages the product passes through from its conception to its end of use are generally referred to as 'lifecycle'. The processes in the product lifecycle can be distinguished by three main phases (Kiritsis et al., 2003), namely BoL, MoL, and EoL. Within this article, manufacturing assets have been considered as large-scale products hence addressing the asset lifecycle and product lifecycle interchangeably (Roda & Macchi, 2018). The 27 articles have been mapped according to which lifecycle phase they address, as displayed in Table 5, and an in-depth discussion of the roles of the digital thread in each of the lifecycle phases is provided below. Figure 6 shows the results of the synthesized roles and a summary of the roles of the digital thread in the product lifecycle.

Roles of digital thread in BoL

The BoL is the phase where the digital thread has been receiving most of the attention in the literature. The BoL encompasses manufacturing and design, where design is a multilayered step that includes the design of products, processes, and plants, while manufacturing is the process of creating products and the associated internal plant logistics (Terzi et al., 2010). The following are the roles of the digital thread in the BoL phase:

- *Improved product design*: The digital thread acts as a collaborative framework for the design process that enables practitioners to use previous lifecycle data about the behavior of the material/components from the service/use stage to guide future designs (Cogswell et al., 2022; Gharbi et al., 2017; Paramatmuni & Cogswell, 2023; Singh & Willcox, 2018, 2021). This allows for improving the design of the product by allowing informed decision-making based on the behavior and use of the product.
- *Traceability of failures*: Tracing the drivers of component failures to the materials by creating serial numbered digital threads for each component, leading to better decisions on the choice of materials in the design stage (Cogswell et al., 2022).
- *Traceability of information during the AM process*: The digital thread is an information systems architecture for AM that allows all stakeholders to access, view, and edit the data using standard file formats that are technology-independent (Bonham et al., 2020; Kim et al., 2015).
- *Improved process planning by linking of the process data to quality data*: In manufacturing process management, the digital thread can be used to link the product lifecycle information with the product quality data for better decision-making and process planning of the manufacturing activities in real-time (Jagusch et al., 2021; Kwon et al., 2020; Liu et al., 2023; Zhang et al., 2022).
- *Provide an interlinked data pipeline for AI* (Huang et al., 2023).

Roles of digital thread in MoL

MoL comprises external logistics, use, and maintenance (Terzi et al., 2010). In the MoL the product ownership lies in the hands of the customer. The following are the roles of the digital thread in the MoL phase:

- *Provides an integrated view of the operational data to all stakeholders*: The digital thread allows monitoring and inspecting the component while it is in production and operation to determine the operational status both for customers and manufacturers (Pang et al., 2021).

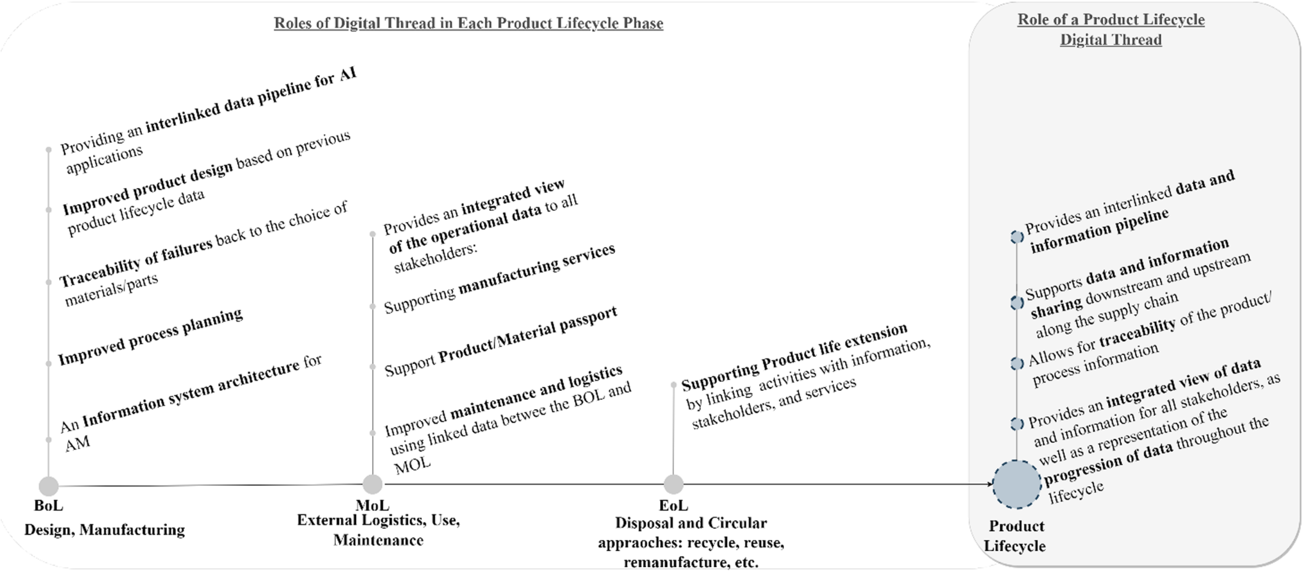


Fig. 6 Roles of digital thread in the product lifecycle

- *Supporting manufacturing services*: The digital thread provides connection between customer-generated data or requests with service providers in real-time for platform-based business solutions (Niu & Qin, 2021) and cloud manufacturing services (Yang et al., 2022).
- *Product/Material passport*: The digital thread could be used to create and keep track of the product/material passport to trace product information during maintenance and use (Cogswell et al., 2022).
- *Improved maintenance and logistics*: Connecting BoL with MoL data for better decision-making in maintenance and logistics processes based on design data and manufacturing process data (Cogswell et al., 2022).

Roles of digital thread in EoL

EoL is where the products are collected to be given a second life, undergoing circular manufacturing processes such as recycling, re-manufacturing, re-use etc., or to be disposed of (Terzi et al., 2010). The use of digital thread for EoL phase has not received attention comparable to the BoL and MoL phase. In fact, out of the analyzed 27 articles only one article (Deng et al., 2021) addressed in detail the circular strategies of extending the EoL for products using digital threads. Deng et al. (2021) explained that in the process of extending the life of a product, the digital thread provides the chance to link activities with information, stakeholders, and services, which would encourage their close cooperation and interoperability and make activity tracing possible. Other authors mentioned, without detailed discussion, the potential roles the digital thread could have in the EoL phase, for example, Paramatmuni and Cogswell (2023) mentioned that the creation of a material passport could have a role in guiding companies on the recyclability or reusability of a component.

Roles of a digital thread for product lifecycle

In summary, the roles of the digital thread for the product lifecycle are:

- *Provides an integrated view of data and information for all stakeholders, as well as a representation of the progression of data throughout the lifecycle*: The digital thread serves as a comprehensive repository and channel for data and information across the entire product lifecycle. It offers an integrated view that consolidates diverse data sources and formats, facilitating seamless access for all stakeholders involved in the lifecycle, ranging from design and engineering teams to production and maintenance personnel. This role is paramount in ensuring that decision-makers have a holistic understanding of product-related data, enabling them to make informed choices and optimizations at various stages of the lifecycle. Moreover, the digital thread acts as a visual representation of how data evolves and transitions through different phases, enhancing transparency and continuity (Cogswell et al., 2022; Gharbi et al., 2017; Pang et al., 2021; Paramatmuni & Cogswell, 2023; Singh & Willcox, 2018, 2021).
- *Allows for traceability of the product/process information*: The digital thread enables the meticulous tracking and documentation of product and process information. This traceability extends throughout the product's entire lifecycle, from its initial design and development to manufacturing, utilization, maintenance, and eventual decommissioning. (Bonham et al., 2020; Cogswell et al., 2022; Kim et al., 2015)
- *Supports data and information sharing downstream and upstream along the supply chain*: The digital thread acts as a conduit for data and information sharing, fostering collaboration not only within an organization but also up and down the supply chain. It enables the seamless exchange of critical information between suppliers, manufacturers, distributors, and end-users. This capability enhances supply chain visibility, enabling more efficient coordination, demand forecasting, and inventory management. It also facilitates rapid responses to changes in customer preferences, market dynamics, and unforeseen disruptions. (Cogswell et al., 2022; Deng et al., 2021; Yang et al., 2022)
- *Provides an interlinked data and information pipeline*: The digital thread functions as an interlinked pipeline that ensures the continuous flow of data and information across disparate stages of the product lifecycle. It establishes connections and relationships between data points, creating a cohesive and structured information network (Cogswell et al., 2022; Huang et al., 2023; Niu & Qin, 2021).

Additionally, two types of digital threads have emerged from the analyzed articles: (i) Thread that enables smooth *data progression horizontally*, i.e. from one stage of the product lifecycle to the other, and (ii) Thread that connects *data vertically*, i.e. incorporating the product lifecycle data with the corresponding process information. An example of horizontal data connection has been demonstrated by Cogswell et al. (2022) who used digital thread for data connection along the product lifecycle by passing data from BoL phase (in particular, manufacturing) to the MoL phase (in particular, after-sale services) for proactive utilization of materials and components data when problems occur. On the other hand, Zhang et al. (2022) developed a framework for implementing DT using digital threads that vertically connect the data by creating directed graphs of the product data and the process information.

Discussing the digital thread for smart manufacturing

As a result of the performed review an application framework for the digital thread for the product lifecycle is proposed. The proposed framework offers a structured approach for manufacturing companies to decipher the complexities of the digital thread's integration. By delineating technological architecture components like data types, storage modalities, data linking, and transfer technologies, companies can systematically assess and identify appropriate technologies tailored to their unique production ecosystems. Furthermore, the framework elucidates the multifaceted roles of the digital thread on the product lifecycle, from providing an integrated view of data and information and an interlinked data pipeline, allowing for traceability, and supporting data sharing, enabling manufacturers to harness its full potential. Consequently, companies leveraging this framework can achieve a more synchronized and data-driven production environment, bridging gaps between siloed operations throughout the different phases of the product lifecycle, and ensuring a consistent digital continuum. This structured approach, therefore, acts as both a strategic blueprint and an operational guide, facilitating more informed technological choices and a clearer comprehension of the digital thread's implications for production and manufacturing dynamics.

The framework is displayed in Fig. 7 and consists of the technological architecture of the digital thread as well as the functions and the needed supporting infrastructure. The technological architecture of the digital thread represents the foundational infrastructure that underpins the seamless integration and flow of digital information throughout an organization and along the product lifecycle. This layer encompasses four critical components:

- *Data Types*: Data types refer to the various structures of the information represented within the digital thread. These can range from production data, process data, design data, etc. Effective management of diverse data types is essential for a comprehensive digital thread. Planning and having an understanding of the types of data and their format that are to be encapsulated within the digital thread is an important first step that guides the following choices of technologies for storage, transfer, and mapping. For example, while designing the digital thread Kwon et al. (2020) specified that the data types to be encapsulated in the digital thread are design information in the STEP AP242 format and the inspection information in the QIF format. Bonham et al. (2020) developed a digital thread for customized AM and specified that the data collected are the customer preferences using a web based UI and the design data.
- *Data Storage Technologies*: Data storage technologies involve the systems and methods used for storing and managing data. This encompasses choices like databases, cloud-based storage solutions, etc. The selection of appropriate data storage technologies depends on factors like scalability, accessibility, and data volume. For example, the MySQL database was chosen by Zhang et al. (2022) because it is lightweight, quick, and multithreaded, making it ideal for storing equipment operation data, process parameters, and simulation data.
- *Data Transfer Technologies*: Data transfer technologies are the mechanisms by which data is transmitted and shared within the digital thread. This includes integration tools such as APIs, PLM software, web-based platforms, and cloud platforms. Efficient data transfer is vital for access and collaboration across diverse systems and stakeholders. PLM software has been used by various authors for data transfer and allowing accessibility of the data to stakeholders that are otherwise operating in siloed ecosystems. For example, Zhang and Zhu (2019) utilized the Teamcenter software to transfer the 3-D design model of the fan blade parameters to process engineers of the manufacturing department using the digital thread. This allowed the process engineers to design the process model rapidly.
- *Data Mapping Technologies*: Data mapping technologies focus on the transformation and harmonization of data between different formats and systems. This involves the use of ontologies, knowledge graphs, and ad-hoc techniques. Effective data mapping ensures data consistency and interoperability within the digital thread. Ontologies have been used by Deng et al. (2021) to map circularity protocols to the activities to be done for end-of-life extension.

The Functions and Supporting Infrastructure layer within the framework addresses the functional aspects of the digital thread, highlighting the key capabilities it must deliver and the supporting infrastructure needed. Interoperability is the ability of different systems, components, and stakeholders to seamlessly exchange and utilize information within the digital thread. Achieving interoperability involves standardizing data formats and microservices. Traceability refers to the ability to track and trace the lifecycle of the product and data within the digital thread. This includes the utilization of unique identifiers and knowledge management systems. Secure stakeholder collaboration emphasizes the importance of maintaining data security and privacy while facilitating collaboration among various parties involved in the digital thread. This involves implementing robust training programs for stakeholders, investing in secure technology, and implementation of policies to protect sensitive information. At the bottom of Fig. 7, the interaction of the digital thread within the product lifecycle is displayed. Data and information are fed continuously into the digital thread from the various operations and activities along the product lifecycle, allowing different stakeholders to view and access these data. The figure also presents the roles of the digital thread for the product lifecycle as discussed in Sect. 5.3.4.

To demonstrate the potential use of the framework by industry professionals in the planning of a digital thread, an example of creating a digital thread for an industrial asset is demonstrated. The asset, considered as a large-scale product, is present withing the didactic assembly line of the Industry 4.0 laboratory of the School of Management of Politecnico di Milano (Fumagalli et al., 2016). The establishment of the digital thread is undertaken with the primary objective of surveilling the operational status of the asset while facilitating the integration of disparate data types derived from various systems, all of which pertain to the maintenance aspects of the asset. This integration is intended to streamline maintenance operations for operators. Accordingly, the digital thread's scope encompasses the MoL phase. The data represented within the digital thread are maintenance data, which are mainly static data like the asset manuals from

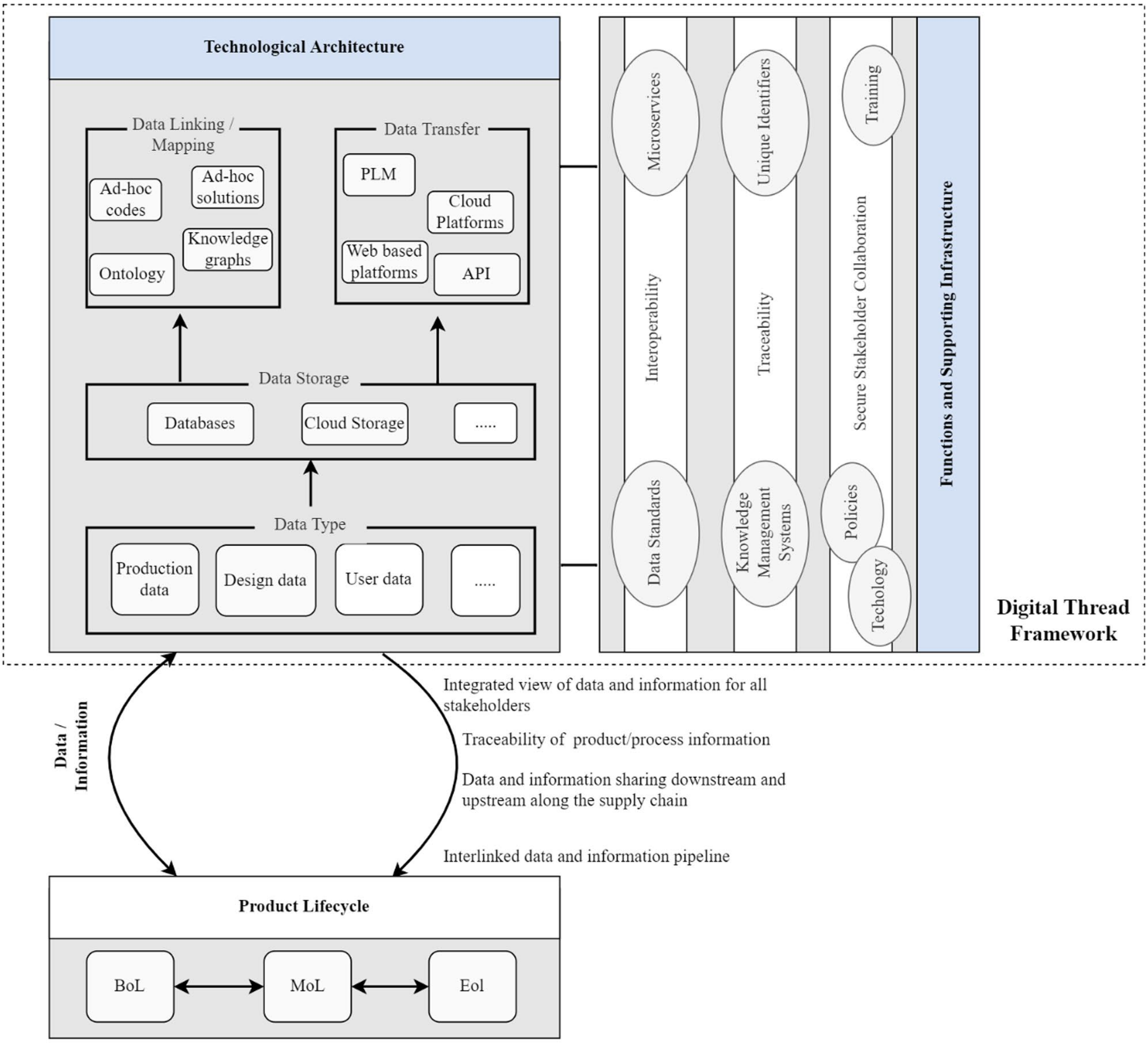


Fig. 7 Product lifecycle digital thread framework for manufacturing

the manufacturer, list of spare parts, maintenance schedule, safety concerns etc. These data are stored on typically siloed systems such as on the Manufacturing Execution System (MES) and on localized computers. The primary objective of the digital thread is to facilitate the seamless integration of diverse data types and information sources, thereby affording operators a unified and readily accessible perspective of maintenance instructions as and when required. In order to maintain a comprehensive record of maintenance activities throughout the asset's lifecycle, operators must also be granted the necessary access privileges to modify and append maintenance-related information within the digital thread. To achieve this objective, the Asset Administration Shell (AAS) has been chosen as the data model for representing information in a standardized and easily comprehensible format. The AAS not only encompasses static details such as manuals and visual resources but also incorporates the capability to uniquely identify each asset and stakeholder through the utilization of unique identifiers. In terms of storage and accessibility, AAS models are stored in a cloud-based storage solution, complemented by a web server that facilitates accessibility and data transfer through REST APIs. Consequently, whenever operators require access to maintenance-related data, the digital thread supplies them with the capability to view all pertinent information through a singular web application while simultaneously preserving a detailed record of maintenance activities for future reference.

Conclusion

In conclusion, this research article addressed the lack of clarity and standardization on the digital thread's integration into the product lifecycle within manufacturing companies and the research environment. Employing a comprehensive systematic literature review comprising both bibliometric and systematic content analyses, the research articles addressing digital thread for manufacturing have been analyzed. The bibliometric analysis has yielded insights into the rising number of yearly publications addressing digital thread, and brought forward the lack of collaboration between authors and research teams. Additionally, this analysis has highlighted key focal areas of research, including the application of digital threads in additive manufacturing, digital twins, data modeling throughout the product lifecycle, and simulation and model-based applications in the aerospace industry. The systematic content analysis has contributed to an in-depth understanding of the digital thread's various dimensions, where a review of the definitions, technologies and supporting infrastructure, and the roles of the digital thread has been presented. It has revealed that while there exists a lack of uniformity in terminology, there is a consensus that the digital thread spans the entirety of the product lifecycle data, serving two primary purposes: the integration of data and information to offer a unified view to all stakeholders, and the collection and storage of data and information to enable sharing and transmission. The technologies have been reviewed under the categories of data types, data storage/transfer, and data mapping/linking. Additionally, the supporting infrastructure needed to provide the functions of interoperability, traceability, and secure stakeholder engagement has been addressed. The roles of the digital thread within each phase of the product lifecycle (BoL, MoL, and EoL) have been discussed and summarized. Finally, a framework for the digital thread has been proposed, encompassing the technological architecture, the supporting infrastructure and functions, and the interaction of the digital thread with the product lifecycle. This framework establishes a consistent view of the elements that make up the digital thread environment and allows for planning of the implementation of a digital thread. Consequential challenges appear with the increased access, collaboration, and connection that the digital thread provides. Implementing the digital thread may require significant changes to the existing processes and systems to allow for a collaborative environment built on data continuity, specifically in the data collection and data processing tools. The framework proposed in this article has been conceptualized from literature papers that have used the digital thread within the manufacturing organization, or between the manufacturing organization and their direct customers/suppliers. Accordingly, a limitation of this work is that the issue of data availability has not been addressed. Data availability is especially relevant, and presents as a significant challenge, for EoL treatment of the product where the needed information is often present outside the bounds of the company. Therefore, future work should focus on studying the digital thread application in the EoL, with a focus on the needed data, their sources, and the business models that would drive companies to share their data. Additionally, empirical research is needed of the applications of the digital thread within companies, the challenges and opportunities, as well as the testing and implementation of the proposed framework within companies for various roles, such as for circular manufacturing.

Relevance for research

The findings and insight derived from the reviewed literature have significant relevance for researchers in the field of industrial engineering, management, and manufacturing. This section aims to highlight the implications of the literature review for researchers and to outline potential areas for future investigation. The literature review has provided a comprehensive overview of the current state of research on the digital thread in manufacturing. By synthesizing and analyzing the existing literature, this review has identified key areas of research, research groups, research trends, and the roles, functions, and supporting infrastructure of the digital thread. Researchers can benefit from this review by gaining a nuanced understanding of the research landscape and building upon the existing body of knowledge. Based on the review, some gaps in the literature have been identified:

1. The application of the digital thread for the EoL stage and for circular manufacturing approaches such as recycling, re-manufacturing, etc. has not received attention.
2. Research is lacking on the security and safety of the digital thread.

Based on the gaps identified, several potential research directions emerge. The proposed framework in this article can guide researchers by providing a standardized view of the digital thread environment, and hence encourage further investigations that may provide new perspectives and enhance the validity of future studies. For example, empirical investigation on the digital threads' data and information for EoL circular strategies.

Relevance for industry

Several companies market their use of the digital thread as a competitive advantage, yet with an inconsistent understanding of what the digital thread is, and how it can benefit the manufacturing process and their customers. Accordingly, the findings and insights of this article also have significant relevance for industry professionals. This review provides practitioners in manufacturing companies with a better understanding of the roles of digital thread and the supporting infrastructure needed, which results in a more informed decision-making process about the use of digital threads, and avoids the lack of clarity that surrounds the topic. The proposed framework acts as a planning guide for the implementation of digital threads within companies that allows practitioners to plan the digital thread in a modular fashion depending on the desired objectives. Additionally, the review may reveal opportunities for collaboration and partnerships between industry practitioners and researchers based on the standardized understanding of the digital thread this article provides.

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Data availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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