The development of digital thread: the relations to digital twin and its industrial applications

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Abstract

Purpose – Through this research study, the authors found that digital thread has made significant progress in the life cycle management of the US Air Force. The authors hope that by reviewing similar studies in the aerospace field, the meaning of digital thread can be summarized and applied to a wider range of fields. In addition, theoretically, the definition of digital twin and digital thread are not unified. The authors hope that the comparison of digital thread and digital twin will better enable scholars to distinguish between the two concepts. Besides, the authors are also looking forward that more people will realize the significance of digital thread and carry out future research.

Design/methodology/approach – Complete research about digital thread and the relevant concept of the digital twin is conducted. First, by searching in Google Scholar with the keyword “digital thread”, the authors filter results and save literature with high relevance to digital thread. The authors also track these papers’ references for more paper of digital thread and digital twin. After removing the duplicate and low-relevance literature, 72 digital thread-related literature studies are saved and further analyzed from the perspective of time development, application field and research directions.

Findings – Digital thread application in industries other than the aviation manufacturing industry is still relatively few, and the research on the application of digital thread in real industrial scenarios is mainly at the stage of framework design and design-side decision optimization. In addition, the digital thread needs a new management mechanism and organizational structure to realize landing. The new management mechanism and the process can adapt to the whole life cycle management process based on the digital thread, manage the data security and data update, and promote the digital thread to play a better effect on the organizational management.

Practical implications – Based on a review of digital thread, future research directions and usage suggestions are given. The fault diagnosis of high-speed train bogie as an example shows the effectiveness of the method and also partially demonstrates the advantages and effects brought by the digital thread connecting the data models at various stages.

Originality/value – This paper first investigates and analyzes the theoretical connotation and research progress of digital thread and gives a complete definition of digital thread from the perspective of the combination of digital thread and digital twins. Next, the research process of digital thread is reviewed, and the application fields, research directions and achievements in recent years are summarized. Finally, taking the fault diagnosis of high-speed train bogie as an example partially demonstrates the advantages and effects brought by the digital thread connecting the data models at various stages.

Keywords Digital twin, Digital thread, Life cycle management

Paper type Research paper
1. Introduction
The digital thread was formally proposed in the Air Force Global Horizons report in 2013 and has been viewed as a “game-changing” disruptive opportunity (Maybury, 2013). Many companies, including Boeing, Lockheed Martin and Pratt and Whitney, have conducted related research projects and achieved significant outcomes. The idea of digital thread applied in U.S. Air Force aircraft lifecycle management has achieved significant cost reductions and efficiency improvement. By seamlessly connecting all phases of the life cycle and capturing, synthesizing and analyzing data, digital thread with advanced modeling and simulation tools can support well-informed decision generation.

Digital thread is commonly defined as “an extensible, configurable and Agency enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision-makers throughout a system’s life cycle by providing the capability to access, integrate and transform disparate data into actionable information” (Kraft, 2016). And the digital twin is “an integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin” (Glaessgen & Stargel, 2012).

Theoretically, the definition of digital twin and digital thread are not unified, and there are few studies on the comparison and association between these two concepts. In practice, the digital thread has made significant progress in the life cycle management of the U.S. Air Force, and we hope that by reviewing their research, we can summarize the meaning of the digital thread, which can be applied to a wider field. In this paper, we give the definition of digital thread, and the relationship between digital thread and digital twin, to help scholars distinguish these two concepts, and then we present the development of digital thread research in terms of application areas and directions and show a case about the idea of digital thread and finally analyze the possible future research directions.

2. Methodology
Complete research about digital thread and the relevant concept of the digital twin is conducted. These two concepts are compared and associated, and the digital thread-related papers are further organized and analyzed from specific perspectives. The flow chart of our methodology is shown in Figure 1. Firstly, by searching in Google Scholar with the keyword “digital thread”, we filter results and save literature with high relevance to digital thread. We also track these papers’ references for more paper of digital thread and digital twin. After removing the duplicate and low-relevance literature, 72 digital thread-related literature studies are saved and further analyzed from the perspective of time development, application field and research directions. The literature research for digital twins includes highly cited and newly released review articles and their references, as well as digital twin-related papers in the reference section of previously saved digital thread literature. A comparative analysis of the definition is conducted with the literature on these two concepts, and the association between the two is discussed.

3. Digital thread and digital twin
The concept of digital thread and digital twin are closely correlated, and in practice, these two ideas are often combined to achieve effective life cycle management. This part will summarize the concepts of digital thread and digital twin and the relationship between these two ideas.
And finally, we will give a detailed definition of a digital thread based on the discussions and analysis.

3.1 Digital thread concept
The concept of digital thread appeared in the report of global horizons final report: US air force global science and technology vision (Maybury, 2013). As the report pointed out, the idea of digital thread is to extend MBE (model-based enterprise) and digital twin to better cover and link the life cycle. In this report, digital thread is described as “the creation and use of a digital surrogate of a material system that allows dynamic, real-time assessment of the system’s current and future capabilities to inform decisions in the Capability Planning and Analysis, Preliminary Design, and Detailed Design, Manufacturing and Sustainment acquisition phases”, and the digital surrogate is “a physics-based technical description of the weapon system resulting from the generation, management, and application of data, models, and information from authoritative sources across the system’s life cycle”. Before the emergence of the digital thread, the main emphasis in practice was on the vertical integration of systems and platforms. To achieve the goals of rapid deployment, cross-platform integration and modular upgrades, a digital thread based on data storage and analysis, model building and computation was proposed to enable quick equipment building, testing and upgrading in conjunction with technology upgrades and requirements iterations.

Digital thread now is commonly defined as “an extensible, configurable and Agency enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision-makers throughout a system’s life cycle by providing the capability to access, integrate and transform disparate data into actionable information” (Kraft, 2016). A digital thread can be viewed as a framework that provides a holistic view of a system and full life-cycle traceability based on system information, models and the standards and contextual state in which the system operates. The information in a digital thread contains data from multiple sources, including flat files such as tabular documents, computer models, real-time data streams, data from hardware, etc. (Margaria & Alexander, 2019).

Providing a single, authoritative “source of truth” is an essential function of the digital thread (Kraft, 2018). The ability of a digital thread to provide knowledge of the current state of the system for all types of needs is critical to support decision analysis in a digital environment. As a single, authoritative source of truth, the digital thread also enables all
Seamlessly connecting all phases of the life cycle is an essential feature of the definition of the digital thread. Digital thread collects, analyzes, processes and presents data and information from each phase and realizes data interaction and decision supports in different phases. For example, data from the operation stage and maintenance stage can be linked to establish fault detection and health management mechanisms better, and knowledge from the operation and maintenance stage can also be fed back to the design stage to achieve higher quality and high-reliability design iterations through key parameter improvements, etc.

As an example to illustrate the application of digital thread, Northrop Grumman established a digital thread infrastructure to support the material review board (MRB) in making F35 defective product handling decisions. Collect data from all stages of the life cycle, such as design, production and operation, to achieve feedback in the entire life cycle and the entire value chain. Based on these data, combined with the study of automatic algorithms in a 3D environment, fast and accurate structural qualification analysis is achieved to reduce processing time. The MRB process for F35 project structures, supported by digital thread, can reduce processing time by 33%.

We will compare and correlate digital thread with digital twins in the latter part of this paper to provide a deeper understanding of digital thread’s connotations and functions and give a complete definition.

3.2 Digital twin concept

A concept that is closely related to digital thread and is currently widely used is digital twin. To better understand the meaning and application of digital thread, the definition and functions of digital twin are summarized to further compare with digital thread and to have a complete understanding of these two concepts.

The initiation of the digital twin concept can be traced back to the conception of Grieves’ course on lifecycle management in 2002 (Grieves, 2014), where he mentioned the concepts of real space, virtual space and data transfer process as the initiating prototype of the digital twin. The concept of the digital twin was formalized in a National Aeronautics and Space Administration (NASA) report (Glaessgen & Stargel, 2012), where the digital twin is “an integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin”. The digital twin concept was first applied in aerospace, including aircraft design and simulation, real-time inspection of operating environments and capabilities, failure and fault prediction, maintenance and health management, etc.

![Digital thread concept](source(s): Singh & Willcox, 2018)
After the digital twin concept was proposed, research on the definition, paradigm, framework and supporting technologies of the digital twin has been carried out in academic circles. There are richer theories about the essence and scope of the digital twin. Views on digital twins can be mainly divided into two types. One is to classify digital twins as design prototypes in virtual space and digital twins of the physical object in real space. The other is to type digital twins into the design, production and operation-related digital twins according to their functions.

The first type of theory, such as Grieves et al. published in 2017, defines a digital twin as a collection of virtual information capable of representing an upcoming or existing entity at micro and macro levels. They propose that the digital twin can be divided into two categories: one is DTP (digital twin prototype), i.e. digital virtualization of prototype design information such as requirements, 3D model, bill of materials, etc. for an entity, and another is DTI (digital twin instance), i.e. the simulation of the life cycle of a physical product including but not limited to specific 3D models, real-time operational status, maintenance status, future trend prediction, etc. (Grieves & Vickers, 2017). That is, one type of digital twin is constructed from the requirement definition stage, first the virtual prototype, and after the physical prototype appears, the selected virtual prototype becomes the DTP; the other type of digital twin is constructed at a later stage, mapping the response to the state characteristics and operation of the physical object.

The second type of theory, such as in Post, Groen, and Klaseboer (2017)’s article, proposes that the digital twin is a real-world representation capable of simulating all relevant behaviors of a product or process during the life cycle or part of the life cycle. In this definition, it is considered that digital twins can be constructed for specific phases of the life cycle or according to different purposes such as design or maintenance. In practice, the Siemens Digital Twin application includes “product digital twin,” “production digital twin” and “operation digital twin,” which three system models are equipped with different objects and capabilities and are also integrated.

Tao Fei et al. conclude that the digital twin is a technical means to digitally create virtual models of physical entities and simulate, verify, predict and control the life cycle process of physical entities with the help of historical data, real-time data and algorithmic models (Fei, He, & Qinglin, 2020) and propose a five-dimensional structural model of digital twin regarding the entity, data, model, connection and service (Tao et al., 2018). Jiang, Yin, Li, Luo, and Kaynak (2021) believe that since digital twin is a multidisciplinary and interdisciplinary research topic, practitioners each understand it from a unique professional perspective, so there is no unified definition. So they summarize the characteristics of the digital twin from the components, modeling, interaction, synchronization and complete lifecycle.

Different scholars and industry personnel have different understandings of the digital twin. There are differences in the perceived digital twin’s content, structure and functions, which has led to difficulties in conducting theoretical research on the digital twin and in implementing the digital twin. Tao et al. (2019) proposed a standard system for digital twin in 2019, which contains the basic terminology, architecture, standards for applicable guidelines, etc. However, the development of specific criteria, the construction and development of platforms, and the implementation and promotion in the industry are still to be completed.

Combining definitions and applications, the digital twin is for a complete model of the entity lifecycle and for a phase to build a detailed local model at the subsystem level. The digital twin captures and maintains information during the life cycle of a product or system and uses the data and models for simulation and decision-making. The digital twin is created early in the life cycle during the design and manufacturing phases. As the product enters operational service, sensor data and operational records are collected and updated in the digital twin model. The digital twin is not only synchronized with the physical world in the
virtual digital world but also identifies problems and optimizes decisions through model simulation and algorithm analysis.

3.3 The relationship between digital thread and digital twin
A concise explanation of the relationship between digital thread and digital twin is that the digital thread contains all the necessary information to build and update digital twins. The digital thread establishes a framework that seamlessly connects business systems across the product lifecycle. The digital thread is created to convert disparate data into actionable information. It can provide data access, integration and transformation capabilities for the digital twin, a vital interface and an integrated global view of all data, models and information.

As mentioned earlier, the definition of a digital twin can be divided into two categories. One is based on the idea of DTP and DTI to build a design twin for pre-production design models and a physical twin for operational systems. Another considers the complexity and multi-functionality in the system's lifecycle to propose a digital twin model from design, production, operation and maintenance, and other multi-functionality. Researchers have proposed models illustrating the relationship between digital thread and digital twin.

Based on the first type of idea, Pang et al. (2021) proposed a model combining the design digital twin and entity digital twin with a digital thread. In building the digital twin of product design and entity, the digital thread provides data and models for each digital twin. It connects each stage seamlessly to realize the total circulation of information and models throughout the product life cycle.

According to the second type of idea, Ramesh's model is based on the multi-stage functional digital twin theory in Figure 3 (Ramesh, Qin, & Lu, 2020), which constructs an As-Designed digital twin, As-Planned digital twin, As-Built Digital Twin, and As-Maintained digital twin for the system, and the information of digital thread flows and interacts among the models to realize the connection and update of each twin. The BOM in Figure 3 represents the bill of materials.

Zhou et al. (2020) proposed the construction of a digital thread that obtains models and data of each subsystem through an integrated interface and can extract and manage structured and semi-structured data with a consistency check. Using these authoritative and trustworthy models and data, the digital thread can support the digital twin construction and update process.

In all the models above about digital thread and digital twin, digital thread, as the interface of data, models and information, provides a holistic digital view of the system and seamlessly links different stages to make information freely flow within the system in the life cycle. Therefore it improves the effectiveness of lifecycle management.

3.4 Features and functions of digital thread
The features and functions of digital thread can be summarized as three key points: full connectivity, bi-directionality and decision-support ability.

As a communication framework that seamlessly connects the life cycle phases, the digital thread can connect physical data and virtual simulation data streams, integrate information from multiple data sources and realize horizontal interstage data connection and vertical intrastage data integration. In the situation of multi-stakeholder cooperation, the digital thread can connect various data, timely update and synchronize, and meet the requirements of all parties’ data security and intellectual property rights through access rights constraints.

Bidirectionality means that the digital thread not only enables the transfer of data and information from the early stage to the later stage in the life cycle but also enables tracing back the relevant information and decisions from the earlier stage at the later node, thus
enabling a closed-loop iteration of the whole cycle through the feedback of the posterior information and knowledge to the earlier phase.

With digital thread, managers can make better decisions at critical points with a data-driven global perspective. Thanks to the digital thread’s holistic view provision and its ability to access data as an authoritative source of truth; decision-makers have complete and interactive information references. Besides, with the powerful modeling and simulation tools, decision-makers can predict unknown situations and make optimal and reliable decisions.

In summary, by relating and comparing the idea of digital thread and digital twin, we can provide a complete definition of the digital thread. A digital thread is a communication framework that connects entities and data flows in the lifecycle, enabling digital twins and physical objects to maintain authoritative data source homologies, creating an integrated data view that seamlessly connects the entire lifecycle stages of a system. The digital thread connects all digital twin functions, such as design, production and operation. It provides data chains that can be traced in both directions, enabling improved data correlation across lifecycle stages and optimized decision analysis, thus unlocking the potential of the entire value chain through cross-domain integration. The digital thread is not a product or software but an actionable conceptual idea.

4. Research progress of digital thread

In this section, according to the methodology obtained in section 2, we further organize and analyze the literature related to digital thread from the perspective of timeline, research fields and research directions.

4.1 Application fields and progress of digital thread

Since the digital thread concept was formally introduced in the report in 2013 and designated as an essential technical direction, the quantity of digital thread-related research articles has been growing, as shown in Figure 4. In these 72 literature, by analyzing the abstracts of digital thread related literature and drawing a word cloud shown in Figure 5, we can find that digital thread and digital twin are closely related, and “system” and “model”, two words that are closely associated with the function and content of the digital thread, are mentioned more often. More attention is paid to “design” among the life cycle stages.

Application areas of digital thread research are almost exclusively in industrial manufacturing, and in other fields, one study combines digital thread with medical care.
Some articles related to industrial manufacturing focus on the application of digital thread in additive manufacturing processes (Nassar & Reutzel, 2013; Mies et al., 2016; Kim, Witherell, Lu, & Feng, 2017; Bonnard, Hascoët, Mognol, & Stroud, 2018; Bonnard, Hascoët, & Pascal, 2019; Bonnard, Hascoët, Mognol, Zancul, & Alvares, 2019; Bonham et al., 2020), and some articles have targeted subdivisions whose main areas are related to aerospace equipment and ships (Jagusch, Sender, Jericho, & Flügge, 2021; Pang et al., 2021). Most literature on the digital thread is in the aviation domain, mainly in the research and practice led by the US Air Force. The earliest and most classical application area of digital thread is the US Air Force equipment manufacturing. Boeing, Lockheed Martin, General Electric, etc., apply digital thread to the life cycle of the equipment. For example, General Electric has created a smart factory based on the digital thread to realize the data cloud storage and connection interaction, effectively reducing the failure rate in the production process. Lockheed Martin applied digital thread to produce F35 and improved the automation of the production process. Through better data connectivity, they can communicate with suppliers worldwide more efficiently (Gharbi, Briceno, & Mavris, 2018). In addition, many articles do not explicitly target the domain and investigate generic methodologies and application frameworks of the digital thread.

4.2 Research directions and outcomes of digital thread

By summarizing the related papers, the research directions of digital thread can be divided into three categories: research on the practice and effect of digital thread in the whole course of life cycle management, research on mathematical modeling and algorithms in the process of digital thread implementation, and research on the digital thread platform and software design.
One classical research about the practice and effectiveness of life cycle management is effectiveness studies and practical presentation of the US Air Force’s digital thread. In two articles published by the USAF Research Laboratory, the role of digital thread is explained from the stage of concept development and equipment solution analysis to technology maturation and risk reduction (Zweber, Kolonay, Kobryn, & Tuegel, 2017) and from engineering and manufacturing development, production and deployment, operation and sustainment to end-of-life disposal (Kobryn, Tuegel, Zweber, & Kolonay, 2017), respectively. Digital thread, in combination with uncertainty-informed modeling and simulation techniques, is demonstrated to help the US Air Force achieve faster design iterations, lower development costs and safer and more effective maintenance management throughout the lifecycle.

The objective of the digital thread is to achieve a seamless connection of the life cycle stages, and research on mathematical methods and algorithms for data and information linkage is of interest. Based on Bayesian inference methods and decision theory, Sigh uses the wing ribs of an aircraft as the research object and proposes a digital thread methodology to integrate material information, manufacturing process information and operational load information to make multi-stage decisions in a design process with uncertainty to achieve data-driven iterative design (Singh & Willcox, 2018). This study fills the research gap in applying digital thread in critical design decision stages and fully demonstrates the value and significance of digital thread to connect multiple life cycle stages seamlessly. In addition, some scholars use multidisciplinary knowledge-based engineering (KBE) systems of product life cycle to realize manufacturing digital thread. Joe David put forward four directions based on KBE, including knowledge representation, implementation of trust mechanisms, modeling and analysis, knowledge acquisition and reuse, so that KBE tools can help the realization of digital threads in manufacturing enterprises (David, Järvenpää, & Lobov, 2021). This study employs the KBE system as an integral part of a digital threading framework in a collaborative assembly environment between humans and robots.

To put data thread into practice and enable their application to more scenarios, research on application frameworks and software architecture design for connecting digital thread to other platforms has evolved. Bajaj and Hedberg (2018) build the SLH (system lifecycle handler) platform based on LIFT (lifecycle information framework and technology), which enables the identification of entity and virtual components and relationships and provides unique global identifier system (GID) to search and locate across data system platforms, enable multi-step GID-based parsing, build digital thread with traceability, enable impact analysis and continuous validation and fusion, and enable visualization and graph query. Pang et al. (2021) develop a new framework that combines the digital twin and digital thread for better data management in order to drive innovation, improve the production process and performance and ensure continuity and traceability of information. And they stated the twin/thread framework encompasses specifications that include organizational architecture layout, security, user access, databases and hardware and software requirements. Some companies have developed system lifecycle management products for digital cueing ideas, such as Aras (Panthaki & Tim Keer, 2022).

5. Case study
This part is about the digital thread application in fault diagnosis of bogie in high-speed trains.

The application of digital thread in the life cycle of high-speed trains follows the architecture as shown in Figure 6. The life cycle of high-speed trains is divided into six stages. They are requirements concept, development, acquisition reserve, production deployment, operation and maintenance, and disposal. The content and types of data collected and
generated at different stages are different. The industry currently has related management systems for data management and function realization at different stages, such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), etc. The use of digital thread will make the data exchange and update between the various management systems of high-speed trains seamlessly connected with the support of authoritative data sources and realize cross-stage data traceability and transmission between virtual and real data.

If we do not use digital thread, the data of each stage will be an information island. When we want to use these data to make decisions, such as manufacturing deviation correction, operation status monitoring and fault diagnosis in the maintenance stage, we can only use the data in this stage, and the outcome of the decision may not be comprehensive. In the subsequent cases, if we do not use the experimental data in the testing phase, it is not even possible to give a fault diagnosis model for the train.

At each stage, in the process of transmitting the data of the high-speed train management system to the digital thread, the data is first structured and standardized. In particular, for feature extraction of unstructured data such as Computer Aided Design (CAD) files, the key necessary information for digital reconstruction is retained. The consistency and validity of the processed standard data are checked to ensure the authenticity and effectiveness of the data recording and transmission process and to reduce data errors and null values. Model or data record versions for multi-version iterations provide clues for subsequent data tracking.

The digital thread framework has the capability of bidirectional data transfer. As a data integration management platform for high-speed trains, the digital thread can edit and modify data under authoritative certification. It is also possible to relevant information retained in system records earlier in the life cycle can also be transferred to later systems. And it also can communicate data decisions to the corresponding system to change key parameters and schemes so that knowledge and experience can be shared and play an important role in different stages. This will enable closed-loop management and iteration of the life cycle of high-speed trains.

Diagnosis of operating conditions of high-speed trains is a key element of the inspection and maintenance of trains after they are put into operation phase, and it is also a vital task concerning the safety of life and property. In practice, fault detection methods mainly include mechanical diagnostics and data-driven fault detection methods and the main data-driven detection methods are statistical learning machine learning methods and deep learning methods. Unlike traditional machine learning methods that require a priori knowledge of signal processing, deep learning uses a deep hierarchy to automatically extract abstract features and directly establish the relationship between learned features and target outputs. A large amount of data are needed to train a deep learning model, digital thread as an authoritative data source can play an important role.
Fault classification detection, especially for objects with high safety and reliability requirements like high-speed trains, suffers from a lack of fault samples. Therefore, it’s difficult to use supervised learning data-driven method to build a classification model. If the idea of digital thread can be used to link the data, models and knowledge of different phase and from different stakeholders, we can manage to obtain data in fault working conditions. The results of bench tests conducted by the manufacturing side for different working conditions and simulation results in operation digital twin can be used to learn normal and abnormal features and train supervised learning models for classification, which can help the train to detect faults in the operation phase.

By combining the abundant data sources to get signal samples in different working conditions and designing effective model hierarchy, a working condition model can be trained, and operation health can be predicted. By the way, data are appropriately adjusted to protect the company’s trade secrets.

We use the bogie test data of a type of high-speed trains for fault diagnosis research. The data collected by the test has four channels of data collected by four sensors, which are the No.1 body lateral acceleration, the No.2 body lateral acceleration, No.1 lateral acceleration above the axle box ang the No.5 lateral acceleration above the axle box. In the test, the frequency of 1000Hz is used for testing and data collection under normal operating conditions and 6 failure modes, respectively. The labels and descriptions of the seven working conditions are shown in Table 1. Among the six failure conditions, three are the failure of the antisnake shock absorber and three are the failure of the lateral shock absorber.

In this case, four algorithms are used for model construction and training, namely RSN (residual shrinkage network), ResNet (residual network), CNNs (convolutional neural networks) and SVM (support vector machine). The confusion matrices of the classification results of the four models on the test set are shown in Figure 7a, b, c, d are the confusion matrices of RSN, ResNet, CNNs and SVM, respectively. From the results, the three neural networks corresponding to (a) (b) (c) can classify the samples under normal conditions (label 0) with high accuracy, and the accuracy rates are 100, 100 and 92.44 %, respectively. However, there is a problem of insufficient accuracy for the classification of the other six abnormal conditions. For abnormal working condition samples, there are certain challenges in distinguishing the type and location of specific fault anomalies, and the accuracy of the model is insufficient.

The classification accuracy of the neural network model of deep learning is better than that of SVM. The confusion matrix results of the deep learning model have obvious concentrated distribution on the diagonal, while there is no obvious diagonal distribution in the confusion matrix of (d), and it cannot effectively analyze the normal conditions (label 0) and abnormal conditions (label 1 to 6) for classification.

With the model trained based on test data which has more balanced samples of different conditions, we can predict the condition of operating train. Going forward, if real vehicle and simulation data can also be fed into the test phase, the dataset can be expanded, and models can be built that perform better in practice through transfer learning methods.

| Label | Descriptions                                               |
|-------|------------------------------------------------------------|
| 0     | Normal                                                     |
| 1     | No.1 antisnake shock absorber failed                       |
| 2     | No.1 and No.2 antisnake shock absorber failed              |
| 3     | All antisnake shock absorbers failed                       |
| 4     | No.1 lateral shock absorber failed                         |
| 5     | No.1 and No.2 lateral shock absorber failed                |
| 6     | All lateral shock absorber failed                          |

Table 1. Bogie normal and fault condition classification labels and descriptions
In this case study, we hope to present how to use the data from each operating condition in the bench test or simulation environment to build a classification model and to leverage the ability of the digital thread to connect data and models from various stakeholders in each phase to inform health and fault diagnosis in the operational phase. The ability of the digital thread is to seamlessly connect all phases of the life cycle and enable bi-directional connectivity. As the idea of digital thread is implemented and the technology matures, digital thread can play a more powerful role, and the ability of connecting all parties in all phases of digital thread can also show greater value in lifecycle management.

6. Conclusion
In general, the research on the digital thread is mainly focused on the life cycle management process of aircraft equipment in the US Air Force. Digital thread application in industries other than the aviation manufacturing industry is still relatively few, and the research on the application of digital thread in real industrial scenarios is mainly at the stage of framework design and design-side decision optimization. Our research attempts to connect data models in different life cycle stages of high-speed trains to realize digital thread, which, in the future, shall be able to extent to more fields. In particular, combined with the full life cycle digital twin model of the product, data interoperability and decision assistance of the digital thread at different stages can also be realized.

Figure 7. Confusion matrix of four models (RSN, ResNet, CNNs and SVM) on the test set

(a) Confusion matrix

(b) Confusion matrix

(c) Confusion matrix

(d) Confusion matrix
On the other hand, the application of digital thread has some preconditions that might otherwise limit its effectiveness. First, an enterprise must have comprehensive digital models of their product, which usually come from a successful MBSE (model-based systems engineering) adoption. Second, before using digital thread to make decisions, it is necessary to confirm the accuracy and usability of the digital models. Third, the sharing of data or digital models may involve issues related to intellectual property rights. New technologies, such as block-chain and privacy-preserving computation, might be the solution. Last but not least, the adoption of digital thread may need a new management mechanism, even a new organization structure, to achieve its full efficiency. We need a new management system that are capable of adapting to the life cycle management based on digital thread, managing data security, update, connection and traceability in an integral way, promoting data-driven decision-making and enabling continuous improvements.

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