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Research on the Construction of Aerospace Equipment Maintenance Support Chain Models

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Abstract

The current space launch missions are intense, and the utilization of equipment is frequent, demanding increasingly higher responsiveness and capability in maintenance and support. The aerospace equipment maintenance and support chain relies on aerospace equipment maintenance and support facilities, deploying various maintenance and support resources rationally according to specific requirements and principles, ultimately forming a unidirectional functional chain or network from the supply side to the demand side. This system helps address the "bottleneck" issue in the generation of aerospace equipment support capability and significantly improves the level of aerospace equipment maintenance and support. The model construction is a prerequisite for analyzing the formation and operation mechanism of the chain, and identifying factors affecting the efficiency and effectiveness of maintenance and support. With consideration of the particularity of aerospace equipment maintenance and support, the paper extensively investigates the construction of the aerospace equipment maintenance and support chain model by drawing on research achievements in modern supply chain and logistics theories, as well as model construction methods. It develops a structural diagram-based chain model, with symbols as key elements, and establishes an evaluation indicator system, providing insights into understanding and grasping the composition of the aerospace equipment maintenance and support chain effectively. Furthermore, it offers a reference for solving other equipment support chains' construction and optimization problems.

Keywords

Space Equipment, Safeguard Chain, Evaluation System, MMS

1. Introduction

Presently, in the realm of aerospace technology, the competition is fervently underway and the circumstances are formidable. The launch missions are meticulously orchestrated, and the proliferation of aerospace equipment, with its intensive development, production, deployment, and enhancement, will inevitably lead to a marked surge in the requisites for maintenance and support. This necessitates the imposition of elevated standards upon the realms of equipment maintenance and support.

By examining the relevant literature on chain construction in previous studies, in terms of the overall approach, [1] adopts a stratified construction approach for the demand side, supply side, and distribution side of the supply chain. constructs the equipment maintenance supply chain based on the principles of demand-driven, coordinated planning, integration of peacetime and wartime operations, and overall optimization. Furthermore, [2] considers the holistic approach of constructing a quality trend network for aerospace equipment through the stages of generation, manifestation, design, and optimization. As for construction methods, [3] employs comprehensive integration methods to address path optimization issues in the distribution system of city-level areas, achieving the "four satisfactions" standard. [4] solves the problem of "information islands" in the shipbuilding process by defining BOM multi-view mapping models through three steps: BOM view definition, mapping rule establishment, and algorithm design, from the perspective of structural mapping of information flow. In terms of evaluation criteria, [5] utilizes the reliability-based minimal path set method and minimal cut set method to measure the connectivity of link nodes. [6] divides supply chain performance into outcome performance, operational performance, and support performance, constructing efficiency indicators for equipment maintenance support chains from the perspectives of end indicators, process indicators, and support indicators.

2. The Structure of the Paper

The first chapter introduces the research content of the paper, while the second chapter delineates its structure. The third chapter delves into the concept and characteristics of the aerospace equipment maintenance support chain, presenting for the first time the notion that aids in precisely grasping its essence and patterns. In the fourth chapter, the train of thought, principles, methods, and processes involved in constructing the aerospace equipment maintenance support chain is expounded upon. This systematic construction of the aerospace equipment maintenance support chain serves as a reference for tackling the contradictions that arise during its practical operation. The fifth chapter establishes evaluation indicators for the aerospace equipment maintenance support chain, offering guidance for establishing a periodic evaluation mechanism and promoting the sustainable development of the chain. Finally, the last chapter concludes the entire manuscript.

3. The Essence and Characteristics of the Aerospace Equipment Maintenance and Support Chain

3.1. Conceptual Connotation of the Aerospace Equipment Maintenance and Support Chain

The domain of aerospace equipment maintenance and support pertains to the endeavors directed towards sustaining, refurbishing, or enhancing the technical state and performance of the equipment through maintenance and repair endeavors [7]. From a perspective of command and decision-making, the aerospace equipment maintenance and support chain assumes a pivotal role in launch missions. It necessitates assimilation within the launch mission system and embedding within the operational chain to actualize its efficacy completely. This encompasses a recurring process of fault monitoring, diagnostic analysis, decision-making, and action implementation, which exhibits periodicity and feedback. Regarding the operational procedures of maintenance activities, within the sphere of equipment maintenance and support pursuits, diverse elements of maintenance and support are methodically controlled and orchestrated to ensure the establishment of an integrated, purposeful, end-to-end functional chain connecting maintenance and support entities, operational units, and administrative authorities, encompassing the flow of technology, information, materials, and finances. In terms of equipment and spare parts provisioning, by leveraging the principles of supply chain management and contemporary logistics concepts, the aerospace equipment maintenance and support chain can be perceived as a distinctive supply chain and logistics chain, fundamentally encompassing the punctual conveyance of repair equipment and spare parts to aerospace equipment repair demand points via specific transportation means, alongside the reverse process of transporting equipment for repair from dedicated logistics channels to repair points at various levels. Thus, the concept of the aerospace equipment maintenance and support chain can be distilled as follows: it encompasses interconnected functional chains or network systems, comprising the chain of command and decision-making, the chain of maintenance operations, and the chain of equipment and spare parts supply, all of which are interrelated and possess maintenance and support functions for aerospace equipment.

3.2. Characteristics of the Aerospace Equipment Maintenance Support Chain

Due to the multidimensional and multidomain nature of aerospace missions, alongside the integration of military and civilian aspects, as well as the diversity of types and substantial distinctions in aerospace equipment, the aerospace equipment maintenance support chain displays the following characteristics:

1) Complex Interconnections and Network Distribution

Aerospace equipment is present both on the ground and in space, with distinct environments near the Earth and deep space. The scale and quantity of space-based equipment are vast, with multiple operational space levels to consider, including equipment pre-positioning, information exchange, and remote control. The extensive distribution of maintenance resources and equipment on the ground determines that the maintenance support chain has numerous peer nodes and complex interconnections. Additionally, aerospace equipment involves multiple disciplines and fields. Many equipment units are unique and constantly improved and updated as missions evolve. Stable mass-produced equipment models are rare. Furthermore, the significant differences in aerospace equipment's physical and technical composition result in varied technical and capability requirements for maintenance support. Thus, the maintenance support chain exhibits network-like distribution characteristics, labeled by "short," "multiple," and "detailed" connections.

2) Diverse Combinations and Agile Response

Given the high mission value and significant impact on aerospace equipment, the maintenance entities on the maintenance support chain must possess the ability to support various equipment models and batches. Equally important is their ability to provide agile feedback and timely response capabilities to equipment maintenance demands. Untimely or inaccurate responses can impair the operational efficiency of aerospace equipment, potentially leading to operational interruptions, thwarting the established research and operational objectives, and ultimately resulting in mission failure.

3) Integration of Military and Civilian Aspects, and Cross-linkages

Aerospace equipment spans multiple specialties and generations of products, requiring equipment repair manufacturers who are usually single and fixed to rely on manufacturers for routine maintenance. However, in complex competitive situations, equipment upgrades, and mobility of specialized maintenance personnel, the role of military and civilian maintenance forces remains essential. Both military and local enterprise maintenance forces must possess equipment maintenance support resources and technologies. In special circumstances, resource and capability integration and hierarchical implementation are necessary. This military-civilian integration model, with military forces as the main component and local manufacturers as a supplementary force, inevitably exhibits physical or technical domain crossovers during the operation of the aerospace equipment maintenance chain.

4) Changing Dynamic and Flexible Outstanding

The aerospace equipment maintenance and support chain is not a static chain but a continuous process of improvement and refinement. Subjectively, it should dynamically change with factors such as physical relationships, maintenance capacity, repair capabilities, transportation methods, and flow. Objectively, the aerospace equipment maintenance and support chain changes due to variations in maintenance support requirements, environmental conditions, and resource aggregation. At the same time, resource and information flow must also be dynamically updated. To adapt to these changes, the aerospace maintenance and support chain must be flexible, allowing for resource reconfiguration and chain reconstruction after modifications. The maintenance entities and their interrelationships within the chain will also be modified accordingly.

4. Construction of the Aerospace Equipment Maintenance and Support Chain Model

Developing the aerospace equipment maintenance and support chain is an abstract undertaking that embodies the tangible course of action and foundational constituents about the maintenance and support of aerospace equipment. Through the creation of a framework delineating the maintenance and support chain, it becomes feasible to explicate the formation and operational mechanisms thereof, while concurrently providing theoretical substantiation for factors influencing the efficiency and efficacy of maintenance and support activities.

4.1. Construction Ideas and Principles

1) Construction Ideas

The construction of the maintenance and support chain is a complex decision-making problem that requires comprehensive consideration of various factors, such as support objectives, the scope of support, military requirements, resource conditions, and operational modes. By analyzing and organizing existing aerospace equipment maintenance and support resources, drawing on research theories and construction ideas from supply chains and graph theory, and applying scientific methods and systems engineering thinking, an abstract representation of the maintenance and support chain can be formed.

Due to the extensive elements involved in the aerospace equipment maintenance and support system, this study focuses on the network planning of the aerospace equipment maintenance and support chain, without specifically studying the specific maintenance activities. It primarily emphasizes the coordination of resources and integrates with demand to guide the construction of the aerospace equipment maintenance and support chain.

2) Construction Principles

During the aerospace equipment maintenance process, the functionality of the equipment system and devices can only be fully utilized by forming an interconnected chain with continuous and organic activities. Therefore, the construction of the equipment maintenance and support chain should adhere to the principles of "demand-driven, comprehensive system, technological innovation, collaborative efficiency, and bidirectional integration".

a) Adhere to demand-driven: Support requirements are generated by combat missions, and support tasks are determined by those requirements. In the context of joint operations, there is significant pressure on aerospace equipment support. In the process of transitioning from "fighting" to "support," it is necessary to construct the equipment maintenance and support chain in response to mission requirements, aligning with the demands of task requirements. This includes a comprehensive range of support for multiple professional fields and various types of battle-damaged equipment and the support of aerospace equipment under battlefield conditions within a limited time frame.

b) Adhere to a comprehensive system: The construction of the aerospace equipment maintenance and support chain should highlight the entire process and all elements of aerospace equipment maintenance and support under specific conditions. It requires comprehensive and systematic thinking and plays a supportive role in the overall task of equipment support. The aerospace equipment maintenance and support chain includes equipment repair, spare parts reserves, logistics, and technical support, among other links. When constructing the aerospace equipment maintenance and support chain, the importance of each link should be considered, and resources and time for each link should be allocated rationally, forming a systematic chain that connects all entities, including military and civilian units and departments. Construction should be approached systematically.

c) Persist in technological innovation: The future characteristics of high value and high difficulty in equipment maintenance in aerospace necessitate the continuous development of maintenance support in aerospace equipment towards efficiency, precision, and reliability. Aerospace-specific equipment inherently possesses the genes of "integration" and "integration." The maintenance support chain should have advanced development concepts and technological connections, utilizing advanced intelligent technology, equipment facilities, and management methods. Particularly in comparison to ground-based aerospace equipment maintenance, the fault repair and maintenance support of in-orbit spacecraft rely more on intelligent maintenance equipment and means. This requires the construction of a maintenance support chain through deep integration.

d) Uphold collaborative efficiency: The aerospace equipment maintenance support chain involves various entities both within and outside the military during the equipment maintenance support process, spanning the domains of social support and military support. Constructing the aerospace equipment maintenance support chain necessitates prioritizing collaborative efficiency, enhancing the willingness for collaboration among entities, establishing joint incentive mechanisms between the military and civilian sectors, strengthening the collaborative capabilities of entities, connecting key links between the military, civilian industries, and operational areas, integrating all high-quality maintenance resources from the unit level to the base level, and incorporating all operational region-based maintenance units and local maintenance support resources into the aerospace equipment maintenance support chain.

e) Maintain bidirectional coherence: In the design of the aerospace equipment maintenance support chain, there exist two design methods: top-down and bottom-up. The top-down approach involves the decomposition of the maintenance chain, designing the whole before designing the parts. Conversely, the bottom-up approach is a process of integrating the maintenance chain. Strategic planning and decision-making are fundamental steps when designing the aerospace equipment maintenance support chain. The basis for planning and decision-making comes from mission requirements and strategic plans. The execution processes at lower levels provide feedback on the planning. Thus, bidirectional coherence should be maintained during the design process to ensure the overall integrity and efficiency of the chain.

4.2. Methodology Construction

Regarding the construction method of the support chain, there is currently no relevant research or ready-made application methods. This paper systematically proposes the Method of Maintenance and Support (MMS). It integrates the constituent elements or influencing factors using systems engineering thinking. Drawing analogies from supply chain and logistics models, it constructs the aerospace equipment maintenance and support chain based on the actual structural mapping of maintenance and support activities. Please refer to **Figure 1** for an illustration of the related process.

4.2.1. The Meta-Synthetic Approach (MsA)

This approach utilizes systems engineering thinking to integrate, refine, elevate, and enhance various maintenance and support resources in aerospace equipment maintenance and support activities. Through a specific mechanism, these resources are combined to form a systematic, dynamic, organic, and coordinated maintenance and support chain. The ultimate goal is to ensure rapid and efficient maintenance and support, leading to the restoration of the operational capabilities of aerospace equipment when malfunctions occur.

The Meta-synthetic Approach can enhance the efficiency and quality of the maintenance and support chain through the integration, optimization, and management of resources. In practical applications, it is also necessary to strengthen the sustainability, controllability, and reliability of the maintenance and support chain. This includes improving the chain's capacity to respond to challenges and its resilience in the face of risks, all aimed at ensuring the safe and stable utilization of aerospace equipment.

4.2.2. Model Analogism (MA)

The Model Analogism is a method used to derive relevant conclusions and recommendations. In the process of constructing the aerospace equipment chain, the Model Analogism approach involves drawing analogies between the supply chain and logistics models with the aerospace equipment maintenance and support chain. This helps simplify complex real-world problems into known models or similar problem characteristics. Please refer to **Figure 2** for an illustration of the related process.

This article draws inspiration from successful practices in other industries or fields, such as the closed-loop supply chain model in the supply chain or the maintenance service supply chain model. These models are compared with the characteristics of aerospace equipment maintenance and support to comprehensively understand and analyze the maintenance and support chain for aerospace equipment, to solve the problem of constructing the maintenance and support chain.

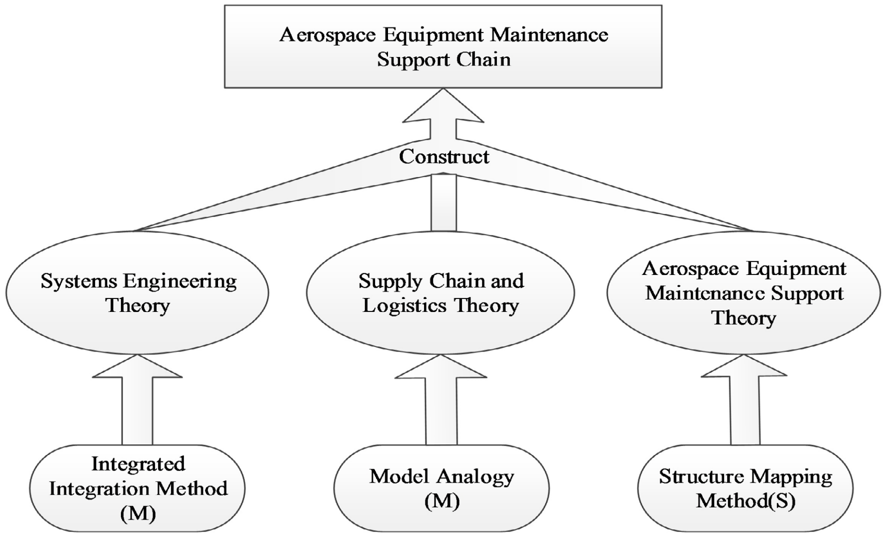

Figure 1. Diagram of the MMS method.

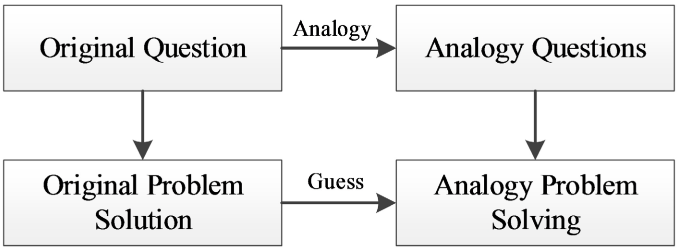

Figure 2. Model analogy operation diagram.

4.2.3. Structural Mapping (SM)

In the construction of the model for aerospace equipment maintenance and support chain, Structural Mapping (SM) is a commonly used method. SM analyzes and maps the relationships between different components (such as logistics, information flow, and personnel flow) in the maintenance and support activities of aerospace equipment, establishing the overall structure of the maintenance and support chain. Please refer to **Figure 3** for an illustration of the related process.

Structural Mapping is an effective method for constructing and optimizing the model of aerospace equipment maintenance and support chain. By analyzing and mapping various links and functional modules, it is possible to establish the overall structure of the maintenance and support chain, which is beneficial for further optimization and validation.

In the process of addressing the problem of constructing the model for the aerospace equipment maintenance and support chain, relying solely on a single method cannot abstract the complete chain structure comprehensively. It fails to represent the nature and characteristics of the chain. The method based on MMS (Multi-dimensional Modeling and Simulation) integrates the theories of system engineering, chain modeling, and practical problems from three dimensions. It demonstrates the operational status of the aerospace equipment maintenance

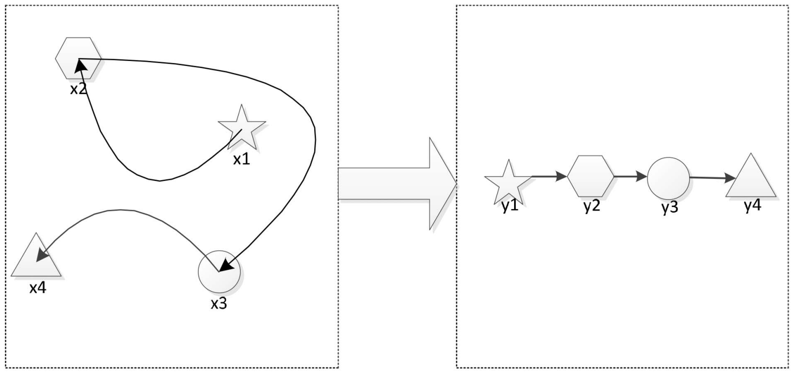

Figure 3. Structure-mapping representation.

and support chain, facilitating a better understanding of its characteristics and patterns. This lays the foundation for adjusting and optimizing the multi-equipment aerospace equipment maintenance and support chain in future specific tasks.

4.3. Model Construction

1) Constituent Elements

The maintenance support chain for aerospace equipment is composed of three primary constituent elements: maintenance entities, maintenance activities, and operational mechanisms. These elements, in turn, serve as the three essential factors that influence the construction process of the maintenance support chain.

a) Entities responsible for maintenance: Maintenance entities refer to units or institutions that provide maintenance services for aerospace equipment. These entities can be legal, functional, or physical. Legal entities are institutions established by law, such as equipment support units, user units, and repair units. Functional entities are specific departments within legal entities, such as equipment support agencies, after-sales departments of repair units, and control centers. Physical entities are specific locations that primarily handle tasks related to spare parts storage and product maintenance, such as repair facilities, equipment warehouses, and maintenance personnel. Properly qualified maintenance entities should possess the necessary functions and capabilities to undertake professional maintenance support work, equipped with advanced technology, equipment, and skilled maintenance personnel capable of providing maintenance services with higher technical content and difficulty.

b) Maintenance activities: Maintenance activities play a critical role in the aerospace equipment maintenance support chain. They can be categorized into preventive maintenance, corrective maintenance, and improvement maintenance, depending on their nature and purpose. Corrective maintenance activities involve fault diagnosis, fault location, fault repair, and inspection, along with corresponding management processes such as issuing maintenance work orders, creating maintenance plans, and utilizing maintenance resources. The process of maintenance activities involves the application of maintenance techniques and the supply of equipment and spare parts to maintain and restore equipment performance and condition. The aerospace equipment maintenance support chain facilitates the bidirectional flow of logistics, personnel, funds, and information between the upstream and downstream ends.

c) Operational mechanisms: The operational mechanisms of the aerospace equipment maintenance support chain consist of the command and decision-making relationship and the operational relationship of business activities. In terms of the command and decision-making aspect, it includes mechanisms for command organization, information communication, decision-making planning, and coordination control. Under the joint influence of these mechanisms, the rapid connection of various equipment links in the maintenance support process is achieved, forming a closed-loop maintenance chain with time and effectiveness as the main objectives. In terms of the operational relationship of business activities, this is primarily reflected in the execution process of maintenance plans. It includes mechanisms such as information transmission and sharing, demand generation, resource allocation, autonomous collaboration, evaluation, and assessment, ensuring the smooth flow of various flows.

2) Process Analysis

The aerospace equipment maintenance support chain is an open chain, and changes in the military, local, market, and battlefield environments can lead to adjustments and reorganizations in the chain, making its construction dynamic and complex. Its construction involves basic components of brewing, argumentation, selection, implementation, and evaluation, with different focuses at different stages. Based on these characteristics, it is reasonable to construct the space equipment maintenance support chain using system engineering methodology and the whole life cycle theory. After qualitatively judging the overall chain and the conceptual models of each link, it is desirable to convert them into mathematical models or structural diagrams to obtain intuitive and specific models.

a) Symbolic model: The aerospace equipment maintenance support chain can be abstracted into a symbolic model where each level of maintenance entity is represented by individual points called nodes, represented by letters and numbers. Legal entities, functional entities, and physical entities can be represented by LEb, LEs, LEx, FEj, FEs, FEz, PEc, PEk, and PEl, respectively. Equipment flow can be represented by EF, with EFz representing equipment logistics, EFb representing spare parts logistics, and EFq representing maintenance equipment logistics. Information flow can be represented by IF, with IFs representing data information flow, and IFk representing control information flow. Technology flow can be represented by TF, where TFy represents remote technical support, and TFx represents on-site technical support using personnel or equipment as carriers. Maintenance entity capacity and ability can be represented by C (Cz, Cx) and A, respectively, where Cz represents the total capacity and Cx represents the current capacity. Time can be represented by T (t1, t2, t3), while μij represents the repair rate of equipment j by link i, μci represents the intact rate, spare part utilization rate, and satisfaction rate of equipment i, and Spending is represented by S (s1, s2, s3). A model describing the aerospace equipment maintenance support chain can be represented as $PE_{ij}(Cz, Cx)$: A => $PE_{ij}(Cz, Cx)$, where the jth physical entity and the ith chosen basic structure of the chain link are included.

$$A \Rightarrow \begin{matrix} PE_{11}(Cz,Cx) - & PE_{12}(Cz,Cx) - & PE_{13}(Cz,Cx) \\ PE_{21}(Cz,Cx) - & PE_{22}(Cz,Cx) - & PE_{23}(Cz,Cx) \\ PE_{31}(Cz,Cx) - & PE_{32}(Cz,Cx) - & PE_{33}(Cz,Cx) \end{matrix}$$

b) Graphical model

In the construction of the graphical model, circles (referred to as nodes) symbolize points of equipment demand, repair, and the manufacturing and storage of spare parts. Legal entities and functional entities are depicted by squares (known as nodes) which include entities such as the military, local corporate legal bodies, military equipment management agencies, and manufacturers. The lines (referred to as edges) represent the connections between maintenance entities, with solid lines indicating material flows, dashed lines representing information flows, and arrows denoting the direction of these flows. The width of the edges signifies the rate of equipment flow per unit time, signifying the maximum capacity between the entities, while the vertical length depicts the time required for the entire chain's operation. Nodes are interconnected in a specific manner, forming a graph-theoretical maintenance support chain. For a visual representation of the process, please refer to **Figure 4**.

Indeed, within the chain, aerospace equipment possesses intricate technical complexity and often involves multiple subcontractors throughout the stages of development and production, assuming roles and functions akin to suppliers within a supply chain. These subcontractors hold indispensable positions as nodes within this chain. In the aerospace equipment maintenance support chain,

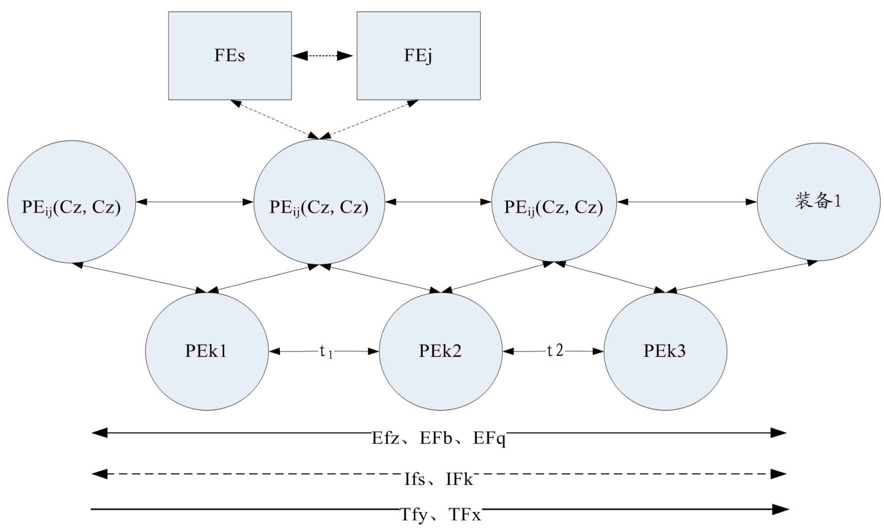

Figure 4. Presents the model representation of the aerospace equipment maintenance support chain.

certain additional auxiliary equipment is entrusted to secondary repair contractors for maintenance. Hence, similar to the demand side, the social component of maintenance support in the maintenance support chain encompasses multiple entities engaged in the mutual transmission of various flows, rather than solely relying on a single subcontractor.

Maintenance facilities bear the responsibility of multiple maintenance sites or user units, often consolidating diverse equipment from different locations for repairs at a single maintenance facility, based on its capacity and capability. Thus, a network model becomes a more precise means of elucidating the intricate maintenance support relationships present in real-world aerospace equipment scenarios. Its descriptive power in capturing the equipment maintenance support relationships is considerably stronger, lending itself aptly to macroscopic comprehension of these support relationships.

The network model theoretically encompasses all maintenance support units and acknowledges the existence of connections among these entities. Typically, a node is only correlated with a limited number of other nodes, yet this does not impede our theoretical framework for the maintenance support chain model. Drawing on insights from supply chain models and aerospace equipment maintenance support, we formalize the resources dedicated to aerospace equipment maintenance support into the model depicted in **Figure 5**.

Indeed, the formation of maintenance support chains ensues naturally throughout the process of guaranteeing the equipment's ability to complete its tasks. The greater the complexity and intensity of the tasks, coupled with the number of equipment involved, the more maintenance support chains will emerge. Furthermore, there may exist overlapping sections within a particular range. Information and material flows within the maintenance support chain must be bidirectional. Subpar equipment (or spare parts) flows from the using unit, maintenance site, or base to the repair unit's factory, whereas repaired parts flow from the factory to the supply at various levels, ultimately reaching the using unit. In exceptional cases, equipment logistics and information flows may bypass intermediate nodes and directly propagate towards both ends.

5. Construction of Equipment Maintenance Support Chain Evaluation System

According to the literature and input from relevant experts, the aerospace equipment maintenance support chain integrates the characteristics of both military supply chains and equipment maintenance support. When developing evaluation indicators, it is crucial to follow system evaluation theory, discarding insignificant factors and only considering those that have a significant impact on equipment maintenance support. The evaluation should be based on the structure of the maintenance support chain, taking into account the key elements that influence equipment maintenance support. The primary focus is on assessing the operational effectiveness of the maintenance support chain, providing a

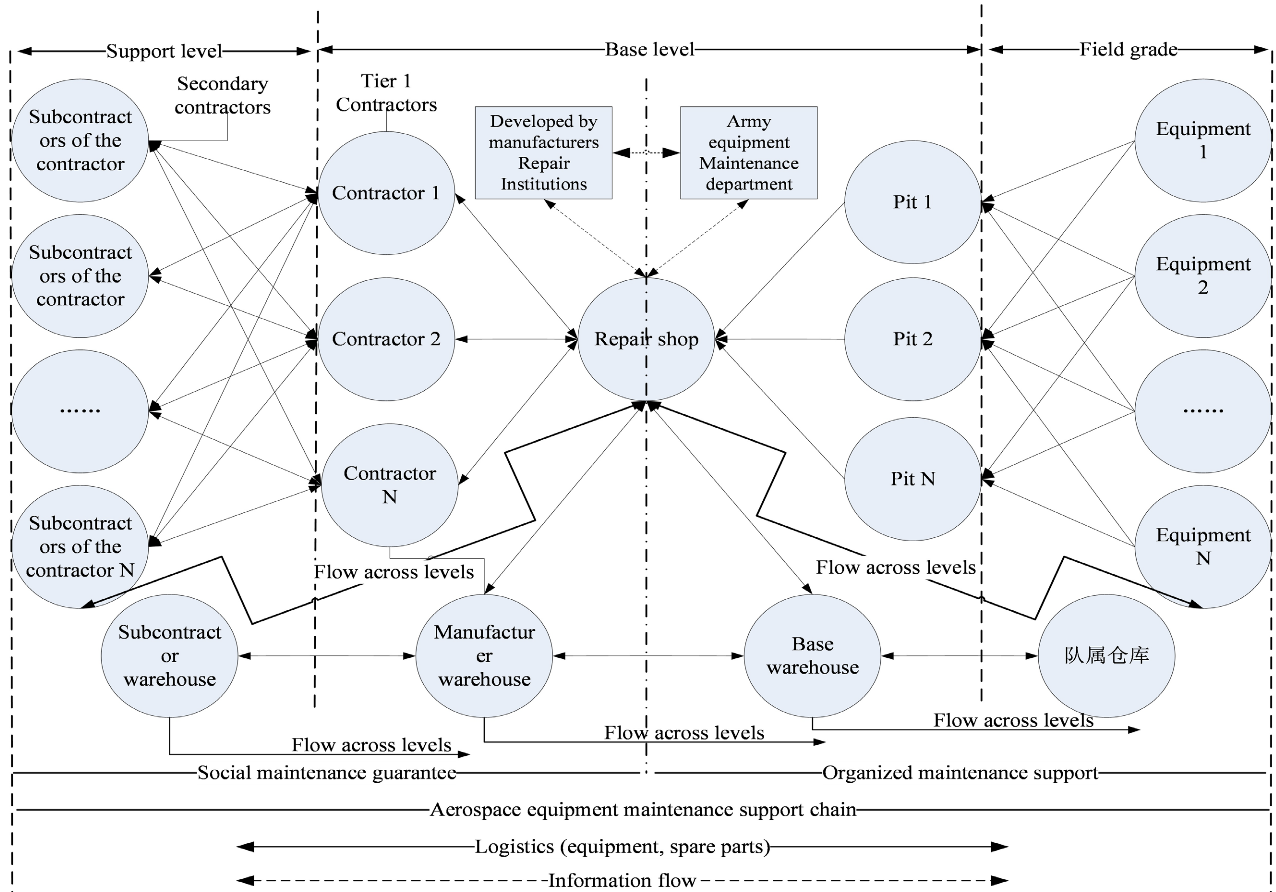

Figure 5. The model of aerospace equipment maintenance support resources.

comprehensive evaluation of "achieving equipment maintenance support tasks within a stable foundation and a specific cost range." This evaluation encompasses stability, cost-effectiveness, and military benefits.

Consequently, the evaluation indicator system is devised from three main aspects: stability, cost-effectiveness, and operational efficiency of the equipment maintenance support chain. As depicted in **Figure 6**, the stability indicator evaluates how much the structure of the equipment maintenance support chain is influenced by the environment. The cost-effectiveness indicator assesses the cost constraints associated with the equipment maintenance support chain. Lastly, the efficiency indicator evaluates the performance of the equipment maintenance support chain from a functional perspective.

5.1. Stability Indicators

The reliability of the equipment maintenance support chain structure refers to its ability to function properly within specified timeframes and conditions. The specified time refers to the operational duration of the equipment maintenance support chain, while the specified conditions encompass the prescribed structural configuration, facility, and equipment setup, as well as the operational environment of the support chain.

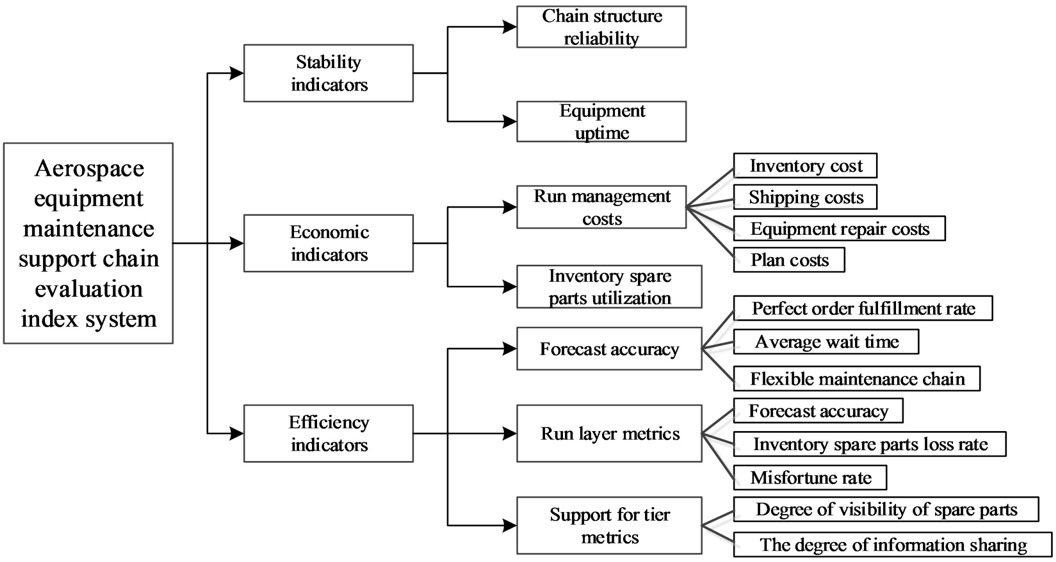

Figure 6. The evaluation indicator system.

The reliability of the equipment maintenance support chain structure can be evaluated by examining the reliability of the equipment maintenance support chain itself. Drawing inspiration from reliability measurement methods utilized in supply chains, as mentioned in literature sources [8] [9], both the minimum path set method and the minimal cut set method can be employed. The minimum path set method can be mathematically represented by the equation:

$$R = 1 - \prod_{S=1}^{P} \left(1 - \prod_{[i,j) \in Ps} R_{ij}\right) \quad (1)$$

The method of determining the minimum cut set can be formulated as follows:

$$R = \prod_{S=1}^{K} \left\{1 - \prod_{[i,j) \in Ks} \left(1 - R_{ij}\right)\right\} \quad (2)$$

whereas R signifies reliability, p denotes the minimum count of pathways, $[ij)$ represents the chain fundamental unit composed of the initial node i and its adjacent node j, R_{ij} signifies the reliability of the chain fundamental unit, Ps stands for the set of fundamental units in the s-th minimum pathway, Ks represents the set of fundamental units in the s-th minimal cut set, and k symbolizes the minimum count of cut sets in the chain.

The Equipment Serviceable Rate (ESR) reflects the equipment's condition over a specific period and, to some extent, mirrors the management of the equipment by the employing entity. The Equipment Serviceable Rate is calculated as follows: ESR = (Number of Functioning Equipment/Total Number of Equipment) × 100%.

5.2. Cost-Effectiveness Indicator

When evaluating the maintenance support chain of equipment, it is imperative to consider its operating cost. Operating cost encompasses various expenditures incurred during the operation of the maintenance support chain, including human resources, resources, materials, equipment, and technical support. Although maintenance support costs are relatively limited in their consideration for tasks, the direct impact of operating costs on the economic benefits and development potential of the contracting enterprise within the entire aerospace equipment maintenance support chain cannot be disregarded. It also influences the cost-effectiveness of military expenditures. Lowering costs can enhance the overall benefits of the equipment maintenance support chain, thereby improving efficiency, preserving resources, and strengthening the chain's stability. This includes the evaluation of the costs of chain operation and spare parts utilization.

a) The Maintenance Support Chain Cost (MSCC) signifies the expenses involved in the operation of the maintenance support chain and can be categorized into four parts: Plan Cost (PC), Storage Cost (SC), Logistic Cost (LC), and Repair Cost (RC). The formula for calculating MSCC is MSCC = PC + SC + LC + RC. RC denotes the cost incurred from repairing faulty equipment within the various levels of maintenance organizations. If the repair cost is excessively high and the equipment is deemed beyond repairable value, it will be directly discarded.

b) The Spare Parts Utilization Rate (SPUR) is described as the ratio of the quantity of spare parts used in a certain period to the average inventory level, reflecting the management and utilization of spare parts inventory. Generally, a higher spare parts utilization rate implies a faster turnover rate of spare parts in the equipment maintenance support chain, indicating good operation of the equipment maintenance support chain. A low spare parts utilization rate indicates either a backlog of inventory or poor operation in the maintenance support chain.

However, excessively high utilization rates of spare parts can increase costs due to increased logistics frequency, while low inventory levels may lead to stockouts and threaten the supply chain's stability.

5.3. Efficiency Indicators

Borrowing from the supply chain theory, the performance of equipment maintenance and support can be categorized into three divisions: outcome performance, operational performance, and support performance [9]. The efficiency indicators for the equipment maintenance and support chain are constructed based on three perspectives: outcome layer indicators, operational layer indicators, and support layer indicators. The outcome layer indicators represent a comprehensive evaluation of equipment utilization, while the operational layer indicators assess the efficiency of the chain's operations. The support layer indicators evaluate the fundamental conditions that facilitate the chain's operations.

a) The outcome-level indicators signify the final output performance of the chain and are measured in terms of speed, quality, and flexibility using three indicators: average waiting time for users, perfect order completion rate, and adaptability to demand surges. The perfect order completion rate (POC) is a comprehensive measure of the chain's ability to fulfill the requirements of the end-users, defined as the ratio of the number of flawless orders to the total number of orders. The average waiting time (AWT) refers to the mean duration users wait for maintenance spare parts within a specific period, encompassing both the average equipment repair time and order delivery time. The adaptability to demand surges is characterized by the stochastic occurrence of equipment failures resulting from fluctuations in equipment usage time and environmental factors. During periods of substantial equipment losses, the demand for equipment maintenance surges within a short span, necessitating the flexibility of the maintenance support chain. Generally, the adaptability to demand surges is employed to measure the chain's flexibility, which can be determined through statistical analysis of the completion status during periods of increased orders in the actual operational process.

b) The operational layer indicators encompass all activities associated with the maintenance and support process. Among these pivotal elements, the key aspects primarily comprise planning, maintenance, inventory, and transportation. To this end, the evaluation of these three key aspects is conducted utilizing three indicators: forecast accuracy, resource loss rate, and logistics error rate. Forecast accuracy assesses the precision of predicting maintenance demands (referred to as Forecast Accuracy, FA) through a comprehensive maintenance plan developed by equipment support units. The accuracy is measured by the degree of conformity between the predicted maintenance demand quantity (ADF) and the actual maintenance provision quantity (AAP) within a given time frame, denoted as PA. The calculation formula can be expressed as follows:

$$\mathrm{PA}=\begin{cases}\dfrac{\mathrm{ADF}}{\mathrm{AAP}}, \mathrm{ADF}<\mathrm{AAP}\\ 1, \mathrm{ADF}=\mathrm{AAP}\\ \dfrac{\mathrm{AAP}}{\mathrm{ADF}}, \mathrm{ADF}>\mathrm{AAP}\end{cases} \tag{3}$$

The resource loss rate is defined as the prompt response of the equipment maintenance support chain to defective equipment, necessitating a certain level of surplus resources at each link of the chain. Owing to inefficient utilization of such resources, they incur unwarranted losses over some time. The resource loss rate (RLR) quantifies this phenomenon as the ratio between the quantity of lost resources and the total resource quantity within a specific time frame. The logistics error rate (LER) relates to multiple logistical interactions involving the circulation of equipment and spare parts among repair contractors, military warehouses at various levels, and user units within the maintenance support chain. In addition to meeting time requirements, spare parts logistics must also ensure accuracy in terms of quantity, type, and delivery location. The logistics error rate measures this performance by calculating the ratio of the number of logistics errors occurring in the equipment maintenance support chain over a given time frame to the total number of logistics orders.

c) Regarding the support layer indicators, the acquisition and communication of information serve as the fundamental pillars supporting entities within the equipment maintenance support chain in fulfilling their supporting tasks. It is also a crucial element influencing the performance of equipment maintenance and support. The assessment of these indicators encompasses the extent of visualization and information sharing. Enhanced visualization can expedite the processing and delivery speed of equipment maintenance requests, while the degree of information sharing influences the formulation and implementation of plans at various links of the chain, thereby measuring the speed and quality of information transmission. Due to the difficulty of quantitatively analyzing these two indicators, expert assessment methods are employed for their evaluation.

6. Conclusion

This study incorporates supply chain and logistics theories, in conjunction with the practicalities of aerospace equipment maintenance and support, to proffer a systematic depiction of the aerospace equipment maintenance and support chain. A model for this chain is formulated and initial research on its evaluation metrics is conducted. The ensuing step centers on refining the design of the aerospace equipment maintenance and support chain to cater to specific tasks. Through the development of mathematical or simulation-based evaluation models, the aerospace equipment maintenance and support chain can be comprehensively evaluated.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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