

Ontology-approach for Modelling of Maintenance Capability of Complex System Environments

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Abstract. The increasing complexity of maintenance operations in Industry 4.0 environments demands more structured approaches to managing capability-related data across multiple stakeholders. This paper presents a proof-of-concept ontology for maintenance capability, grounded in the DOTMLPFI framework, Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, and Interoperability, originally developed for military capability modeling. The ontology is constructed and evaluated through a case study of the Finnish Navy's Squadron 2020 (SQ2020) Corvette Program, selected for its rich and well-defined maintenance capability requirements. By integrating model-based systems engineering principles with formal semantic technologies, and incorporating expert input, the approach enables structured reasoning over heterogeneous data relevant to maintenance planning and capability assessment. The study demonstrates how the DOTMLPFI framework, when formalized ontologically, can support improved data integration and interoperability across organizational boundaries. This supports more coherent capability development and decision-making in both military and civilian contexts. The initial ontology was validated using competency questions and logical reasoning, confirming semantic adequacy. This research contributes a reusable semantic framework for maintenance capability modeling and offers a foundation for ontology-driven decision support and future integration with digital twin architectures.

Keywords. Capability Development, Capability ontology, System of Systems, Data Management

Introduction

A traditional way of evaluating the success of an organization is to measure its performance and around this idea several theory frameworks have been formed. These include but are not limited to the Resource-based View(1), Balanced Scoreboard (2), Porter's Five Forces (3), Stakeholder Theory (4) and Dynamic Capabilities Framework (5). Each of these frameworks emphasizes specific aspects of performance, often requiring distinct metrics such as effectiveness, efficiency, quality, profitability, productivity, quality of work life, and innovation (6). Performance metrics or Key Performance Indicators (KPI) are essential in performance analysis, connecting theory to practice by providing the empirical evidence necessary to apply and validate these theoretical frameworks (7). However, not all KPIs are equally relevant to all stakeholders within the same organization. More fundamentally, these performance outcomes are

dependent on the organization's capabilities, its structured ability to coordinate resources, systems, and processes in pursuit of strategic goals. Capability development thus forms the foundation upon which measurable performance is built, especially in complex environments where responsibilities, technologies, and data are distributed across multiple actors.

In complex maintenance operations and successful execution of selected maintenance concepts and strategies (8) the need for different data is significant. Data is a key factor in Maintenance 4.0 which has been formed from the concept and tools of Industry 4.0. As with the first three industrial revolutions, the fourth has its identifying innovations. Industry 4.0 is the next evolutionary step, and it is governed by the advancements of the information society. Embedded within Industry 4.0 are virtual technologies or related areas like Cyber-physical systems, Internet of Things, cloud computing, machine learning, and Additive Manufacturing (9–13). Interest towards data utilization in the defense maintenance context is also increasing (14) due to requirements for cost optimization and demand for increased operational availability (15).

To holistically develop and identify the interdependencies between systems and capabilities, many military organizations have adopted structured and scalable capability models (16). One of the most widely used frameworks is DOTMLPFI (Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, and Interoperability) which standardizes capability development across domains (17,18). While such frameworks may reduce some flexibility in the development process, they provide a systematic approach to quantifying capability across both individual systems and complex system-of-systems. According to Handy (1992), organizations require both local independence and centralized governance to function effectively (19) and DOTMLPFI supports this balance by encapsulating all major capability elements within a common structure. In this study, the DOTMLPFI framework is applied specifically to maintenance capability development, addressing the challenge of organizing and interpreting heterogeneous maintenance data across systems and stakeholders. The framework is then evaluated through a real-world case: the Finnish Defence Forces' Squadron 2020 (SQ2020) Corvette Program. This program involves two main industrial partners, Saab Surveillance, responsible for delivering the combat system, and Rauma Marine Constructions, which provides the ship platform and related systems, both coordinating with a wide network of subcontractors and OEMs supplying subsystems (20). The SQ2020 program presents a rich, multi-stakeholder environment with well-defined capability requirements, making it an ideal setting for constructing and validating the proposed ontology.

In the context of public-private partnerships, such as those found in defense maintenance ecosystems, the challenge of managing capabilities becomes even more pronounced. Here, strategic oversight by public entities must align with the operational

execution of private organizations, often across institutional and geographical boundaries (21). Balancing centralized governance for purposes like compliance and KPI alignment with the need for local flexibility in implementation is critical. Handy's federalism model underscores this need to maintain both coherence and autonomy (19). The DOTMLPFI framework, by offering a comprehensive and modular structure, supports this balance by enabling capability integration across organizational interfaces (17,18). Its multidimensional scope allows for the development of a shared ontology that bridges the diverse perspectives of public and private actors. This approach enhances interoperability (22), facilitates structured data exchange and strengthens coordinated maintenance capability planning, especially in complex, system-of-systems environments where performance depends on both strategic direction and operational agility (23).

Although there is extensive literature, standards, and research on maintenance, capability development, and performance evaluation, as well as studies addressing ontology concepts in maintenance management (8,24–27), a conceptualization of maintenance capability, its capability elements and data drivers for these remains underdeveloped. This study uses the DOTMLPFI framework and its capability elements to identify the data drivers that act as a point of interest for the maintenance organization regarding its capability. We will provide an ontology based on a literature review and military maintenance expert interviews. Processing on ontology enables the synthesis of conceptual solutions for managing and sharing information, the use of authoritative truth, and continuous life-cycle support. The military capability model, the DOTMLPFI framework, is used as an input for the conceptual design of the maintenance system and is supplemented with previous domain knowledge from various stakeholders. Although most of the ontology is still under development, the feasibility of the chosen approach was successfully evaluated with CQs. The developed initial ontology for maintenance activity terms serves as a tool to coordinate reliability requirements between the System-of-interest (SOI) and the maintenance organization. The rest of this paper is structured as follows:

- 1) **Literature Review on Capability Development:** We conducted a comprehensive literature review to explore capability development in both military and civilian organizations, with a focus on maintenance capability. Special emphasis will be placed on integrating the capability elements of the DOTMLPFI model with existing theoretical frameworks used in civilian capability development, bridging the gap between military and civilian perspectives.
- 2) **Framework for the Reference Ontology of a Maintenance System:** We developed a reference ontology for maintenance systems using the DOTMLPFI framework as the foundation. Collaborating with a team of defense

maintenance experts from Millog Oy (a strategic partner of the Finnish Defence Forces), we will identify key data drivers that influence maintenance system performance. CQs will be formulated to validate these data drivers, and relevant stakeholders in the maintenance capability process will also be identified.

- 3) **Creation of the Ontology:** We formed ontological terms and constructs related to maintenance capability and used the DOTMLPFI framework to create the ontology. This ontology will provide a structured representation of maintenance capabilities, supporting data-driven decision-making and performance optimization.
- 4) **Modelling and testing the Ontology:** We tested the concept ontology with the CQs to analyze the coherence of the ontology.

As a result, we will present the first conceptualized ontology of the maintenance capability produced by using a DOTMLPFI capability model.

Literature review

Basis for ontology

Most systems include both human and machine-produced data. While humans benefit and understand graphical and textual data models, these are often too simple for machine interpretation. As systems are presented with structured views, i.e., configurations, the data streams have at least the same structures, but often they use different models or modelling languages. In order to run simulations and calculate the necessary KPIs for the system, the model used and thus the ontology need to be formal enough to be understood by information systems and graphic enough for human interpretation (28).

Ontologies are based on subject-predicate-object statements called "triples", which can be expressed in a language called the Resource Description Framework (RDF). Triples are statements that describe the entities of the modelling domain, their properties, and their relationships with other entities. The triple represents the data set to be described; a predicate expresses a relationship between a subject and an object. RDF and RDF Schema (RDFS) form the basis of the Web Ontology Language (OWL) (29,30).

A domain-neutral top-level ontology can be used in conjunction with lower-level ontologies to support data exchange, search, discovery, integration and analysis (31). Lower-level ontologies are implemented in domain-specific languages, where a domain refers to a collection of entities that are of interest in a particular domain, such as military maintenance. In addition to being a conceptual representation of knowledge, ontology is also a model for systems to be built and is thus also normative in nature.

Semantic technologies not only facilitate communication but also create the basis for reasoning and decision-making by enabling computers to understand the meaning behind information. Ontologies are built on the principles of formal logic, which can be used to draw conclusions based on the rules of logic through the reasoning process. These formal bases allow implicit data to be created by inference from existing data. In addition, rule formalisms have been built on top of the ontologies, which further supplement the data with if-then style rules. Data and metadata stored in the ontology can be retrieved and stored using a standardized graph query language called SPARQL. Unlike standard SQL queries, SPARQL queries can range from metadata to data because they are both stored in the same triple format.(32)

The degree of formality of ontology is mainly determined by the purpose of the ontology. If the ontology is a framework for human-to-human communication, the representation can be informal, but if the ontology is to be used in software tools or intelligent agents to support automated tasks, a more formal representation is needed, as is the case here. To encode the ontology, an ontology representation language (RDF/OWL) has been chosen. Ontologies of time and space are particularly important in military domains because reasoning in a dynamic world requires formal ways of describing spatial and temporal entities. The order and temporal sequence in which entities are perceived are crucial for their interpretation. Ontological design requires a development environment that facilitates the construction and maintenance of ontologies, especially as the number of concepts and relationships grows. Tools, such as Protégé (Musen, 2015), provide functionality for editing concepts, browsing the ontology, etc. In cases where conceptual structures are primarily descriptive or hierarchical, rather than requiring rich logical semantics, the Simple Knowledge Organization System (SKOS) offers a lightweight alternative to formal ontologies. As a W3C standard built on RDF, SKOS is designed for representing controlled vocabularies, taxonomies, and classification schemes (33).

Capability Development

Within systems engineering, capability refers to the ability of a system, subsystem, or component to perform a specific function or set of functions within a given operational context. Capabilities can be defined and specified at various levels of abstraction, from high-level mission requirements to detailed functional and performance specifications (34). This leads to the idea of an embedded hierarchy of capability where lower-level capabilities form or contribute towards higher-level capabilities within the maintenance support infrastructure (16,35).

Several studies support the idea that capabilities consist of different elements, such as resources, processes, routines, knowledge, and competencies (5,36,37) or, as stated, lower-level capabilities. Teece et. al. in their study present the idea that the different

elements of corporate capabilities, like technological, managerial and financial, are interdependent and should not be viewed separately (5).

The connection between capability and performance is seen in theory frameworks. The Theory of The Growth of the Firm (36) depicts firm as a collection of resources, processes and capabilities and the Dynamic Capability View expands this by asking “(i) why firms exist in a market economy; (ii) what determines the boundaries of the firm; (iii) how firms should be organized to align incentives for managers and owners; and (iv) how they should be structured financially to maximize profits and minimize managerial malfeasance”(38).

Because hybrid organizations are increasingly common in modern business environments (39), the identification and management of firms’ capabilities, as well as their relevant data drivers, have become more challenging. A central issue lies in determining the appropriate level of abstraction for these capabilities: they must be defined broadly enough to support centralized KPI formulation, yet not so rigidly as to undermine the autonomy of local units. This dilemma was illustrated by Handy, who introduced a federalism model for organizations aiming to balance central authority with local independence. According to Handy, both elements are necessary; however, challenges emerge when flexibility and coherence must be simultaneously maintained. Enhancing one often comes at the expense of the other (19).

As there is not a unified terminology for commercial and military capability development frameworks, for the purpose of this study and modelling in Protégé, we use the following definitions to form an adequate level of abstraction:

- *Capability: ability of a system, subsystem, or component to perform a specific function or set of functions within a given operational context (40).*
- *Capability element: A fundamental component or factor within a capability framework that contributes to the development, execution, or support of a system's or organization's ability to perform its intended functions. In Protégé these are modelled as Classes.*
- *Data driver: A data driver is a quantifiable factor or metric derived from available data that influences decision-making, informs the evaluation of performance, or drives improvements in a specific capability element. In Protégé these are modelled as Properties.*
- *CQ: A structured query designed to identify key data drivers for maintenance capability by probing specific aspects of each capability element within the DOTMLPFI framework. CQs serve two purposes: (1) as research questions that guide the identification and analysis of relevant data, and (2) as test questions used to validate the ontology.*

Maintenance Capability design framework and its Stakeholders

The performance of SOI and its KPIs, like reliability, availability and maintainability and of its supporting maintenance system are primarily measured by evaluating a system's ability to perform its intended function in its designated operating environment. This evaluation relies on probability and statistical analysis, which both require sufficient and well-defined data (41). Reliability, availability and maintainability are sometimes described to be part of the so-called system "ilities" (42–44) which are non-functional or quality attributes of the system that often cannot be explicitly quantified numerically in a system of systems context. They still represent desirable attributes of systems, and they are usually seen only after the system has been commissioned (43,44). These properties and their impact and effects are either hard to plan or predict in the design phase for a number of reasons (45,46) but mainly due to the complexity of multi-unit systems and economic, stochastic, structural or logical interdependencies between different system elements (13).

Maintenance operations are divided and grouped into different levels. The number of levels in different categorizations varies, but the basic idea remains the same: the maintenance tasks vary based on their difficulty, needed resources and/or by executing organizations (7,47–49). For example, after Desert Storm, the US Air Force, in advance, started testing a more streamlined maintenance organization constructed only from two levels instead of four. The Two-Level Maintenance concept was created to optimize the maintenance capability and to meet the requirements of expeditionary, operational, and home-station domains simultaneously (50,51). In the French standard "Industrial Maintenance - Maintenance function", maintenance is divided into five levels based on the complexity of the maintenance tasks (49). The increased number of maintenance levels and increased outsourcing of maintenance have brought more enterprises into the overall value chain of maintenance.

According to Mobley, all preventive and predictive maintenance programs are time-driven (52). This means that the performance indicators of the system are dependent on the time stamps of different incidents. This is why the link between the *availability of the SOI* and the *capability of the maintenance system can be found through availability and the system of interests required in up states and down states*. For the system of interest, the availability timetable set in Figure 1 applies. The corrective maintenance time limits the planned availability (i.e., required time) of SOI. Preventive maintenance actions are preplanned, and they are done during the non-required time of the SOI (53). However, they still restrict the operations of the SOI, and thus, the execution of preventive maintenance and its related delays need to be considered during the planning process. Time-related maintainability parameters that need to be specified at every maintenance level according to Dudley et. al. are:

- Mean time to repair (MTTR): Average time required to bring the system from a failed state to an operational state. Strictly design dependent. Assumes maintenance personnel and spares are on hand (i.e., does not include logistics delay time). MTTR is used interchangeably with mean corrective maintenance time (Mct).
- Mean maintenance manhours (M-MMH): Total manpower per year (expressed in manhours) required to keep the system operating (not including logistics delay time).
- Mean time to restore system (MTTRS): The average time it takes to restore a system from a failed state to an operable state, including logistics delay time
 $MTTRS = \text{logistics delay time} + MTTR$. Logistics delay time includes all time to obtain spares and personnel to start the repair. This is also referred to as maintenance Turn Around Time (TaT) (7).
- Preventive maintenance (PM): Time associated with the performance of all required preventive maintenance. Usually expressed in terms of hours per year. (54)

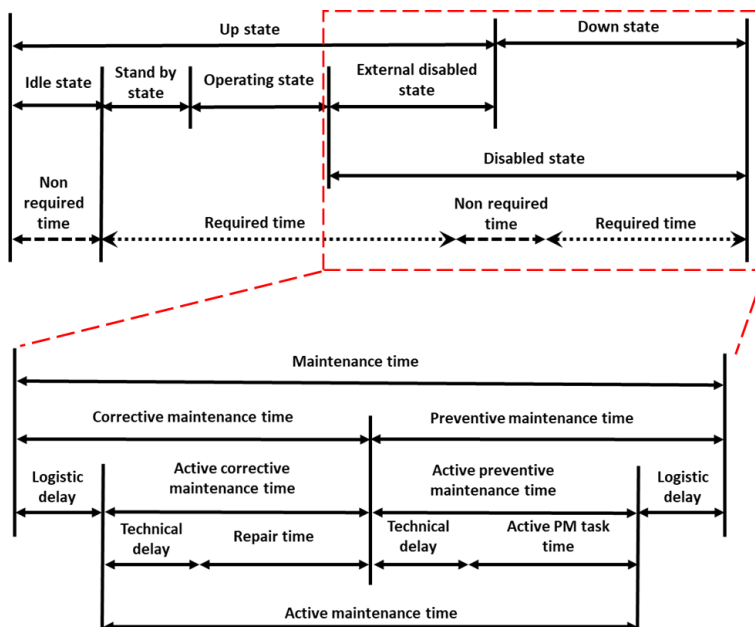


Figure 1. Link between the system of interest availability and supporting maintenance organizations capability (53).

Holt depicts a systems (design) framework made up of different viewpoints of stakeholders of the system and an ontology, which is used to describe the system (Figure 2). *Process set* is used to develop the framework and its related ontology, and to

model which is based on the ontology and the individual viewpoints of stakeholders. A stakeholder can be any real or abstract party, for example, a person, an organization, a process, or another system (55).

The system design and development process consists of five key stages: Conceptual Design, Preliminary Design, Detailed Design and Development, Production/Construction, and Operational Use and System Support. Throughout this process, the system of interest and its supporting maintenance organization are established using requirements and configuration management. This process follows a structured, well-established methodology with defined procedures and tools, which are documented extensively in systems engineering literature, standards, and the engineering practices of organizations (56,57).

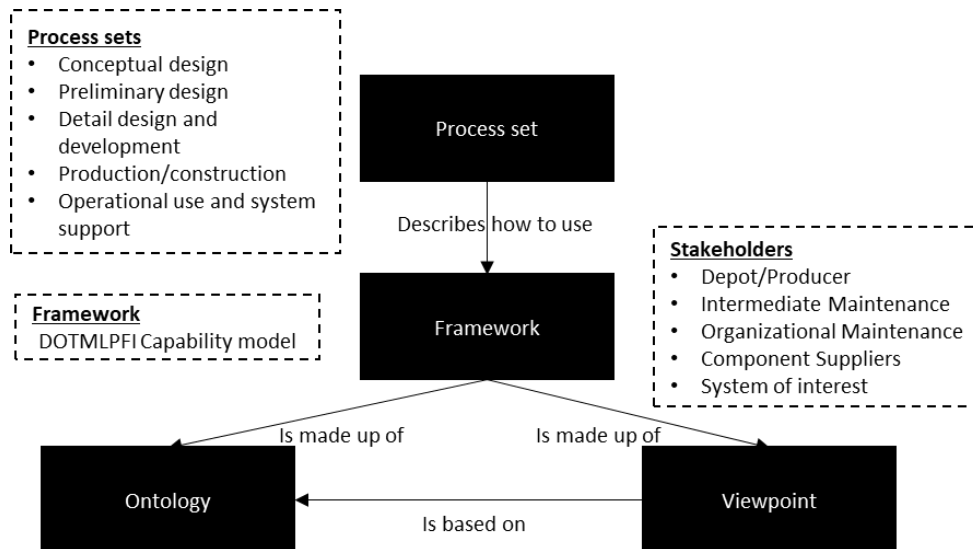


Figure 2. Approach for Conceptualizing the Maintenance Capability (7,55).

Several attempts have been made to form a general maintenance concept (58–60) however, according to Robson et al., they are challenging to follow due to the attempt to integrate both "process" and "content" (61). Also, the terms “maintenance strategy” and “maintenance type” and other maintenance-related terms are often used interchangeably (62,63). In the current research field, maintenance types in addition to corrective and predictive are, for example, Predictive, Prescriptive, Condition-based and Scheduled. These, however, can be seen as an extension of the primary categories of the first two (62) and as a part of the maintenance strategy “toolbox” (61).

According to the NASA's System Engineering Handbook from 1995, in the concept design phase maintenance concept is “typically described in terms of the anticipated levels of maintenance, general repair policies regarding corrective and preventive maintenance, assumptions about supply system responsiveness, the availability of new or existing facilities, and the maintenance environment” (47). During each step of

design, the SOIs configuration is expanded and developed, driven by the operational requirements and constraints of the SOI and the capability parameters of the maintenance design framework (54,64). The operational constraints for the maintenance capability set by the system of interest are (54):

- Operating hours per unit calendar time and/or per mission
- Downtime, maintenance time, or availability constraints
- Mobility requirements
- Attended/unattended operation
- Self-sufficiency constraints
- Reaction time
- Operational environment (e.g., chemical, biological and nuclear)
- Skill levels of maintenance personnel
- Manning
- Types of diagnostics and maintenance support equipment that can be made available or implemented (built-in test, manual test equipment, external automatic test equipment, etc.).
- Levels at which repair takes place
- Use of off-the-shelf equipment versus newly designed equipment

The operational constraints in the concept development phase of the SOI act as a requirement for the maintenance capability. Based on these requirements, all the crucial data drivers for the maintenance system performance can also be derived. When there is not sufficient involvement of the maintenance personnel or there is a lack of proper processes or practices to include maintenance-related requirements in a concept design phase (45) it does not provide enough prerequisites to implement for example increased machine or structural monitoring or automated and computer/artificial intelligent assisted decision making in maintenance task creation and optimization of system usage through its life cycle (65–67).

Capability element data drivers in maintenance performance

Over the past decade, advancements in data analysis methods and tools have shifted the focus of maintenance operations towards predictive and prescriptive maintenance (13,65–68). Predictive and prescriptive maintenance strategies utilize a data-based decision-making process. This emphasized the importance of data transfer between

different parties and information systems in electronic form through the system's whole life cycle (69). This leads to increased volume, variety, and velocity, also known as the three dimensions of Big Data (70,71). The properties of Big Data have also affected the industry sectors and their maintenance functions, resulting in the leaders of these organizations wondering whether or not they can fully utilize the available data (13,72).

Pincioli et. al. identified four practical challenges in maintenance optimization in regards of Industry 4.0. They are (1) the complexity of the industrial systems, (2) data acquisition and processing, (3) new optimization criteria and (4) prescriptive maintenance. For the first challenge, they call the development of methods that can deal:

- multipurpose systems for which multiple criteria should be jointly optimized;
- the uncertainty of the complex system behavior and the stochasticity of the environment in which the system operates;
- unknown dependences and inter-dependencies among components, subsystems, systems and even systems of systems (13).

The same kind of complexity as within capability development and hierarchies can be seen in data management. Janssen et. al. study the concept of Big Data and state that it is crucial to integrate multiple diverse data sources into a decision-making process. However, they also emphasize the fact that the simple assumption that Big Data alone improves the decision-making process is a simplistic one. They found that the “quality of the source data, the processing of the data and how the transfer of the data is handled influences the quality of decision-making”. They suggest that “to develop appropriate and effective contractual and relational governance mechanisms for managing the BD chain” (73).

Annunen et. al noticed that data management processes are not sufficiently recognized or defined for maintenance, and this leads to problems with data integrity, multiple data repositories (electrical and otherwise), roles and responsibilities in data management, and most of all discrepancies in relevant and irrelevant data (45). Also, the increased number of stakeholders that produce data in a system of systems context has led to a need to form standardized data models (74). R.L. Ackoff made a perceptive observation, whose importance has become increasingly evident with the rise of Big Data. He noted that, rather than requiring more relevant information, the key is to reduce the amount of irrelevant information (75). With a scalable capability model with elements including relevant data drivers, it is possible to "generate, obtain, confirm, transform, retain, retrieve, disseminate and dispose of information, to designated stakeholders" (35).

The challenges in defining data drivers in the DOTMLPFI model for capability development are similar to those encountered in Big Data and data management. Both

fields rely on identifying critical metrics that guide the structure, sharing, and management of data to achieve effective decision-making and performance optimization. By linking the two concepts, the term "data driver" can be seen as a key metric or influence factor in both the capability development process (DOTMLPFI) and data management, helping organizations manage complex systems and data-sharing environments effectively.

Doctrine

Doctrine is defined as the fundamental principles by which the organization, system, or force conducts its intended actions (76). In the context of manufacturing and maintenance performance, comparable overarching principles can be identified. Frameworks such as Lean Manufacturing, Total Productive Maintenance (TPM), Just-in-Time (JIT), and Six Sigma function similarly to doctrine, as they offer long-term strategic guidance and support consistent decision-making. For instance, Cua et al. argue that JIT, TPM, and Total Quality Management (TQM) should not be viewed in isolation but rather as components of an integrated framework for operational excellence (77).

Organization, Personnel and Training

An organization is a "person or group of people that has its own functions with responsibilities, authorities and relationships to achieve its objectives." (40). Organizational theory is largely studied in the field of sociology. It is divided into three main areas: organizational structure, organizational design and change and organizational culture. From these, the organizational design answers the questions of how and why a certain organizational structure is chosen, when the organizational structure and culture are means to achieve the objectives of the organization (78).

Material, Facilities and Personnel

The maintenance systems also include physical assets like Facilities, Materials and Personnel. These capability elements comprise all the physical resources, or attributes, of the maintenance system that are required to achieve the intended internal and external purpose of the system. Asset management is used to maximize the value of an organization and its respective stakeholders by prioritizing different functions. To achieve maximum benefits, asset management processes should be integrated into any existing parallel processes such as quality, finance, accounting, safety, security, risk, and human resources (67,79) which can also be stated through Organization, Training, Leadership, Interoperability and Doctrine. Many companies still see the maintenance strategy as separate from, for example, manufacturing and business continuity strategies, and thus it cannot fully support the companies' efforts (61) and optimize its assets.

Leadership

Leadership has a significant role in the performance of the organization (80). Leadership has also been studied from different perspectives. Burns (1978) identified two main styles of leadership: transactional and transformational leadership (81). Successful leadership in organizations requires leaders with the right qualities like the ability to learn, knowledge, confidence, motivation and loyalty. The leadership's role in strategic management and planning is central (80). Leadership's overarching influence over all of the organization's functions and processes connects it to all the other capability elements.

Interoperability

The central part of interoperability is ICT systems and data (82). According to the European Union, interoperability "is the ability of organizations to interact towards mutually beneficial goals, involving the sharing of information and knowledge between these organizations, through the business processes they support, by means of the exchange of data between their ICT systems" (83). The data-driven processes within different information systems utilize databases as a storage of information (84). When handling structured data, successful data management and interoperability between stakeholders require the usage of a common template, i.e., an ontology, to ensure the consistency of all future views of the systems (55,74). Problems arise when different data streams and their relationships are not clear. In systems with multiple stakeholders and information systems, similar and overlapping data needs are bound to happen. Because unnecessary overlap of data collection should be avoided (85) the different viewpoints of stakeholders should be combined to form the structured data model (86).

Materials and Methods

The conceptualization of maintenance capability was informed by a literature review of key systems engineering standards (Table 2) and enriched by insights from a team of defence maintenance experts at Millog Oy, a strategic partner of the Finnish Defence Forces. All the experts (Table 1) have extensive experience in maintaining a wide range of systems and technologies. The team's primary responsibility was to design maintenance capabilities for the Finnish Navy's new multipurpose corvettes as part of the Squadron 2020 project. The goal was to answer a primary question of "*what the maintainer needs to know in order to fulfil the set availability requirements for the SOI*". This was done by harmonizing the diverse maintenance capabilities of the different system suppliers (OEM) and integrating their individual capabilities into the overall maintenance capability of the SQ2020 corvettes (20).

Based on the initial work done by the Millog team, the need to conceptualize and develop a unified template for the corvettes' various systems (e.g., gas turbine, radar,

generator, main gun, etc.) and their characteristics was driven by the following considerations:

1. Ensuring the ability to observe and verify the maintenance and life cycle support elements provided by different system OEMs.
2. Providing measurable evidence and KPIs to demonstrate the maintenance system's capability in meeting the operational availability requirements of the SQ2020 Corvettes.
3. Formalizing Millog's internal capability development for future projects.

Table 1. The team of experts and their individual expertise

	Degree	Experience	Competencies
Expert 1	<i>B.Sc. Electronics Engineering, Meng. Technological Competence Management</i>	<i>6 years of experience in electronics manufacturing, 8 years of experience in product development and R&D, 4 years of experience in system engineering</i>	<i>R&D, Electronics and embedded software, System Engineering, Project Management, Sales and Customer Support.</i>
Expert 2	<i>B.Sc. Tech</i>	<i>10 years of experience in ICT, over 10 years of experience in Navy maintenance</i>	<i>ICT management, Project management, SW development and Systems engineering</i>
Expert 3	<i>B.Sc (tech), MSc (tech) student</i>	<i>About 4 years in the industry, of which 3 years in the military industry</i>	<i>Machine design, ILS, Systems Engineering, project work</i>
Expert 4	<i>Warrant Officer (retd.)</i>	<i>20 years of experience in the military and military industry</i>	<i>Expertise in naval armament systems, navigation systems, and systems engineering</i>

The work was carried out over a six-month period and consisted of four workshops, with individual tasks assigned to the experts between workshops. The work was guided by CQs formulated in the first workshop based on the planned maintenance concept, the

top-level operational requirements of the SQ2020 project (87), and the general operational constraints for maintenance are derived from both the maintenance concept and these requirements.

The structure of the workshops was as follows:

Workshop 1

- Identifying key literature and relevant standards (Table 2).
- Gaining familiarity with the DOTMLPFI framework within a military context, including its application in the Finnish Defence Forces (FDF).
- Understanding the top-level capability requirements for the SQ2020 project and how they influence or constrain maintenance capability.
- Comparing the Integrated Logistics Support (ILS) approach with the DOTMLPFI framework to assess their compatibility.
- Using these insights to draft initial CQs for identifying key data drivers.

Workshop 2

- Developed an initial DOTMLPFI framework for maintenance capability, identifying initial data drivers for each capability element and initial descriptions for each data driver. This was achieved through expert responses to the CQs. An Excel template was chosen as the foundation for the tool.
- Aligned terminology with the findings from the literature review.
- Refined the CQs based on insights from the literature review.

Workshop 3 and 4

- Finalized the data drivers for each capability element.
- Provided detailed descriptions for each data driver.
- Further developed the Excel template based on the DOTMLPFI framework to serve as a tool for verifying the maintenance capabilities of individual systems (e.g., gas turbine, radar, generator, main gun, etc.).
- Established a process to guide the implementation, allowing maintenance technicians to monitor the build-up of maintenance capabilities for each system.
- Specified the requirements for a potential ICT system that would enable the tracking of maintenance capabilities by system, by capability element, or by fleet.

Table 2. Key literature, standards, and their contributions are used to form the ontology framework.

Source	Main contributions to the ontology
<i>NASA Systems Engineering Handbook</i>	<ul style="list-style-type: none"> - <i>Benchmarking for other SE processes, NASA's approach acts as a reference because of their system's unique operating environment.</i>
<i>Guide to the Systems Engineering Body of Knowledge (SEBoK)</i>	<ul style="list-style-type: none"> - <i>Concepts of systems</i> - <i>Systems of systems</i> - <i>System architecture design process (functional, logical, physical), Stakeholder identification</i>
<i>ISO/IEC/IEEE 15288, Systems and software engineering — System life cycle processes</i>	<ul style="list-style-type: none"> - <i>Concepts of systems</i> - <i>System of systems</i> - <i>Enabling systems</i>
<i>NATO CD&E Handbook</i>	<ul style="list-style-type: none"> - <i>DOTMLPFI model and its drivers</i> - <i>Models in capability development</i>
<i>SFS-ISO 10007:2018, Quality management. Guidelines for configuration management</i>	<ul style="list-style-type: none"> - <i>Terminology for configuration management.</i> - <i>Configuration management process</i>
<i>Systems Engineering and Analysis</i>	<ul style="list-style-type: none"> - <i>Systems Engineering processes and practices.</i>
<i>Logistics Engineering and Management</i>	<ul style="list-style-type: none"> - <i>Supporting functions for SOI and their best practices.</i>
<i>IEC 60300-3-11, Dependability management. Part 3-11: Application guide. Reliability-centred maintenance</i>	<ul style="list-style-type: none"> - <i>Maintenance strategy, reliability-centred maintenance applicability and connection to asset management.</i>
<i>EN 13306, Maintenance. Maintenance terminology</i>	<ul style="list-style-type: none"> - <i>Terminology for maintenance.</i>

<i>ISO 55000, Asset management — Overview, principles and terminology</i>	- <i>Benefits and basics of asset management</i>
<i>ISO 55001, Asset management. Management systems. Requirements</i>	- <i>Asset management system and its requirements</i> - <i>Capability identification and measurement</i>
<i>ISO 55002, Asset management. Management systems. Guidelines for the application of ISO 55001</i>	- <i>Information management as a part of asset management</i>
<i>ISO/IEC 21838:2021 Information technology — Top-level ontologies</i>	- <i>Support data exchange, search, discovery, integration and analysis</i>
<i>Military Handbook - Electronic Reliability Design Handbook</i>	- <i>Military maintenance, capability development and systems engineering</i>

The ontology development and the basic concepts of the systems domain followed the methodology introduced by Rousseau et al. (88). This research employed a multi-phase ontology engineering methodology to formally represent military maintenance capability within the context of the DOTMLPFI framework.

1. **Ontology Merging and Alignment with Data Drivers:** To ensure semantic interoperability and formal grounding, the data drivers were aligned and merged with a selected ontology stack, comprising BFO (Basic Formal Ontology) (89) as the upper ontology, and the IOF Core Ontology (90) for industrial and systems-level abstractions. This alignment process involved semantic mapping and class harmonization. Key challenges addressed during this phase included adapting DOTMLPFI constructs into ontologically well-founded classes.

2. **Domain Knowledge Refinement:** Subsequent refinements incorporated domain expert feedback focused on semantic completeness and modeling accuracy. Object properties were enriched with domain- and range-specific constraints. This phase emphasized property characteristics and alignment with reasoning tasks expected in decision-support contexts.

3. **Reasoning-Based Verification and Ontology Validation:** The ontology was evaluated using a combination of logical consistency checking via automated reasoners such as HermiT (91) in Protégé and CQ-driven validation. Protégé's explanation facility (Debugger) was employed to analyze and resolve missing inferences or inconsistencies. This iterative evaluation ensured that the ontology satisfied the intended CQs, and was coherent and consistent.

Results

In this paper, we designed a conceptualization of military maintenance capability based on a literature review and knowledge of defence maintenance experts. To operationalize the integration of the DOTMLPFI framework with the selected ontological stack, a formal mapping was constructed, aligning key DOTMLPFI dimensions with appropriate classes and properties from SKOS, BFO and the IOF Core Ontology shown in Figure 3.

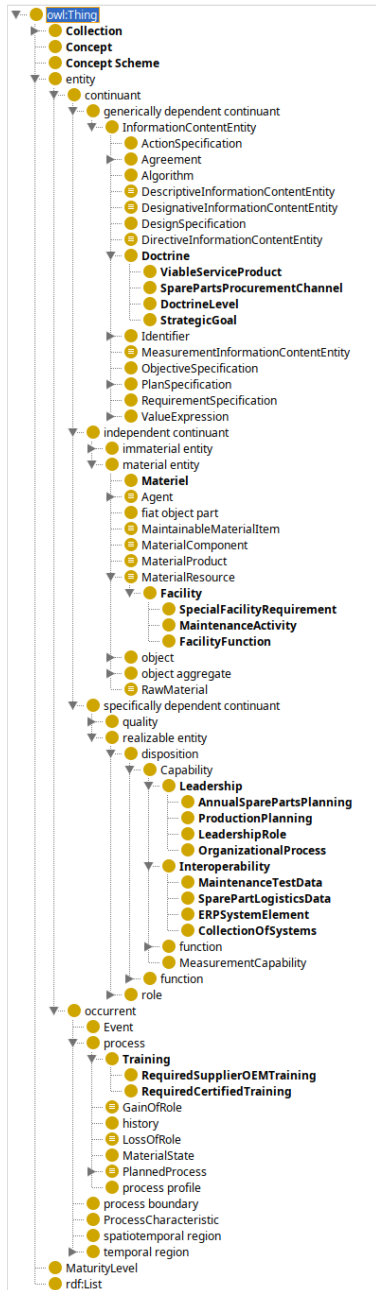


Figure 3 Class and subclass structure of the ontology stack. DOTMLPFI concepts are highlighted in bold to emphasize their role within the overall hierarchy.

Table 4 summarizes the principal class-subclass relationships, associated object properties, their ranges, and whether these ranges are explicitly defined in the ontology or inherited through higher-level constructs. Concepts such as Organization and Personnel, indicated in brackets in Table 4, were not modeled explicitly, as they are already well-defined within the existing ontology stack. Leveraging established representations ensures semantic consistency and avoids redundancy. However, some key object properties, such as *hasSubUnitOf* and *assignedToOrganization*, were defined to enable a more precise specification of their relationships within the doctrinal context.

Table 4 Formal Mapping of DOTMLPFI Dimensions to Ontological Classes and Properties

Class / Subclass	Superclass (Ontology)	Key Object Properties	Range	SKOS Concept	Range Class Defined ?
Doctrine	<i>InformationContentEntity (BFO)</i>	<i>hasDoctrineLevel</i>	<i>DoctrineLevel</i>		
		<i>appliesToForceType</i>	<i>Organization</i>		<i>inherited</i>
		<i>hasStrategicGoal</i>	<i>StrategicGoal</i>		
		<i>appliesToAsset</i>	<i>Material Entity</i>		<i>inherited</i>
		<i>identifiesProcurementChannel</i>	<i>SparePartsProcurementChannel</i>		
		<i>providesServiceProduct</i>	<i>ViableServiceProduct</i>		
Facility	<i>MaterialResource (IOF Core)</i>	<i>hasFacilityFunction</i>	<i>FacilityFunction</i>		
		<i>supportsMaintenanceActivity</i>	<i>MaintenanceActivity</i>		
		<i>hasSpecialFacilityRequirement</i>	<i>SpecialFacilityRequirement</i>		
Interoperability	<i>Capability (IOF Core)</i>	<i>hasInteroperabilityWith</i>	<i>System</i>		<i>inherited</i>

		<i>hasInteroperabilityWithGroup</i>	<i>CollectionOfSystems</i>	
		<i>supportsERPIntegration</i>	<i>ERPSystemElement</i>	
		<i>includesLogisticsData</i>	<i>SparePartLogisticsData</i>	
		<i>includesTestData</i>	<i>MaintenanceTestData</i>	
Leadership	<i>Capability (IOF Core)</i>	<i>realizedIn</i>	<i>OrganizationalProcess</i>	
		<i>exercisesLeadershipIn</i>	<i>Organization</i>	<i>inherited</i>
		<i>hasLeadershipRole</i>	<i>LeadershipRole</i>	
		<i>managesProduction</i>	<i>ProductionPlanning</i>	
		<i>plansSpareParts</i>	<i>AnnualSparePartsPlanning</i>	
Material	<i>MaterialEntity (BFO)</i>	<i>hasAssignedFunction</i>	<i>Function</i>	<i>inherited</i>
		<i>bearsMaterialRole</i>	<i>Role</i>	<i>inherited</i>
(Organization)	<i>Organization (IOF Core)</i>	<i>hasSubUnit / isSubUnitOf</i>	<i>Organization</i>	<i>inherited</i>
		<i>hasOrganizationalFunction</i>	<i>Function</i>	<i>inherited</i>
(Personnel)	<i>GroupOfPersons (IOF Core)</i>	<i>assignedToOrganization</i>	<i>Organization</i>	<i>inherited</i>
		<i>hasTraining</i>	<i>Training</i>	<i>inherited</i>
		<i>hasRole</i>	<i>Role</i>	
Training	<i>Process (BFO)</i>	<i>confersCapability</i>	<i>Capability</i>	<i>inherited</i>

<i>conductedByOrganization</i>	<i>Organization</i>		<i>inherited</i>
<i>involvesPersonnel</i>	<i>Personnel</i>		<i>inherited</i>
<i>requiresCertification</i>	<i>RequiredCertified Training</i>	✓	✓
<i>includesOEMTraining</i>	<i>RequiredSupplier OEMTraining</i>		✓

To balance formal ontology modeling with flexible semantic relationships, we combined OWL class hierarchies with SKOS annotation properties. For example, Doctrine and its subclass DoctrineLevel were modeled as OWL classes. A core class, Doctrine, and its subclass, DoctrineLevel, structured the domain, while individuals (e.g., DoctrineA, DoctrineB) instantiated doctrinal entities. Semantic relationships between individuals were defined using skos:narrower, enabling fine-grained conceptual linkage as shown in Figure 4. The use of SKOS concepts for individuals is applied in cases where such a designation is indicated.

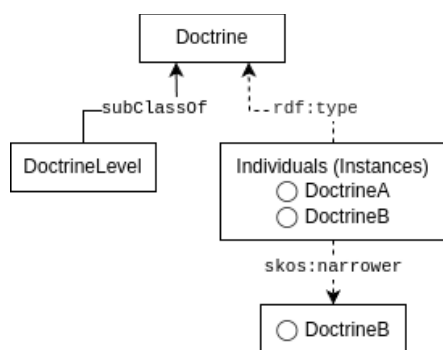


Figure 4 Ontology structure illustrating the class Doctrine and its subclass DoctrineLevel. Instances DoctrineA and DoctrineB are typed as Doctrine. A conceptual relationship is modelled between instances using the SKOS property skos:narrower, indicating that DoctrineB is a narrower concept than DoctrineA

To evaluate the alignment and expressiveness of the BFO and IOF Core within the DOTMLPFI framework, we developed a structured set of CQs. These questions were designed to assess the ontologies' ability to represent and answer relevant queries in the defence maintenance capability domain. The CQs were derived, each associated with a core class (e.g., Doctrine, Facility, Leadership) and mapped to specific object

properties and defined concepts within the ontology stack. The questions covered a broad range of topics, including doctrinal alignment, facility requirements, system interoperability, leadership roles, and training prerequisites. The ontology structure demonstrated strong coverage of DOTMLPFI elements:

1. Doctrine was modelled with precise links to strategic goals, force applicability, and procurement channels.
2. Facility and Material concepts were fully supported through well-defined roles and functions.
3. Interoperability and Leadership capabilities were effectively captured via logical relationships to systems, processes, and planning elements.
4. Training and Personnel were semantically enriched to reflect capability development and organizational alignment.

All CQs were successfully answered using existing ontology properties and SKOS-defined concepts, confirming the semantic completeness and domain relevance of the stack. A summary of these questions and their corresponding answers is provided in Table 5. It was found that a formal representation as an ontology was an appropriate technique to formally encode information that has previously been described in an unstructured or partial manner, often without considering essential interdependencies.

Table 5 CQs and Answers Based on Ontology Stack

Class	CQs	Answer Based on Ontology Stack
Doctrine	<i>What level of doctrine is associated with a given doctrine document?</i>	<i>hasDoctrineLevel > Doctrine Level</i>
	<i>Which force types does this doctrine apply to?</i>	<i>appliesToForceType > Organization</i>
	<i>What strategic goal does the doctrine support?</i>	<i>hasStrategicGoal > StrategicGoal</i>
	<i>What assets are covered by this doctrine?</i>	<i>appliesToAsset > Asset</i>
	<i>What procurement channels are identified in the doctrine?</i>	<i>identifiesProcurementChannel > SparePartsProcurementChannel</i>

	<i>What service products does the doctrine provide?</i>	<i>providesServiceProduct > ViableServiceProduct</i>
Facility	<i>What functions does this facility serve?</i>	<i>hasFacilityFunction > FacilityFunction</i>
	<i>What maintenance activities does this facility support?</i>	<i>supportsMaintenanceActivity > MaintenanceActivity</i>
	<i>What special requirements does this facility have?</i>	<i>hasSpecialFacilityRequirement > SpecialFacilityRequirement</i>
Interoperability	<i>With which systems does this capability interoperate?</i>	<i>hasInteroperabilityWith > System</i>
	<i>What group of systems are interoperable?</i>	<i>hasInteroperabilityWithGroup > CollectionOfSystems</i>
	<i>Does this capability support ERP integration?</i>	<i>supportsERPIntegration > ERPSystemElement</i>
	<i>What logistics data is included in this capability?</i>	<i>includesLogisticsData > SparePartLogisticsData</i>
	<i>What test data is included?</i>	<i>includesTestData > MaintenanceTestData</i>
Leadership	<i>What organizational process realizes this leadership capability?</i>	<i>realizedIn > OrganizationalProcess</i>
	<i>What organization is leadership exercised in?</i>	<i>exercisesLeadershipIn > Organization</i>
	<i>What role does the leader have?</i>	<i>hasLeadershipRole > LeadershipRole</i>
	<i>Who manages production?</i>	<i>managesProduction > ProductionPlanning</i>
	<i>Who plans for spare parts?</i>	<i>plansSpareParts > AnnualSparePartsPlanning</i>
Material	<i>What is the assigned function of this material?</i>	<i>hasAssignedFunction > Function</i>
	<i>What role does this material bear?</i>	<i>bearsMaterialRole > Role</i>
Organization	<i>What sub-units does the organization have?</i>	<i>hasSubUnit / isSubUnitOf > Organization</i>

	<i>What functions does the organization have?</i>	<i>hasOrganizationalFunction > Function</i>
Personnel	<i>To which organization is this person assigned?</i>	<i>assignedToOrganization > Organization</i>
	<i>What training has this person received?</i>	<i>hasTraining > Training</i>
	<i>What role does this person have?</i>	<i>hasRole > Role</i>
Training	<i>What capability is conferred by this training?</i>	<i>confersCapability > Capability</i>
	<i>What organization conducts this training?</i>	<i>conductedByOrganization > Organization</i>
	<i>What personnel are involved in this training?</i>	<i>involvesPersonnel > Personnel</i>
	<i>What certification is required?</i>	<i>requiresCertification > RequiredCertifiedTraining</i>
	<i>Does this training include OEM-specific modules?</i>	<i>includesOEMTraining > RequiredSupplierOEMTraining</i>

Figure 5 presents a sample from the reasoning test suite used to validate the ontology. Each test case targets a specific logical pattern, such as disjoint classes, inverse property inference, cardinality constraints, or disjointness conditions. For each pattern, a pass case demonstrates correct modelling, while a fail case introduces intentional errors to test the ontology's ability to detect inconsistencies. The HermiT reasoner was used to infer logical entailments, and Protégé's explanation facility (Debugger) was employed to analyse and resolve cases where expected inferences were missing or inconsistencies were detected. Entailed test cases were expected to evaluate as true, while non-entailed cases confirmed proper constraint enforcement by evaluating as false. The resulting ontology provides a coherent semantic framework for representing military maintenance capability. It is aligned with foundational ontologies, supports reasoning and interoperability, and is validated against practical knowledge needs.



Figure 5 A sample of test cases and test results from Protégé Debugger.

Discussion

The primary objective of this study was to answer the research question: “What does a maintainer need to know in order to fulfil the availability requirements set for the System of Interest (SOI)?” To address this, we developed a conceptual model of military maintenance capability, informed by a rigorous literature review and the expertise of defense maintenance professionals. Central to our methodology was the integration of the DOTMLPFI framework with formal ontological structures, designed to ensure semantic precision, interoperability, and support for informed maintenance decision-making. To operationalize this integration, we constructed a formal mapping aligning key DOTMLPFI dimensions with ontological classes and object properties drawn from the Basic Formal Ontology (BFO) and the Industrial Ontology Foundry (IOF) Core Ontology. This mapping reflects ontological commitments across multiple abstraction levels and distinguishes between directly defined and inherited properties.

The combined use of OWL class hierarchies and SKOS annotation properties offers a pragmatic modeling strategy for representing both formal ontological structure and lightweight conceptual relationships. For example, Doctrine was modeled as OWL class, while its instances were semantically linked using the `skos:narrower` property. This approach preserves OWL’s reasoning capabilities at the class level while enabling SKOS-compliant concept navigation at the instance level. The use of SKOS concepts is applied selectively in alignment with concept specific requirements.

In this context, the ontology functions as a semantic interface between the high-level conceptual elements of DOTMLPFI and the operational realities of military maintenance organizations. It enables the systematic representation of interdependencies across critical domains, including doctrine, organization, materiel, and personnel. Such capability is especially important in military logistics, where maintenance operations take place in data-intensive, highly regulated environments that demand precise specifications, procedural discipline, and integrated information flows.

To evaluate the semantic adequacy of the model, we developed and applied CQs covering areas such as doctrine, facility requirements, interoperability, leadership, and training dependencies. The ontology successfully addressed all questions, demonstrating a high degree of coverage, internal consistency, and practical relevance to defense maintenance planning scenarios. Therefore, it is suitable for reuse in defense knowledge systems, digital twin architectures, and ontology-driven decision-support environments.

Further refinement of the ontology could follow an incremental and iterative ontology building process (92,93). The iterative process reduces the complexity of ontology development by breaking it into parts, allowing partial definition of requirements, and making the ontology expand in layers, so that only new definitions are included when designing a new version. The iterative process should include validation of the ontological adequacy and logical consistency of the taxonomic relationships (94).

Conclusions

The complex maintenance system involves stakeholders from many different domains. All have different interests and needs for information concerning SOI. These are individual inputs and outputs of the design process. This is clearly seen in complex system-of-systems design processes, like the SQ2020 project, where the number of operational requirements and their technical requirement derivatives are massive. If a unified capability model is not used, the risk of not identifying the critical interdependencies during the overall (capability) design process is imminent.

This study has presented a comprehensive ontological framework that formalizes the concept of military maintenance capability by integrating the DOTMLPFI framework with established ontologies, including BFO and the IOF Core Ontology. Through a rigorous formal mapping and the use of SKOS for hierarchical classifications, the work bridges doctrinal concepts and practical maintenance requirements, enabling a unified semantic representation that captures complex interdependencies across organizational, material, and operational dimensions. Future research will focus on iterative ontology refinement, validation, and expanding semantic interoperability by leveraging mid-level ontologies such as CCO (95) and IOF Maintenance Reference Ontology (24), as well as exploring data mining applications.

Overall, this formalized ontological framework lays a foundational step toward more intelligent, data-driven defense maintenance planning systems that meet stringent availability requirements, ultimately contributing to enhanced operational readiness and mission success.

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