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TechMAPS: technology management for the architecting process of aircraft on-board systems

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Abstract
Due to climate change, low-emission aircraft with novel technologies, such as hydrogen-powered fuel cells, are being investigated. However, navigating the technology knowledge is challenging due to the vast number of existing and emerging technologies. Hence, supporting the engineer during the complex task of exploring, comparing, and selecting technologies from the extensive design space as part of the aircraft conceptual design phase is crucial. To address this challenge, the *Technology Management for the Architecting Process of aircraft on-board Systems* (*TechMAPS*) method is proposed. *TechMAPS* is used to navigate and manage available and emerging technologies. Moreover, the method supports the conservation and provision of technology knowledge in a standardized and formalized way. To this end, *TechMAPS* consists of three parts: a technology radar to identify technologies, a formalized ontology-driven database to conserve knowledge in a machine-readable, queryable way, and standardized technology fact sheets to provide concise data to the engineer. *TechMAPS* is exemplarily applied to different technologies of a hybrid-electric power train, i.e., a fuel cell, an existing electric motor, and battery technologies, to demonstrate the method's capabilities to present the landscape of technologies for different systems and abstraction levels. The study highlights the effectiveness of *TechMAPS* for technology management but also outlines aspects that need further research, such as creating an automated and standardized interface to and from the database.

Keywords Aircraft · Systems architecting · Knowledge management · Technology radar · Technology navigator

1 Introduction

Aviation contributes significantly to climate change, accounting for approximately 5% of total emissions. This estimation includes effects from carbon dioxide (CO_2), nitrogen oxides (NO_x), and ancillary factors like contrails [1]. In response to the environmental impact of aviation, emission reduction targets are presented, e.g., by the European Union within *FlightPath 2050* [2] and the Air Transport Action Group within *Waypoint 2050* [3].

Despite continuous efforts, the evolutionary enhancement of the current power train and on-board systems is projected to increase fuel efficiency by approximately 20% until 2050 [3]. Consequently, there is a pressing need to investigate innovative technologies, such as hydrogen-powered fuel cell systems with the potential for zero carbon emission propulsion [3–5].

To use renewable hydrogen for the power train and on-board systems (OBS), the current focus is on utilizing liquid hydrogen as the energy source [4, 6]. It is worth noting that no commercial aircraft currently runs on hydrogen. Hence, the aviation industry has limited experience and knowledge of relevant technologies, such as fuel cells, and their interrelationships with other OBS. Consequently, developing a hydrogen-powered aircraft necessitates addressing significant uncertainties and challenges associated with incorporating these technologies into the OBS architecture. One such

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challenge with numerous unknown aspects is the trade-off between liquid and gaseous hydrogen distribution within the aircraft.

Uncertainties and challenges are conventionally investigated during the early aircraft conceptual design phase. On the one hand, these challenges are typically rooted in a large pool of possible technology options, forming a vast and complex design space. On the other hand, only limited experiences and knowledge are available, leading to high uncertainties [7, 8]. Mainly, the interdependencies between various OBS and the absence of authorities-defined certification specifications for disruptive technologies, such as fuel cells or hydrogen handling, introduce significant uncertainties [9, 10]. Furthermore, these novel technologies[1] can have a significant influence on the OBS, so that the architecture can deviate significantly from existing solutions [11]. In addition, system costs are typically already influenced and mainly set during this phase, and late changes during development are costly [12–14]. Given these considerations, handling uncertainty and complexity necessitates the execution of numerous technology trade studies during the conceptual design phase to assess different technology combinations.

Those mentioned technology trade studies can include the choice between different types of technologies; in the case of fuel cells, the choice between, e.g., a proton-exchange membrane fuel cell (PEMFC) or a solid oxide fuel cell (SOFC) [15]. Similarly, investigations extend to other OBS, such as the electrical system. This involves trade-offs between different battery technologies [16, 17]. Each of these technologies has its implications. In general, many questions remain open for a hydrogen-powered aircraft, mainly driven by the vast design space of existing and emerging technologies.

To perform early technology trade studies at a functional-logical level, the holistic *Systems Architecting Assistant* (*SArA*) methodology is being developed at the Institute of Aircraft Systems Engineering of the Hamburg University of Technology presented by Kuelper et al. [8, 10, 18]. *SArA* serves as a comprehensive tool to assist the engineer during design space exploration, architecture evaluation, and variants down-selection. The methodology is designed to manage complexity and uncertainty effectively and to ensure traceability using a model-based systems engineering (MBSE[2]) approach. Furthermore, *SArA* incorporates a method for managing and reusing formalized knowledge. However, this method is currently only applicable to knowledge about existing systems architectures, which includes the utilization of parametric design patterns [10]. Moreover, obtaining an overview of relevant technology variants is essential. Additionally, detailed technology knowledge, typically only available at the detailed design level, is crucial for enabling substantial trade studies already during logical systems architecting.

To facilitate effective systems architecting, it becomes imperative to supply engineers with comprehensive knowledge about both existing and novel technologies, so this paper focuses on the following research aspects:

1. Development of a formalized approach to manage and navigate technology knowledge during conceptual design to highlight characteristics and the maturity level based on the present knowledge basis
2. Enable technology knowledge to be a machine-readable and integrated part of systems architecting, enabling traceability of why a certain technology has been selected
3. Definition of the term "technology" in the context of systems architecting
4. Presentation of the identification method for existing and emerging technologies, including quantitative and qualitative data
5. Definition of a generic, formalized, and standardized approach for the effective conservation and retrieval of knowledge
6. Structuring and presenting technology knowledge concisely with a focus on the most relevant information to assist engineers during design space exploration.

To cope with these six research aspects, it is necessary to extend the existing *SArA* methodology and to develop a method purposely for conserving, managing, navigating, and providing knowledge about OBS technologies. This method serves as a "technology map": the *Technology Management for the Architecting Process of aircraft on-board Systems* (*TechMAPS*) method, which is being developed and presented in this paper.

To develop this method, Sect. 2 serves as a foundation by offering background information on existing knowledge management approaches. Additionally, it provides a

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[1] In this paper, the term *novel technologies* refers to a disruptive technology introducing innovative capabilities or previously unavailable or unused applications. It can also refer to significantly improved technology with significantly new functionalities. A novel technology, such as fuel cells, can be disruptive for one industry, such as commercial aviation, while it is already in use in others, such as the automotive or energy industry.

[2] *MBSE* is defined as the use of models to support requirements, design, assessment, evaluation, verification, and validation steps spanning the entire life cycle [19]. *MBSE* can ease the design task of

Footnote 2 (continued)

novel, complex systems with uncertainties during early design [20]. Recently, the potential of MBSE approaches has been increasingly demonstrated, e.g., by Nowodzienski et al. [21] and Voth et al. [11]. Due to information stored in machine-readable models, which ideally function as a single source of truth, the models are assessed, analyzed, and virtually tested [19, 22, 23].

literature overview of existing technology navigator and radar methods. The chapter proceeds to introduce the overall systems design (OSD) framework for conceptual design. Moving on to Sect. 3, an in-depth overview of the *TechMAPS* method is presented. This chapter delves into the automated report generation and details the implementation of the *TechMAPS* method. Afterward, *TechMAPS* is exemplarily applied to a fuel cell, an existing electric motor, and battery technologies in Sect. 4. The paper concludes in Sect. 5, providing a concise summary of the key points discussed, a critical examination of the developed method, and a forward-looking perspective on potential future research endeavors.

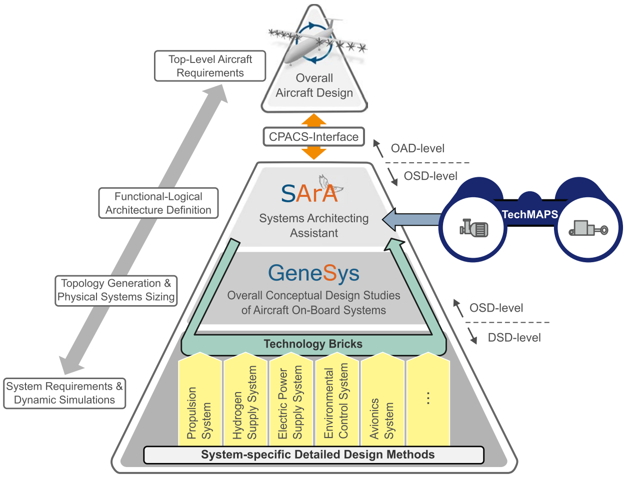


Fig. 1 Overall systems design framework for aircraft conceptual design phase from the perspective of system engineers--image adapted from [8]

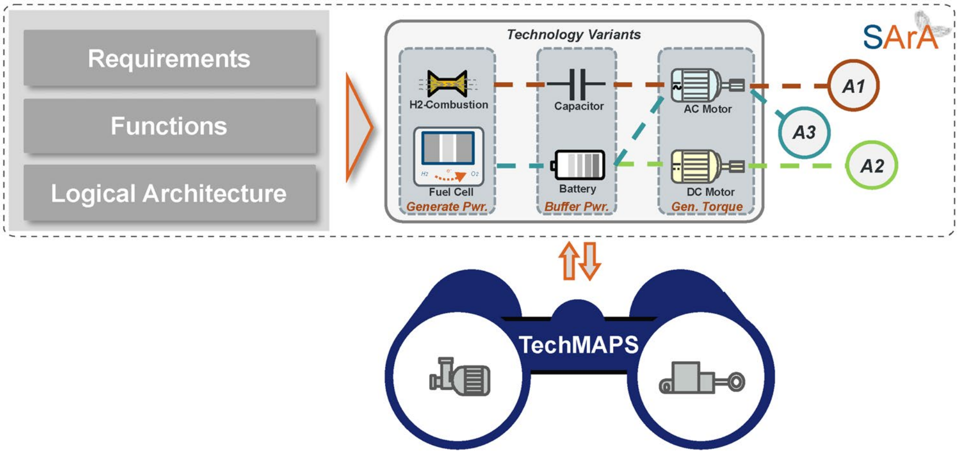
2 Overall systems design framework and knowledge management

To comprehend the context and the rationale behind the development of *TechMAPS*, the paper offers an overview of the OSD framework for conceptual design. This framework serves as background information to understand the integration of *TechMAPS* into the broader systems engineering process, also providing information regarding current knowledge and technology management approaches.

The OSD framework, as illustrated in Fig. 1, serves as a valuable approach for system engineers, providing a structured approach for conducting comprehensive studies of OBS architectures at a holistic systems level. At the highest level, the aircraft is designed, and top-level aircraft requirements are defined during overall aircraft design (OAD). This step is not directly part of the OSD framework and is typically performed by external organizations. To ensure that all relevant aircraft information is available during systems design, the CPACS [24] interface file links OAD to OSD. As part of the OSD framework, the two methodologies *SArA* and *GeneSys* developed in-house are applied [8, 10, 18, 25–29].

At the second level, OBS architectures are defined and evaluated at a functional-logical level with *SArA* using MBSE-driven methods. This means, for example, that operations, requirements, functions, and logical architectures are modeled in a traceable manner and that the model functions as a single source of truth for architecture safety assessment, performance evaluation, and early verification and validation [8, 10, 18, 30]. To enhance the efficiency and effectiveness of systems architecting and to increase the development speed, the *TechMAPS* method is being developed as an integrated method for the MBSE-driven systems architecting process, as shown in Fig. 2. As an integrated element, i.e., part of the architecture generation step and

Fig. 2 *TechMAPS* as an integrated step of functional-logical architecture definition with *SArA* supporting technology selection



seamlessly connected to the MBSE toolchain of *SArA*, the technology selection and decision-making process is facilitated, enabling the making of informed decisions already during conceptual design. The engineer is given an extensive overview of the landscape of possible system technology options. *TechMAPS* also provides a rationale for selecting a technology based on comparing options. This rationale enables the traceability of architectural decisions.

The third level employs the *GeneSys* methodology (cf. Fig. 1). System components are positioned geometrically within the aircraft geometry and then preliminarily sized using physical sizing laws derived from detailed system design (DSD) methods. The outcome of *GeneSys* includes component masses, system masses, and component-specific design parameters, for example, the design power of an electric generator or the displacement of a hydraulic pump. Moreover, a preliminary quasi-static simulation of the overall system behavior is conducted, ultimately providing information on the systems' power off-takes throughout a reference mission profile.

At the lowest level, system-specific DSD is performed, including high-fidelity, dynamic simulations, detailed physical system behavior, and hardware-in-the-loop testing.

The OSD framework accelerates the setup of OBS architecture trade studies, allowing for a quick evaluation of various architectures compared to each other using evaluation metrics, such as OBS mass, risk, complexity, and energy consumption at the aircraft level.

2.1 Knowledge-based engineering for technology management

The concept of knowledge is inherently abstract and driven by experiences and data [31]. Consequently, a structured approach to its management is essential for its effective utilization [32]. In engineering, managing knowledge poses specific challenges, notably incorporating intellectual property constraints [33]. Typically, knowledge exists in diverse forms, including databases, product data sheets, design specifications, process guidelines, heuristics rules, literature, or human expertise, and needs to be formalized to be usable [34].

Technology is often viewed as applied knowledge, closely linked to and dependent on it [35–37]. While there is no universal definition for technology, it is generally understood as a means to fulfill objectives and functions [38, 39]. This definition is also adopted in this work. Moreover, technology exists on different levels of abstraction. The successful interaction of technologies enables functioning systems architectures [37]. Furthermore, technology is closely linked to innovations and future developments, driven either by a push, such as advancements in technology designs, or a pull, which includes external factors like climate change [40]. In addition, knowledge about technologies can be either explicit, i.e., documented in a report, or tacit, i.e., representing qualitative skills [37].

This paper defines *technology knowledge* as information, data, and experiences about technologies in an unstructured, non-standardized form. In contrast, *formalized technology knowledge* denotes organized and standardized technology knowledge [10]. *Technology management* represents the means to collect, store, and use technology knowledge [41, 42]. *Technology intelligence* describes the systematic process of gathering, analyzing, and disseminating information about technological trends, innovations, impacts, and developments used to support decision-making and raise awareness for upcoming technologies [43–46].

To use formalized knowledge, knowledge-based engineering (KBE) can be applied [47]. KBE and associated methods, such as design patterns, are not direct methods to increase creativity but optimize tasks by automating repetitive processes and expediting development [48]. It facilitates a rationalized and less biased design space exploration, especially if an exhaustive search is impractical [49, 50]. Implementing KBE allows for the effective collection, storage, and formalization of knowledge, providing engineers with more time for creative design tasks during conceptual design [31]. However, it is essential to note that formalizing technology information is time-consuming and, therefore, most beneficial for complex systems with extended development times, such as aircraft [50].

2.2 Review of existing technology management concepts

Presently, open-source as well as commercially available technology navigator or radar concepts exist that offer an overview of the novel and emerging technologies, without specific emphasis on OBS or even aviation. Examples include, but are not limited to, *TECHnavigator* [51], Technology Radar [52], *Zalando Tech Radar* [53], or *BMW Group Technology Trend Radar* [54]. These approaches typically employ a radar to visualize and assist the decision-making on whether a technology should be adopted. A different approach is taken by *IEEE Technology Navigator* [55], which enables a buzzword-based search for information, such as papers, e-books, videos, and organizations related to a selected technology. However, for general terms like *compressors*, the search yields over 1500 results. Obtaining more detailed individual results necessitates additional effort, as each source needs to be checked individually. The *L.E.A.D.S. Technology Dashboard* [56] presents the landscape of available physical products for batteries, sustainable aviation fuels, and hydrogen. The focus is on existing products and performance characteristics, which are shown as single parameter points.

Besides commercial tools, technology management approaches are presented in the literature. Gregory [41] proposes a framework for technology management based on process thinking. The framework includes the steps of technology identification, selection, acquisition, exploitation, and protection. Koen [57] presents two technology maps as guides for the engineer: the enabling technology map to assess technological skill levels, competitive position, and hiring needs, and the source of technology map to determine in-house or outsourced technology development. Brockhoff [42] provides planning and controlling processes for research and development. Furthermore, the main steps for technology management, i.e., identification, storage, and reuse, are highlighted. Arnold [58] describes the impact of sudden technological changes and emphasizes strategic management to navigate these novel technologies. Rohrbeck et al. [46, 59] describe technology radars as a tool for technology intelligence. The focus is on the *Deutsche Telekom Laboratories Technology Radar* as one of the fundamental publications regarding technology radars. The radar is a tool for scouting emerging technologies, assessing their potential and risks, and providing valuable knowledge as concise and tailored information, ranging from key statements to more detailed information. Each piece of information is accompanied by its respective source. Cagnin et al. [60] propose *future-oriented technology analysis* for technology foresight, forecasting, and assessment. Rohn et al. [61] and Lang-Koetz et al. [62] present their *resource efficiency technology radar* to find, collect, and assess resource-efficient technologies by performing a criteria-based selection. Viñolas et al. [63] and Lizarralde et al. [64] propose to use the 'integrated value model for sustainability assessments' method to evaluate and select technologies. Golovatchev et al. [65] present technology and innovation radars to effectively identify and track innovations, emerging technologies, and market trends. It further includes a rating mechanism to help the technology selection process. Roper et al. [66] present the importance of forecasting and managing technology knowledge as critical aspects of decision-making. It explores how technological change affects society and businesses. In addition, practical tools and methods for forecasting technology are provided. Pfennig [67, 68] developed an approach for using knowledge about physical sizing laws and geometrical information stored in a database for detailed OBS design. Choi et al. [69] present a fact-oriented technology database for efficient technology management. A function-based approach links a technology to its functions, enabling search capabilities. Judt et al. [7, 70] present an approach for architecture generation based on a component database using experts' knowledge and providing this knowledge to multiple engineers. Sanya et al. [71] focus on a platform-independent framework to ensure knowledge conservation for an extended period. Boe-Lillegraven et al. [72] extend the radar approach from Rohrbeck et al. [46] and present the deployed *Cisco Technology Radar*. Scouts identify emerging technologies, experts regularly assess these identified technologies, and the findings are disseminated quarterly. They emphasize the concept of a concise one-page technology profile describing technology novelty and impact on the reader. Arnold et al. [73] and Kiel et al. [74] use interviews to examine technology identification and adaptation methods in companies identifying that technology identification is of key importance. Cowan et al. [75] extend existing roadmapping processes for smart grids by integrating policy considerations and expert judgment to prioritize factors, address barriers, and identify strategic pathways. Koops et al. [40, 76] focus on aviation technologies by filtering websites and journals and gathering experts' knowledge as key elements for the *Bauhaus Luftfahrt Technology Radar*. The identified technologies are evaluated based on metrics, such as performance, scaling capabilities, and disruption potential, and are then positioned on their radar. The radar indicates technologies with significant innovation potential for aviation and their physical limitations. Technologies that can be adapted for the upcoming aircraft with a strong focus on low-emission flight are highlighted. Younse et al. [77] present a method for managing architectural knowledge. Zheng et al. [78] propose a method for handling knowledge and exploring the design space of architectures. Mietzner et al. [79] summarize and discuss various approaches, such as the quadruple helix model and open innovation platforms, for technology transfer in complex environments and emphasize the role of technology transfer in providing knowledge to the engineer. Fuchs et al. [80–82] describe a method to automatically design aircraft cabins based on a knowledge database, requirements, and system interrelations. Fitzsimmons et al. [83] present a user-oriented knowledge management approach to enable a map for knowledge accessibility. Ellermann et al. [84] propose a 'technology foresight maturity model,' building on the method by Becker et al. [85], using literature reviews for foresight and interview-derived best practices for the technology maturity levels. Just recently, Souza Rehder et al. [86] describe their process to acquire information, conserve the information in a database, and provide the results applied to the topic of human factors. Woelken et al. [87] present technological solutions for cultivated meat based on the literature and experts using an innovation radar to visualize possible technologies and their impact.

2.3 Gap analysis

The review of existing technology management methods shows multiple technology management and intelligence approaches in the market and the literature, addressing various aspects, such as technology radars and document-based technology information sheets. The literature strongly focuses on technology or innovation radars, which are used to identify and visualize novel technologies and track the progress of existing ones. Additionally, document-based technology profiles serve as a means to communicate technology information to engineers in a structured manner.

While these approaches provide valuable insights and serve as the foundation for *TechMAPS*, they are typically developed for general technology management and are not explicitly tailored to aircraft systems technologies. Although aviation could be a potential application area, existing approaches often focus at a high level, addressing broad technology categories, such as artificial intelligence, rather than specific aircraft systems technologies, such as hydraulic gear pumps with external teeth. In aviation, aircraft technologies must comply with strict safety regulations, consider uncertainties, and have complex dependencies with other technologies within logical systems architectures.

Moreover, most references focus on a single element, such as technology radar visualization or knowledge provision, rather than considering technology identification, conservation, and integrated reuse within a holistic, model-based systems architecting methodology. In particular, integrating qualitative and quantitative technology knowledge in a machine-readable format, such as a database, into model-based systems architecting remains rare. Directly incorporating technology knowledge into the architecting process can streamline technology selection, enhance decision-making, and accelerate architecture generation by enabling automated, standardized modeling of technology options. Furthermore, in the future, the rationale for choosing a specific technology option for a defined system function remains clear and retractable.

In addition, if quantitative technology characteristics are considered, they are typically represented as single parameter points, not considering the high uncertainties during conceptual design. A tailored method, which considers uncertainty handling techniques, has the potential to address this drawback and ensure robust decision-making.

To address these gaps, this work introduces the modular *TechMAPS* method for structured technology identification, conservation, management, navigation, and systematic reuse within MBSE-driven systems architecting of *SArA*. As an integrated part of systems architecting, *TechMAPS* establishes a seamless link between system functions and the selected technology within the logical architecture, enhancing traceability and decision-making. Consequently, *TechMAPS* extends beyond static technology conservation, enabling systematic knowledge reuse across projects. It incorporates a link to technology sizing laws, ensuring its applicability in later physical system design stages. Moreover, the approach supports more informed decision-making by representing technology parameter uncertainties through intervals. This work also standardizes and structures technology knowledge by defining the term *technology* in the context of aircraft systems, formalizing technology fact sheets, and developing an ontology for knowledge conservation and reuse. Furthermore, it introduces a flexible, automated, and generic capability to create comprehensive technology landscapes.

3 Technology management for on-board systems architecting

To address the gaps and stated objectives, the key aspects of the *TechMAPS* method are presented in this section.

3.1 Developed TechMAPS modules

Given the complex design tasks, i.e., a vast design space with high uncertainties, during conceptual design, effective management of knowledge about existing and new technologies is crucial [32]. In response to these challenges, the *TechMAPS* method was developed. The primary goal of *TechMAPS* is to manage and map out known and emerging technologies not on the aircraft or system level but with a specific focus on the subsystem level. Depending on the selected application case, the subsystem level may represent single or multiple components or equipment working together to fulfill a specific function [88, 89]. Furthermore, recognizing the absence of a universal definition for the term "technology," this paper adheres to the notion that technology is a means to fulfill objectives and functions. Furthermore, it establishes four levels of abstraction to define technology:

- *Subsystem technology category* (STC) signifies the highest abstraction level of logical technologies at the subsystem level, such as a fuel cell (FC). An FC is an exemplary STC for providing electric power to consumer systems based on hydrogen.
- *Subsystem technology type* (STT) represents a selected functional principle for an STC to fulfill the requirements and functions. A PEMFC exemplifies this as a sub-node and one functional principle of an FC. Other STTs for an FC are, among others, direct methanol fuel cells, alkaline fuel cells, or solid oxide fuel cells [15].
- *Subsystem technology variant* (STV), sometimes also referred to as "techno brick," is a potential sub-node of STTs and represents the lowest abstraction level describing logical subsystem technologies. Conserving technologies on the STV level is crucial for logical systems architecting with *SArA* and for OSD, as it outlines the actual logical technology characteristics. Examples of

STVs are the low-temperature PEMFC (LT-PEMFC) and the high-temperature PEMFC (HT-PEMFC) variants.

- *Physical product* (PP) delineates a physically existing solution and serves as a means of implementing a defined STV, like the *PEMFC stack module NM12 Twin* [90]. As the name suggests, a PP does not describe a logical technology but rather a physical realization.

These four levels, along with their mentioned examples, are illustrated in Fig. 3, depicting vertical dependencies. It is necessary to define "technology" at these four levels in the context of systems architecting since the term is multifaceted, and the technology selection can significantly impact the overall architecture. For example, the decision to use a low- or high-temperature PEMFC as a technology variant requires a fundamentally different cooling system architecture that is not yet obvious with an STC. In addition, the tree-like structure visually represents the variations from one level to another. The blue arrow in Fig. 3 highlights horizontal interdependencies between technologies from different technology trees.

Building upon these technology definitions, the *TechMAPS* method is being developed to assist the engineer in navigating technologies at the four specified levels of detail during the aircraft conceptual design phase. *TechMAPS* serves as a method to support the engineer, particularly during logical systems architecting, by offering more detailed knowledge about technologies than previously available with *SArA*, meaning knowledge about full or partial systems architecture patterns, as described by Kuelper et al. [10].

As shown in Fig. 4, *TechMAPS* comprises three main parts designed to manage and navigate technology knowledge effectively. First, the aspect of a technology radar is integrated, which serves the purpose of identifying new technologies and determining which ones should be collected and conserved with *TechMAPS*, considering existing approaches in the literature. The engineer currently carries out the technology radar approach of *TechMAPS* manually. This manual process is time-consuming and labor-intensive, involving the review of physical product data sheets, patents, literature searches, analysis of in-house reports from past DSD developments, and interviews with subject matter experts. The effort required depends on the technology category being added to the database. For instance, gathering information on battery technologies was straightforward and took less than a day due to the abundance of freely available data. In contrast, collecting data on disruptive technologies, such as hydrogen pumps, has taken weeks and remains ongoing.

However, not every freely available information is useful, relevant, or "good." As the focus of *TechMAPS* is mainly on assisting the engineer during systems architecting and OSD during early design, information is abstracted, and detailed technology information, such as installation brackets of a specific electric motor, is neglected. The considered data depend on the technology and are selected based on experiences and workshops with subject matter experts from the specific design disciplines of DSD. With these experts, the credibility of information is also discussed and rated. Generally, reviewed journal papers, experimental data, and product data sheets serve as reliable sources of information. Additionally, contradictory data are analyzed and assessed based on its trustworthiness, which may be influenced by factors such as personal bias, the novelty of the publication, and the repeated occurrence of a parameter value in multiple sources. To further enhance data reliability, physical characteristics of technologies are stored as intervals, providing engineers with a clearer understanding of the expected range for a given parameter (cf. Fig. 6).

As the second part, *TechMAPS* incorporates a formalized ontology to describe and handle the technology knowledge entities and their features and relations. In this work, the

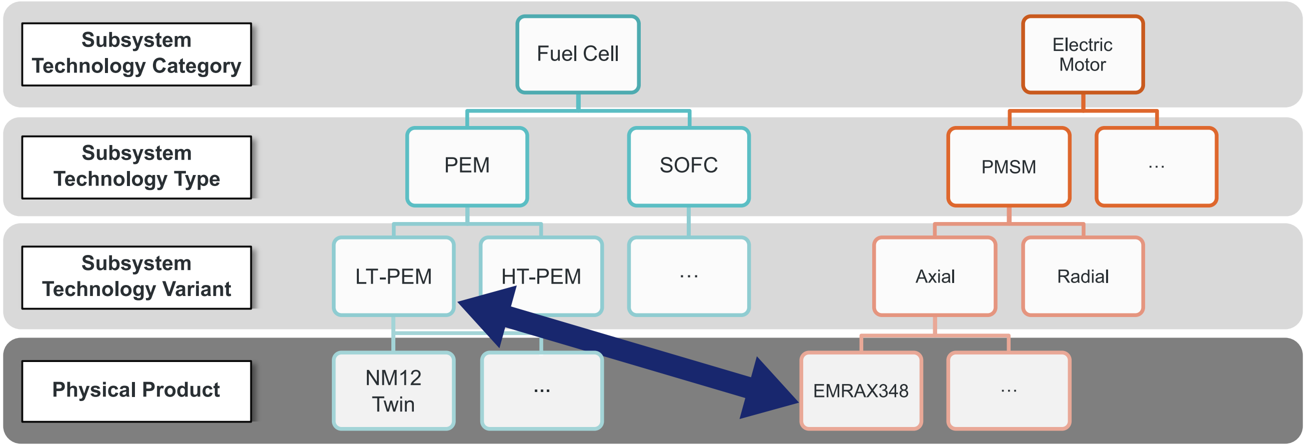


Fig. 3 Schematic representation of the defined technology levels of abstraction including their vertical and horizontal dependencies

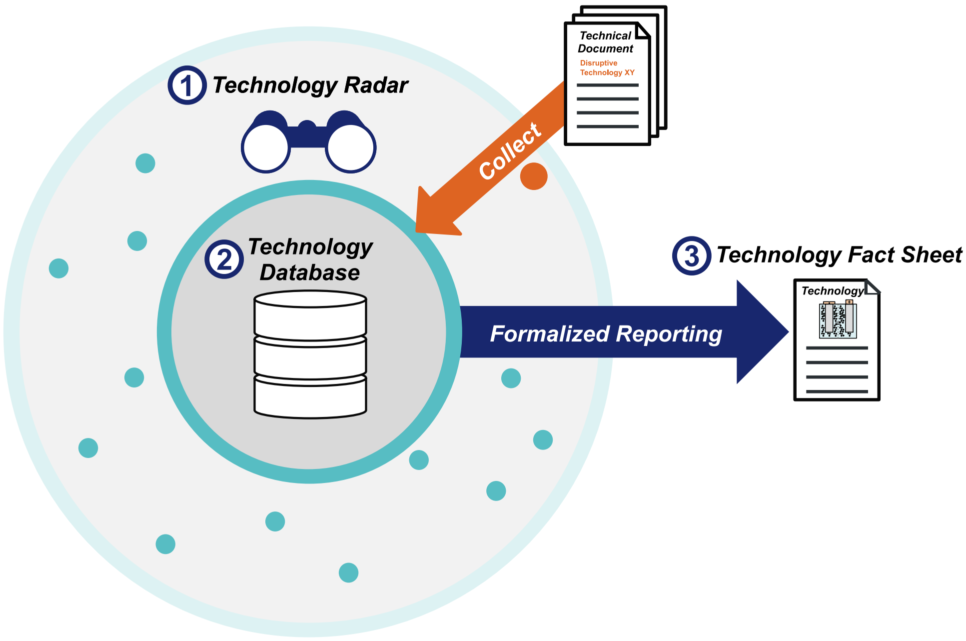


Fig. 4 Schematic overview of the *TechMAPS* method

ontology is implemented with the relational database *intelligent Data Analytics and Management* (*iDAM*) to formally conserve, investigate, and reuse knowledge about existing and novel technologies. *iDAM* has been previously introduced for systems architecture pattern by Kuelper et al. [10]. Built on the open-source, object-oriented *PostgreSQL* [91] database language, *iDAM* serves as a platform to provide accessible and investigable knowledge in a formalized manner to the engineer. Additionally, *iDAM* facilitates a seamless and close interaction with the MBSE-driven architecting tool of *SArA*: *MathWorks System Composer* [10, 92]. Via *MATLAB*, a direct interface to an *PostgreSQL* is possible, enabling the integrated usage of the formalized technology knowledge for systems architecting. Storing technology knowledge within a relational database offers several advantages, including the ability to relate, categorize, query, and reuse knowledge in a machine-readable format [93].

As the third part, *TechMAPS* includes formalized technology fact sheets (TFS), which are inspired by the concept of technology profiles as described by Boe-Lillegraven et al. [72]. A TFS offers engineers compact, document-based information and key data about technologies for OBS architecting. The intent is to automatically generate the TFS based on the information stored in *iDAM* to ensure traceability.

3.2 TechMAPS process for conserving and providing technology knowledge

To integrate the three mentioned bricks of *TechMAPS*, technology radar, database-based knowledge conservation, and TFS, the process for identifying, conserving, navigating, and reusing technology knowledge is illustrated in Fig. 5. The process consists of the two technology knowledge flows of Fig. 4 demonstrated in orange and blue: acquiring knowledge about emerging or overlooked existing technologies and reusing the conserved technology knowledge.

Information and data about new or existing but yet-to-be-considered technologies often exist in unorganized and

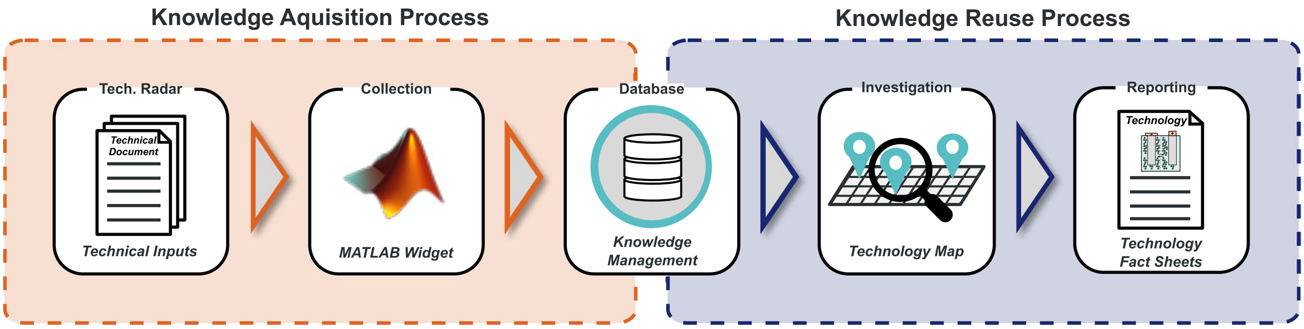


Fig. 5 Underlying process of the *TechMAPS* method to conserve and provide knowledge—MATLAB logo taken from [94])

non-standardized forms. This includes but is not limited to technical documents, reports, product data sheets, patents, literature, and human experiences [10, 34]. Non-standardized information regarding a specific technology is initially identified and collected (cf. *part 1* of Fig. 4). Subsequently, the information is formalized and standardized by employing a graphical user interface widget. This interface widget enables a user-friendly, semi-automated approach to conserve newly gained knowledge, minimizing the necessity for proficiency in the structured query language (SQL) for interaction with the database. To ensure this, the interface widget is a machine-readable representation of the TFS, enabling the formalized and standardized conservation of technology knowledge in *iDAM* (cf. *part 2* of Fig. 4).

In addition to conserving knowledge, *TechMAPS* focuses on investigating and reusing technology knowledge (cf. *part 3* of Fig. 4). This facilitates accessible and usable technology knowledge at a higher level of fidelity than is typically available during the aircraft conceptual design phase, providing valuable assistance to the engineer during systems architecting and overall systems design. Therefore, the technology knowledge within *iDAM* is investigated using queries. Currently, this involves creating individual queries using SQL directly or MATLAB to explore, for example, all conserved STVs for a certain STT and mapping out their characteristics and performance. Based on the investigated knowledge, formalized reports, the TFS, are intended to be automatically generated. A TFS provides engineers with relevant information about a specific technology. Furthermore, the selected technologies are also intended to be directly connected to the model-based architecting process of *SArA*.

In essence, by employing the *TechMAPS* method, with its underlying process, the activities of identifying, collecting, standardizing, and conserving newly acquired technology knowledge are facilitated. Moreover, it enhances the process of analyzing, prioritizing, navigating, and reusing technologies during systems architecting and overall systems design.

3.3 Reporting: technology fact sheets

The *TechMAPS* process (cf. Fig. 5) concludes with the reporting step and the creation of the TFS. However, the TFS is more than just the final output; it is a key element of *TechMAPS*, as it consolidates essential information for model-based systems architecting in a knowledge-driven approach. Furthermore, its significance lies not only in providing technology knowledge in a structured format but also in driving the ontology design of *TechMAPS*, which guides the database design. Since the ontology's structure and content must align with the TFS to ensure consistency, it is logical to describe the *TechMAPS* process in reverse order, starting from the TFS, to clarify the rationale behind the design of the preceding process steps.

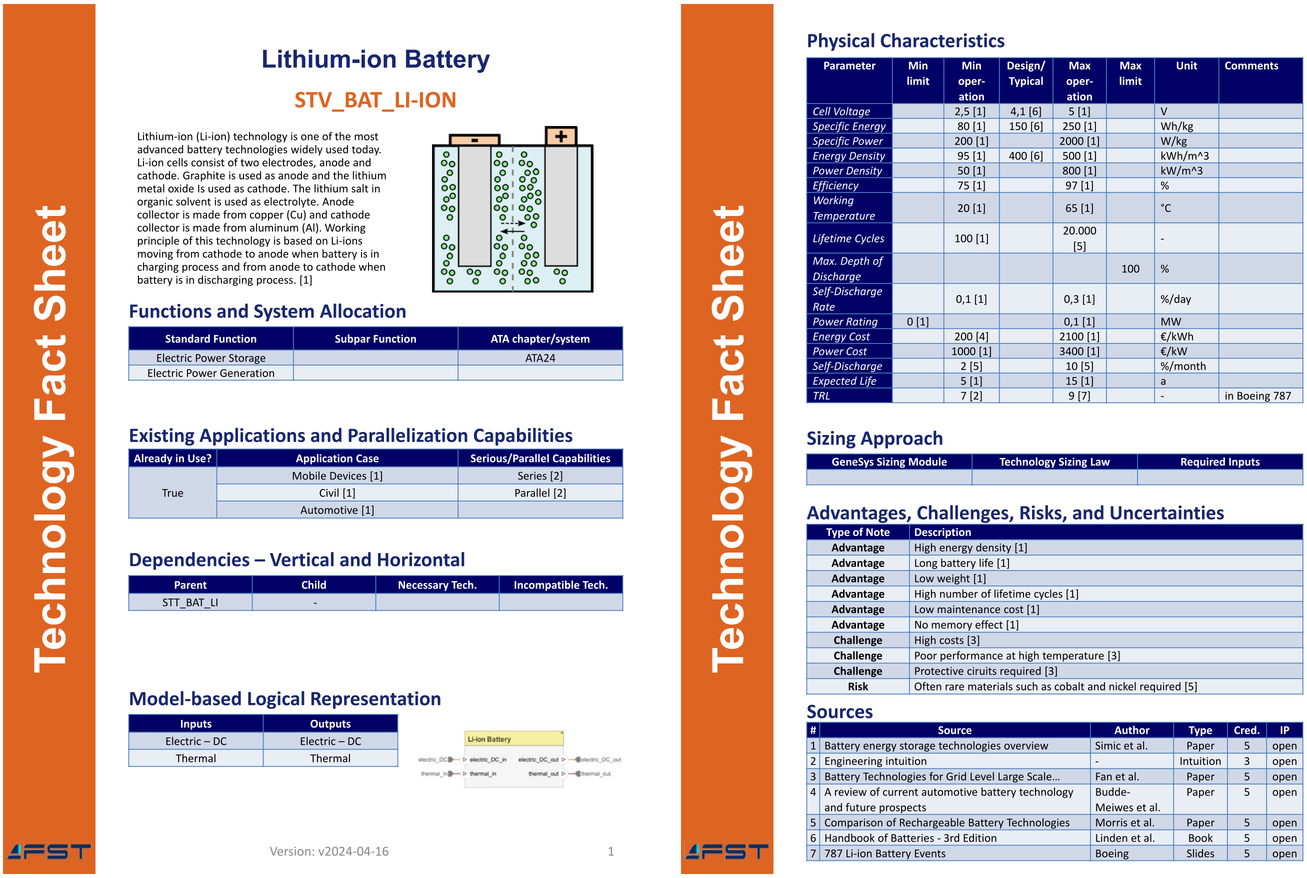
The standardized TFS comprises two pages, double-sided oriented. The decision to include two pages rather than a single page is intentional to provide more relevant information to the engineer clearly and concisely. Additionally, physical product data sheets, such as those presented by *EKPO Fuel Cell Technologies GmbH* [90] and *EMRAX d.o.o.* [95], often consist of two pages. The TFS structure is exemplified by a lithium-ion battery as an example of an STV in Fig. 6.

As shown in Fig. 6a, the front page provides general information about the selected technology to the engineer. The TFS starts with the name of the technology and its unique code at the top, allowing the engineer to identify the technology presented in the TFS directly. The unique code characterizes the type of technology (cf. Fig. 3). Below, a brief description of the technology is provided. A schematic icon or image of the technology is presented, as shown here for a battery. Subsequently, normal and subpar functions are stated, so that this information is an integrated part of architecture generation with the ORFL (operations, requirements, functions, logical architecture) process of *SArA* [30], enabling the selection of a technology for a system function. Normal function refers to the intended or main function of a technology, e.g., *provide electric power* of a PEMFC. In contrast, subpar functions represent a secondary or complementary function, e.g., *provide oxygen-reduced air* of a PEMFC, which can be used as an inert gas. In addition, the allocation to OBS is stated in the TFS. The combination of stated functions and system allocations facilitates the generation of architectural designs and consequently reduces the overall workload associated with development.

It has been identified that it is also necessary to know whether and where a selected technology has already been applied to assess application capabilities. Furthermore, the TFS provides information on whether a serial or parallel connection of a technology variant within a system is feasible. This information is particularly important during the systems architecting process with *SArA*, as it fulfills safety and redundancy requirements.

In addition, vertical and horizontal dependencies are presented in the TFS. Vertical dependencies describe the hierarchical, tree-like reliance and increasing detailing of logical technologies up to physical products (cf. Sect. 3.1). Horizontal dependencies describe the technological interrelations between separate, independent technology trees, as shown in Fig. 3: *LT-PEMFC*, as an example for STVs, provides, among others, electric power in the form of direct current; however, the *EMRAX348* electric motor, as an example for a PP, requires alternating current. By stating this information, the engineer knows already during logical systems architecting that an additional component, an *inverter*, is required or that a different technology variant needs to be selected.

Furthermore, information about required inputs and outputs, connection stereotypes, and an image of the



Technology Fact Sheet

Lithium-ion Battery

STV_BAT_LI-ION

Lithium-ion (Li-ion) technology is one of the most advanced battery technologies widely used today. Li-ion cells consist of two electrodes, anode and cathode. Graphite is used as anode and the lithium metal oxide Is used as cathode. The lithium salt in organic solvent is used as electrolyte. Anode collector is made from copper (Cu) and cathode collector is made from aluminum (Al). Working principle of this technology is based on Li-ions moving from cathode to anode when battery is in charging process and from anode to cathode when battery is in discharging process. [1]

Functions and System Allocation

Standard Function	Subpar Function	ATA chapter/system
Electric Power Storage		ATA24
Electric Power Generation		

Existing Applications and Parallelization Capabilities

Already in Use?	Application Case	Serious/Parallel Capabilities
True	Mobile Devices [1]	Series [2]
	Civil [1]	Parallel [2]
	Automotive [1]	

Dependencies – Vertical and Horizontal

Parent	Child	Necessary Tech.	Incompatible Tech.
STT_BAT_LI	-		

Model-based Logical Representation

Inputs	Outputs
Electric – DC	Electric – DC
Thermal	Thermal

Version: v2024-04-16

1

Technology Fact Sheet

Physical Characteristics

Parameter	Min limit	Min oper-ation	Design/ Typical	Max oper-ation	Max limit	Unit	Comments
Cell Voltage		2,5 [1]	4,1 [6]	5 [1]		V	
Specific Energy		80 [1]	150 [6]	250 [1]		Wh/kg	
Specific Power		200 [1]		2000 [1]		W/kg	
Energy Density		95 [1]	400 [6]	500 [1]		kWh/m^3	
Power Density		50 [1]		800 [1]		kW/m^3	
Efficiency		75 [1]		97 [1]		%	
Working Temperature		20 [1]		65 [1]		°C	
Lifetime Cycles		100 [1]		20.000 [5]		-	
Max. Depth of Discharge					100	%	
Self-Discharge Rate		0,1 [1]		0,3 [1]		%/day	
Power Rating	0 [1]			0,1 [1]		MW	
Energy Cost		200 [4]		2100 [1]		€/kWh	
Power Cost		1000 [1]		3400 [1]		€/kW	
Self-Discharge		2 [5]		10 [5]		%/month	
Expected Life		5 [1]		15 [1]		a	
TRL		7 [2]		9 [7]		-	in Boeing 787

Sizing Approach

GeneSys Sizing Module	Technology Sizing Law	Required Inputs

Advantages, Challenges, Risks, and Uncertainties

Type of Note	Description
Advantage	High energy density [1]
Advantage	Long battery life [1]
Advantage	Low weight [1]
Advantage	High number of lifetime cycles [1]
Advantage	Low maintenance cost [1]
Advantage	No memory effect [1]
Challenge	High costs [3]
Challenge	Poor performance at high temperature [3]
Challenge	Protective ciruits required [3]
Risk	Often rare materials such as cobalt and nickel required [5]

Sources

#	Source	Author	Type	Cred.	IP
1	Battery energy storage technologies overview	Simic et al.	Paper	5	open
2	Engineering intuition	-	Intuition	3	open
3	Battery Technologies for Grid Level Large Scale…	Fan et al.	Paper	5	open
4	A review of current automotive battery technology and future prospects	Budde-Meiwes et al.	Paper	5	open
5	Comparison of Rechargeable Battery Technologies	Morris et al.	Paper	5	open
6	Handbook of Batteries - 3rd Edition	Linden et al.	Book	5	open
7	787 Li-ion Battery Events	Boeing	Slides	5	open

(a) Front page of the TFS

(b) Back page of the TFS

Fig. 6 Formalized and standardized structure of the technology fact sheets exemplified by a lithium-ion battery—content taken from [16, 17, 96–99]

model-based representation is included, enabling a direct link between technology knowledge and model-based architecting. Via a *MATLAB* script, stored technologies can automatically be positioned in the MBSE-tool *System Composer* with assigned attributes and ports. The engineer needs to position and connect this automatically created component manually.

Another crucial aspect of knowledge management is version control and the ability to track technology changes over time. Each version is recorded using a date format, with the date of the most recent modification to the technology database automatically stamped at the bottom of the TFS. Every new database entry via the interface file is logged in a separate table, documenting the modifications made. Comparing the current state-of-the-art data, such as physical characteristics, with previous versions, so-called *version diff*, enables effective version management and facilitates reporting on the evolution of technologies.

As shown in Fig. 6a, the back page of the TFS provides more detailed data about the technology, such as typical design or physical characteristics. These characteristics typically include parameters, such as failure rates and technological maturity, represented as technology readiness level (TRL), since these are two key parameters during conceptual design. For example, the TRL of lithium-ion batteries in aviation is most likely between seven and nine, as this technology is already in use on-board the Boeing 787 [97]. Furthermore, physical parameters and limits are provided, such as specific weight, specific power, efficiency, and temperature. These are typically used parameters, regardless of the selected technology. In addition, technology-specific parameters can be flexibly added to the TFS. It was purposely decided to enable parameter ranges in addition to a typical design value due to high uncertainties and acceptable parameter deviations from -10% to +10% to the actual value [26, 100]. Moreover, every parameter is directly linked to a source, which is described at the bottom of the TFS. Thereby, the source, the credibility of the source, which is rated by the engineers from one (lowest value) to five (highest value) points, and the information on whether parameters are confidential are provided. Additionally, qualitative characteristics such as technology advantages and challenges, as well as sizing laws, if already known, are stated.

All in all, the structure of the TFS is standardized, so that the engineer is provided with the same collection of data for each technology, even if they are from totally different systems. However, standardization poses a significant challenge and always represents a compromise. Still, it offers the possibility to increase the clarity, quality, reusability, and automation capability of existing technology knowledge for model-based OBS architecting and overall systems design.

3.4 Database: machine-readable technology knowledge conservation

To preserve and reuse technology knowledge while automatically generating TFS, storing the knowledge in a machine-readable, standardized format based on the relational database *iDAM* [10] is imperative. This approach ensures accessibility, updateability, traceability, query capabilities, and reusability [47, 70, 71]. Additionally, the utility of a concurrently and widely accessible database, extending beyond a single institution, is beneficial. Moreover, a generic design ensures adaptability across diverse systems characterized by significant differences. Furthermore, the database facilitates straightforward modifications and updates, particularly incorporating novel technology knowledge, such as hydrogen system technologies.

3.4.1 Ontology for OBS technology knowledge management

To meet the aforementioned knowledge conservation aspects, a generic and formalized ontology is initially developed. An ontology defines the structure and interrelations inherent in the conserved technology knowledge [101]. The ontology in this work was created following the *METHONTOLOGY* approach by Fernández et al. [102]. The planning, specification, and conceptualization phases were carried out based on the structured information formalized in the TFS (cf. Sect. 3.3). Data are categorized into classes, also known as concepts or entities. In addition, relationships are defined, making this step both time-intensive and highly iterative. Continuous exchange with in-house and industrial partners ensures the ontology's validity and practical applicability. The resulting ontology serves as the foundation for deriving the database schema, enabling the creation of analyzable and machine-readable knowledge through SQL queries.

As illustrated in Fig. 7, the ontology comprises seven classes, categorized into five color-coded groups: *technology*, *functions*, *model-based information*, *characteristics*, and *source*. Each class is characterized by key attributes, also known as features, and their associated relationships [103, 104]. The present ontology is a simplified version, emphasizing core characteristics and interrelations.

The *technology* class encompasses technology-specific attributes. The *functions* concept describes system functions. One or more technologies fulfill a function. However, a technology can also fulfill multiple functions. The orange-colored classes pertain to the *model-based information*, crucial for systems architectures, as these classes

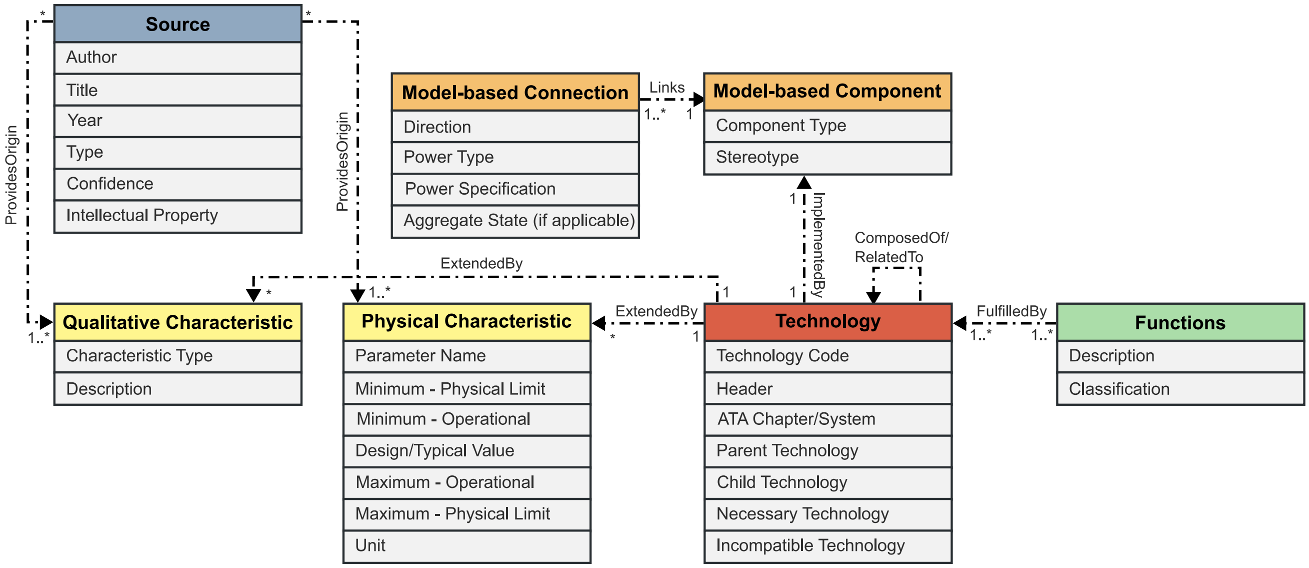


Fig. 7 OBS technology knowledge ontology

represent how technologies are implemented in the model. They included features, such as the *direction* of interfaces. To ensure that only valid entries are entered, namely *input* or *output*, enumerations are defined within the database minimizing erroneous entries. Enumerations are either directly specified or implemented through separate database tables functioning as a set of predefined parameters and names. This approach enhances maintainability, update capability, and controllability, although it does so at the expense of increased database schema complexity. The yellow entities in Fig. 7 delineate typical qualitative and quantitative characteristics and physical parameters essential to compare different technology solutions. In addition, the *source* class provides the origin of a given value or information, ensuring the traceability of data and information.

Cardinality on the relations describes the potential multiplicity of interrelations (1–1, 1–*n*, *n*–*n*). For example, each technology is extended by an undefined number of qualitative and physical characteristics. Consequently, the engineer can search, e.g., for a specific mass and retrieve all corresponding technologies, enhancing accessibility and query capabilities of technology knowledge. This approach ensures that the actual data in the database are unambiguous, i.e., every technology and its information is only listed once and can be addressed via the connections. This is a significant advantage for the maintainability and updateability of the database. At the same time, the generic ontology structure also ensures that new, even unknown technologies with unknown characteristics can be conserved in the relational database.

Formalized knowledge about technologies within *TechMAPS* can be seamlessly transmitted to the model-based tool for systems architecting. This automated utilization of knowledge enables the direct use of technology knowledge for model-based architecting at a logical level [10]. In essence, the database, based on the generic technology knowledge management ontology, contains a wealth of technology knowledge beyond what is explicitly presented in the TFS, representing a comprehensive “150%” conservation approach. However, even though additional information can be stored generically and uniquely, the conservation of required information for the TFS remains paramount.

3.4.2 Managing access security to sensitive data

In the realm of knowledge management, particularly within the context of technology management, a crucial consideration is protecting knowledge by limiting access to sensitive data. Protecting knowledge is essential for ensuring the future competitiveness of an institution and is particularly pertinent in the context of multidisciplinary and multi-institutional research projects [105]. For instance, a student working with *TechMAPS* should be restricted from accessing information about technologies acquired during a classified research project until such knowledge has been officially published or released. Consequently, the incorporation of access security management within *TechMAPS* is imperative. Since knowledge is conserved in and accessed from the database, the access management approach must be implemented in *iDAM*.

Various approaches for managing access security have been evaluated, including employing independent database schemas per confidential source, utilizing a single schema with separate tables for each confidential source, and leveraging row-level security (RLS). Due to the significant complexity increase and compromised accessibility and query capabilities associated with the first two approaches, RLS has been identified as the most suitable solution. *PostgreSQL* supports RLS [106], allowing the database schema administrator to define additional security rules per row, complementing the SQL-standard privilege system. When RLS is enabled for a table, access must be specified for each user or user group. If a user is not granted access to specific rows, the table appears empty, precluding the display, modification, or deletion of entries. This approach offers the advantage that no sensitive knowledge is visible or modifiable in the worst-case scenario, such as for a new user awaiting rights allocation. Additionally, only the administrator can add or modify RLS rules. However, it is acknowledged that implementing RLS introduces additional administrative overhead and higher maintenance workloads. To reduce the overhead and streamline RLS management, various user groups have been defined:

- *Student*: This user group possesses the lowest privilege level, limited to accessing only openly available knowledge.
- *Faculty member*: Members of this group have broader access, including both openly available and institutional knowledge.
- *Project xy member*: Individuals belonging to this group are granted access rights for information related to a designated project xy.
- *Administrator*: This user holds full access and the capability to modify RLS rules.

As shown in Fig. 8, users can be allocated to multiple user groups, allowing scenarios, such that *faculty member A* has additional access to information of *project A*, whereas *faculty member B* has access to *project A* and *project B*. The *administrator* is strictly limited to a selected few individuals, for example, the lead engineers of research institutions. Valid non-disclosure agreements are imperative, given that this group has unrestricted access to view, modify, and delete all technology knowledge.

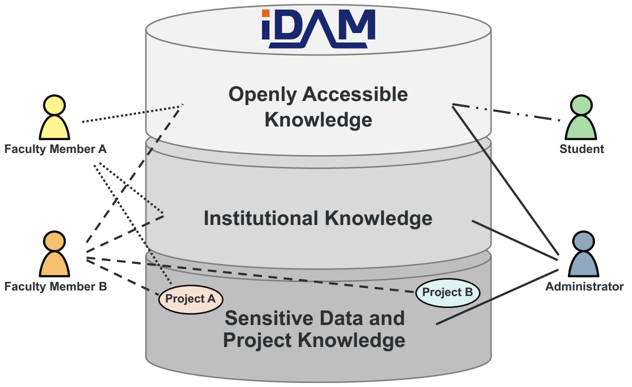


Fig. 8 User access rights shown for different user groups of *TechMAPS*

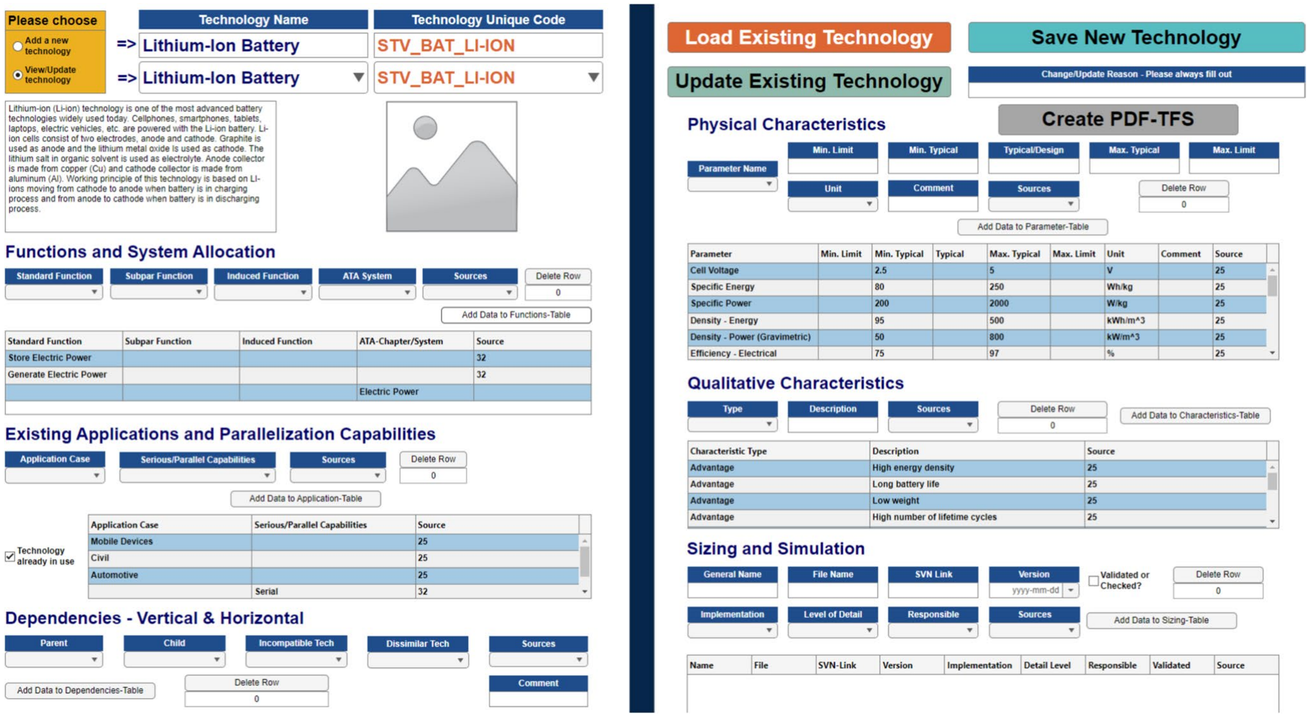
It is noteworthy that engineers with low privileges cannot definitively know whether detailed knowledge for a certain technology is already listed in the database due to the RLS security rules. However, it is essential to acknowledge and address this challenge to establish effective knowledge management that concurrently satisfies access security requirements to protect sensitive data.

3.5 Implementation of *TechMAPS*

As stated in the *TechMAPS* process description in Sect. 3.2, systems architectures are modeled with *MathWorks System Composer*, and the database uses *PostgreSQL* as a language. All interaction with the database is done via *MATLAB* using the *MATLAB App Designer* for the interface widget. This interface app, which represents the TFS, is shown in Fig. 9.

As shown here, new technologies can be added with the interface widget, and already conserved ones can be loaded and updated. In addition, a PDF version of the TFS can be automatically created using the *MATLAB Report Generator*.

In addition to knowledge conservation, modification, and reuse, directly using this knowledge in the MBSE-driven systems architecting process of *SArA* is a main contribution of this paper. Consequently, a separate app has been developed to assist the engineer in selecting technologies for a specific function, as shown in Fig. 10a. A system function stored in the database is chosen initially from a drop-down menu. Only functions already present in *TechMAPS* can be displayed, and if new functions for a disruptive technology or system are identified, these need to be added first. Afterward, the engineer is presented with stored options for STCs, can select one and continue the process with STTs and STVs. The engineer can individually choose which level of detail is needed, selecting only an STC, such as a battery, or an STV, such as a lithium-ion battery. The design



○ Add a new technology => Lithium-Ion Battery | STV_BAT_LI-ION

● View/Update technology => Lithium-Ion Battery | STV_BAT_LI-ION

Lithium-ion (Li-ion) technology is one of the most advanced battery technologies widely used today. Cellphones, smartphones, tablets, laptops, electric vehicles, etc. are powered with the Li-ion battery. Li-ion cells consist of two electrodes, anode and cathode. Graphite is used as anode and the lithium metal oxide Is used as cathode. The lithium salt in organic solvent is used as electrolyte. Anode collector is made from copper (Cu) and cathode collector is made from aluminum (Al). Working principle of this technology is based on LI-ions moving from cathode to anode when battery is in charging process and from anode to cathode when battery is in discharging process.

Functions and System Allocation

Delete Row: 0

Standard Function	Subpar Function	Induced Function	ATA-Chapter/System	Source
Store Electric Power				32
Generate Electric Power				32
			Electric Power	

Existing Applications and Parallelization Capabilities

Delete Row: 0

☑ Technology already in use

Application Case	Serious/Parallel Capabilities	Source
Mobile Devices		25
Civil		25
Automotive		25
	Serial	32

Dependencies - Vertical & Horizontal

Delete Row: 0

Physical Characteristics

Delete Row: 0

Parameter	Min. Limit	Min. Typical	Typical	Max. Typical	Max. Limit	Unit	Comment	Source
Cell Voltage		2.5		5		V		25
Specific Energy		80		250		Wh/kg		25
Specific Power		200		2000		W/kg		25
Density - Energy		95		500		kWh/m^3		25
Density - Power (Gravimetric)		50		800		kW/m^3		25
Efficiency - Electrical		75		97		%		25

Qualitative Characteristics

Delete Row: 0

Characteristic Type	Description	Source
Advantage	High energy density	25
Advantage	Long battery life	25
Advantage	Low weight	25
Advantage	High number of lifetime cycles	25

Sizing and Simulation

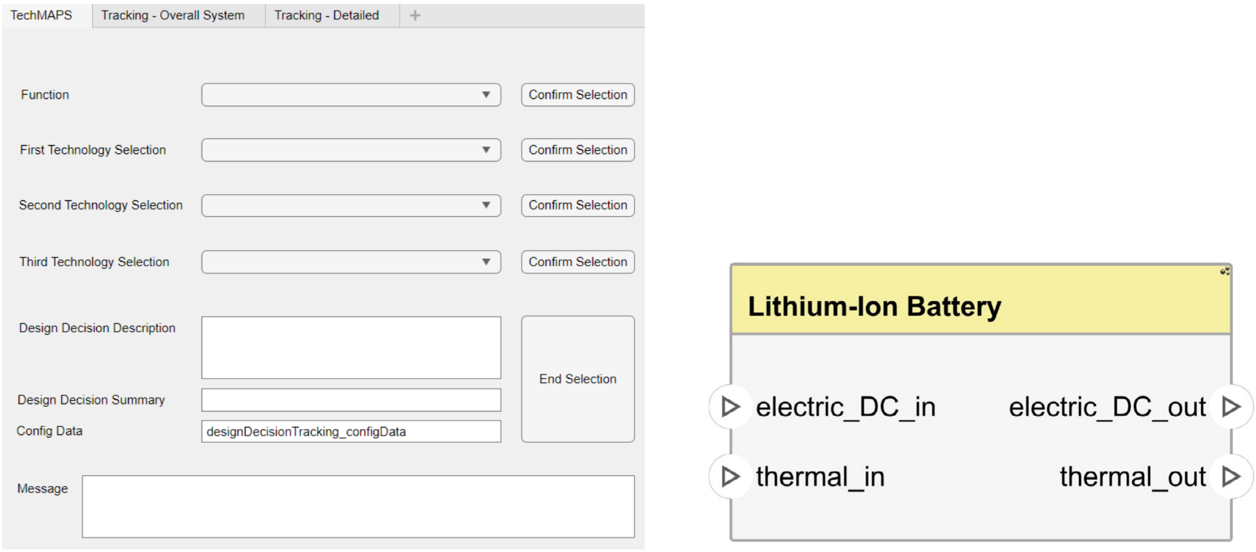
Version: yyyy-mm-dd

☐ Validated or Checked?

Delete Row: 0

Name	File	SVN-Link	Version	Implementation	Detail Level	Responsible	Validated	Source

Fig. 9 Excerpt of the interface widget of *TechMAPS* to read and store information in the database with the example of the lithium-ion battery technology



Config Data: designDecisionTracking_configData

(a) Widget to assist the engineer in the selection of a certain technology for a function

(b) Exemplary representation of the automatically created lithium-ion technology component in *SArA*

Fig. 10 Integration of *TechMAPS* into the MBSE-driven systems architecting process of *SArA*

rationale behind the selection can be stated and is, therefore, traceable. In addition, the automatically created technology component block in *System Composer* is shown in Fig. 10b.

4 Application of TechMAPS method

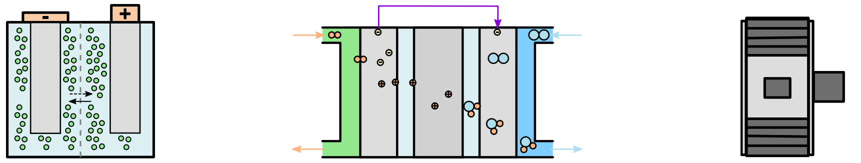
As described above, *TechMAPS* functions as a holistic approach to manage and navigate technology knowledge of aircraft OBS. To demonstrate the capabilities of *TechMAPS* to systematically identify, conserve, navigate, map out, and reuse the mentioned technology knowledge in a formalized manner, *TechMAPS* is applied exemplarily to different technologies of a hybrid-electric power train of a novel single-aisle twin-engine aircraft concept *DLR-F25* as presented by Wöhler et al. [107]. Given that the process of *TechMAPS* (cf. Fig. 5) is strongly influenced by the information necessitated in the TFS, the focus is on demonstrating and evaluating the standardized structure of the TFS and the approach with *iDAM* for knowledge conservation. Furthermore, the capability of *TechMAPS* to map out physical, quantitative attributes of technology alternatives is shown.

4.1 Considering technology fact sheets for different technology levels

To demonstrate and assess the flexibility and generic structure, *TechMAPS* is applied to three distinct technologies, shown in Fig. 11, associated with different systems and situated at different technology levels.

First, the lithium-based electric battery is an example of a subsystem technology type shown in Fig. 11a. This STT includes some technology variants such as *lithium-ion* or *lithium-sulfur* batteries [16]. Lithium-based batteries are widely used, even in high-power applications, such as electric vehicles [17]. Second, the LT-PEMFC, depicted in Fig. 11b, illustrates a subsystem technology variant. LT-PEMFCs are presently under investigation as part of future hydrogen-based aircraft power trains, offering the potential to achieve low-emission aviation. This FC variant uses

Fig. 11 Schematic representation of the selected three use case technologies



(a) Lithium-based electric battery

(b) Low temperature proton exchange membrane fuel cell

(c) *EMRAX 348* axial flux PMSM.

hydrogen and oxygen as reactants to generate electric power, providing water vapor-rich and oxygen-deficient air for OBS, operating at temperatures around 80 °C [11, 108, 109]. Third, the *EMRAX 348* electric motor from *EMRAX d.o.o.* [95], shown in Fig. 11c, is an example of a physical product. This PP is an axial flux permanent magnet synchronous electric motor (PMSM) that includes high power densities and is applied in various industries, including aviation, marine, or heavy machinery [95].

To identify, gather, conserve, and provide the knowledge required by the TFS, diverse literature sources are employed for the lithium-based battery and the LT-PEMFC. Conversely, for *EMRAX 348*, the existing physical product technical data sheet serves as the single source of truth. This underscores a notable difference between technologies at the logical level (STTs and STVs) and the physical one. It becomes evident that significantly more detailed information is available for the *EMRAX 348* compared to the other two, primarily because the *EMRAX 348* is a physically existing component rather than an abstracted logical representation of a technology variant or type. However, this changes if technical data sheets are not shared due to proprietary information.

Significant distinctions between STTs, STVs, and PPs become evident when focusing on the required parameters, as shown in Table 1. All three share a foundational parameter set comprising typical performance indicators like mass, costs, or efficiency. However, it becomes clear that different systems and components require different parameters for their characterization. For example, characterizing the PP *EMRAX 348* involves adding additional component-specific parameters, such as diameter, height, rpm, or voltage. The parameters vary widely across diverse OBS and are highly technology-specific, necessitating the highly flexible and generic *TechMAPS* technology knowledge management approach. Furthermore, it becomes apparent that individual TFS need to be generated for each minor variation of a physical product to account for altered constraints, boundary conditions, and parameters. Using the example of the *EMRAX 348* electric motor, this would result in nine variants and, consequently, nine TFS. This artificially expands the technology knowledge base, giving the impression of encompassing more conserved technology knowledge without necessarily adding significant value or information for the aircraft conceptual design phase. Still, the TFS of a PP remains a simplified and less comprehensive version of the available technical product data-sheet.

Based on these insights, *TechMAPS* will primarily be used for logical technologies, mainly focusing on STVs, considering it is the lowest layer to describe abstracted technology concepts on a logical level. This focus brings substantial value, particularly during conceptual design when working with the OSD framework (cf. Fig. 1), by offering typical technology parameter ranges and physical limits streamlining the model-based systems engineering process. A direct link between the model and the extensive knowledge base is established. It also lays the groundwork for the development of a technology proposal assistant in the future. Despite the focus of *TechMAPS* on logical technologies, ensuring the conservation of technical data sheets for existing PPs is also included.

4.2 Comparison-based technology landscape

In general, during the conceptual design phase, the engineers are not only interested in obtaining information regarding a single technology but also in comparing different technology variants to identify the most suitable technology for a specific application case. To illustrate this capability of

Table 1 Relevant parameters required by the three different technology levels

Lithium-based Battery		LT-PEMFC		EMRAX 348	
Parameter	Unit	Parameter	Unit	Parameter	Unit
Failure rate	1/fh	Failure rate	1/fh	Failure rate	1/fh
Maturity (TRL)	–	Maturity (TRL)	–	Maturity (TRL)	–
Mass	kg	Mass	kg	Mass	kg
Cell voltage	V	Power to weight ratio	kW/kg	Power	kW
Power density	kW/m^3	Power density	kW/m^3	Diameter	m
Energy density	kWh/m^3	Volume	m^3	Height	m
Efficiency	–	Efficiency	–	Efficiency	–
Temperature	K	Temperature	K	Temperature	K
Power cost	€/kW	Cost	€	Cost	€
Energy cost	€/kWh	Complexity	–	Torque	Nm
Lifetime cycles	–			RPM	1/min
Self-discharge rate	%/day			Current	Arms
Max. discharge	%			Voltage	V

TechMAPS, as previously stated in Fig. 5, the battery example from before is taken up.

In addition to the lithium-based battery technology type, other batteries are commonly utilized. These include but are not limited to, lead-acid, nickel-cadmium, nickel-metal hydride, sodium-sulfur, and vanadium-redox flow battery technology variants. To select an adequate variant for a specific application case, such as the power train hybridization of a hydrogen-powered concept aircraft, the engineer can use *TechMAPS* to query existing applications, parallelization capabilities, and qualitative characteristics. Nevertheless, as previously stated, the assessment of physical performance and limitations is of paramount importance. Consequently, the utilization of *TechMAPS* is employed to delineate the physical attributes of distinct STVs based on selected criteria for comparison.

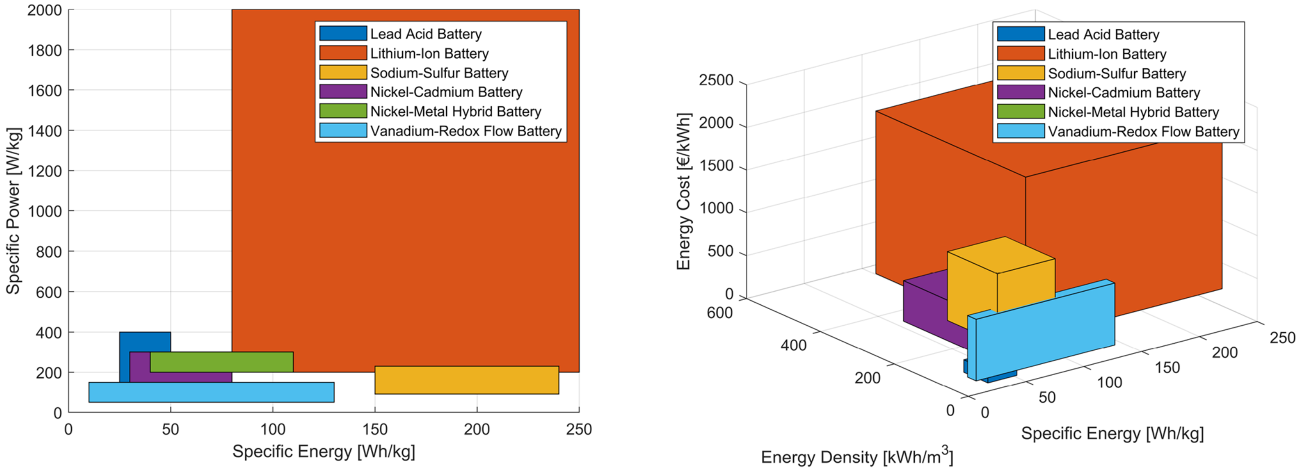
As illustrated in Fig. 12, physical attributes of technology variants are visualized with *MATLAB* by applying *TechMAPS* to map out differences in their performance based on multiple criteria. This comparison can be conducted based on two parameters (2D visualization in Fig. 12a) or three parameters (3D visualization in Fig. 12b). Although it is possible to contrast technologies based on more than three parameters, this task requires a different type of comparison technique, such as a matrix, with a less clear visual comparison.

The information presented in the plots is directly sourced from the *iDAM* database, demonstrating the machine-readable capabilities. Any update or modification to the database is automatically reflected in the plots. Furthermore, the conservation of not only a single value for each parameter but also intervals enables the comprehensive representation of complex and uncertain data as rectangles or prisms, which is helpful during early conceptual design. It can be observed that the lithium-ion battery technology exhibits the highest performance in terms of *specific power* and *specific energy*. However, it also includes the highest uncertainty, which can be a relevant factor during the decision-making process of OBS architecting. Creating the landscape of technologies based on physical characteristics needs to be explicitly specified in the code. This step can be enhanced in the future by incorporating a user interface to flexibly select parameters directly in the interface.

4.3 Lessons learned

The development and exemplary application of *TechMAPS* resulted in several insights and lessons learned on effectively managing and utilizing technological knowledge during the aircraft conceptual design phase:

- *Technology fact sheets:* The knowledge formalization into a structured, machine-readable format through creating TFS has proven to be an effective means of capturing, standardizing, and communicating essential technology information. This structured approach supports engineers in understanding and comparing technologies across varying levels of abstraction and different system domains. The TFS proved beneficial for abstracted logical technology variants but showed reduced effectiveness when directly representing existing technical data sheets.
- *Integration of source traceability:* The allocation of references to each data point significantly enhances the



(a) 2D comparison (b) 3D comparison

Fig. 12 Visualization of the technology landscape with *MATLAB* based on comparing physical attributes for different battery STVs using *TechMAPS*

credibility and transparency of the captured data, thereby increasing confidence during decision-making.
- *Technology database:* Using a database based on a formalized ontology facilitates the long-term conservation, maintenance, update capabilities, and flexible retrieval of technology knowledge.
- *Access security:* While row-level security policies introduce administrative complexity, handling access rights and supporting collaborative, multi-institutional usage is necessary. The approach ensures that sensitive data remain protected while enabling shared access to non-proprietary knowledge.
- *Technology landscape:* The technology landscape, derived from the quantitative physical characteristics, proved to be a valuable decision support tool during technology selection. It helps engineers identify viable options while also highlighting uncertainty.
- *Technology radar:* While the current manual approach to identify and collect technologies as part of the technology radar works, it introduces high workloads and is time-consuming, suggesting a strong potential for automation in the future.

Overall, *TechMAPS* establishes a practical technology knowledge management approach with a strong focus on formalized knowledge conservation, investigation, and reuse.

5 Conclusion and future work

To support engineers in selecting suitable technologies during aircraft conceptual design, the *Technology Management for the Architecting Process of aircraft on-board Systems* (*TechMAPS*) method was developed. It helps navigate existing and emerging technologies while standardizing technology knowledge management. After reviewing existing tools, *TechMAPS* introduces a process for formalizing technology data into a database, enabling queries and automated report generation. The resulting technology fact sheet (TFS) provides engineers with concise information on relevant technologies on two pages. The TFS shapes the underlying ontology for structured knowledge storage. A row-based security approach handles access rights. *TechMAPS* is applied on fuel cells, electric motors, and batteries, showcasing its adaptability and machine-readable technology landscape.

A key finding is that *TechMAPS* represents formalized technology knowledge across various systems and abstraction levels. Parameters are linked to their sources, improving traceability. A database allows for large-scale, flexible knowledge storage and querying. Moreover, the visual comparison of physical attributes as a technology landscape supports the engineer in selecting suitable technologies.

While the *TechMAPS* method outlined in this paper establishes an adequate method for technology knowledge management as an integrated step of systems architecting, further research is necessary to ensure its applicability across a broader spectrum of components and systems technologies. This need extends to accessing and querying the technology knowledge stored in the database, aiming to enhance usability. Furthermore, the current manual execution of the technology radar offers room for improvement. Additionally, for collaborative usage of *TechMAPS*, interfaces to partner institutions need to be established in the future, aiming to enhance collaborative potential.

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Declarations

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