TECHMAPS – TECHNOLOGY MANAGEMENT FOR THE ARCHITECTING PROCESS OF AIRCRAFT ON-BOARD SYSTEMS

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Abstract

Due to the noticeable effects of climate change and defined emission reduction targets, such as *FlightPath 2050*, efforts are being made to achieve low-emission aircraft in the near future. Therefore, many propulsion and on-board systems technologies, such as hydrogen-powered fuel cells, are being investigated. However, due to the vast number of existing and emerging technologies, it is challenging to navigate and manage technology knowledge. Hence, during the aircraft conceptual design phase, providing support to the engineers is crucial as they explore this vast design space of technologies and need to choose among many different technology variants. To handle this complex problem and to navigate the technology variants, this paper presents the *Technology Management for Architecting Process of on-board Systems* (*TechMAPS*) method. It 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 emerging technologies, a database to enable knowledge conservation and query capabilities, and an automated report generation with so-called technology fact sheets to provide the data to the engineer. In addition, intellectual property and confidential data handling are included. *TechMAPS* is exemplarily applied to a fuel cell, an existing electric motor, and battery technologies to demonstrate the method's capabilities for different systems and different technology abstraction levels. The study highlights the effectiveness of *TechMAPS* for technology management but also outlines aspects, which 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 [41]. In response to the environmental impact of aviation, initiatives such as *FlightPath 2050* have been established, emphasizing emission reduction targets [2, 21].

Despite continuous efforts, the evolutionary enhancement of current power train and on-board systems is projected to increase fuel efficiency by only approximately 20% until 2050 [2]. Consequently, there is a pressing need to investigate innovative technologies, such as hydrogen-powered fuel cell systems (FuCS). These technologies hold the potential to achieve carbon emission-free propulsion [2, 3].

To use renewable hydrogen for the power train and on-board systems (OBS), the current focus is on utilizing liquid hydrogen (LH_2) as energy source stored in tanks in the aft fuselage [3]. It is noteworthy that, as of now, no commercial aircraft runs on hydrogen, resulting in very limited experiences and knowledge within the aviation industry regarding relevant technologies, such as FuCS, as well as their interrelations with other OBS. Consequently, developing a hydrogen-powered aircraft necessitates addressing significant uncertainties and challenges associated with the incorporation of these technologies into the OBS architecture. One such 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 logically possible technology variants, forming a vast and complex design space encompassing numerous combinatorially possible OBS architectures. On the other hand, only limited experiences and knowledge are available, which leads to high uncertainties [30, 38]. Particularly, the interdependencies between various on-board systems, as well as the absence of authorities-defined certification specifications for disruptive technologies, such as FuCS or hydrogen handling, introduce significant uncertainties [27, 37]. Furthermore, these novel technologies can have a significant influence on the OBS so that the architecture can deviate significantly from existing solutions [68]. In addition, system costs are typically already influenced and mainly set during this phase and late changes during development are costly [18, 26, 72]. 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) [64]. Similarly, investigations extend to other OBS, such as the electrical system. This involves trade-offs between different battery technologies [45, 58]. Each of these technologies has its own implications. In general, for a hydrogen-powered aircraft, many questions remain open mainly driven by the vast design space of existing and emerging technologies.

To perform early technology trade studies at a 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. *SArA* serves as a comprehensive tool to assist the engineer during design space exploration, architecture evaluation, and variants down-selection [39]. The methodology is designed to effectively manage complexity, uncertainty, and to ensure traceability using a model-based systems engineering approach [38]. Importantly, *SArA* seamlessly connects overall aircraft design (OAD) and preliminary overall systems design (OSD) [38]. 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 [37]. Moreover, obtaining an overview of the pool of relevant technology variants is essential. Additionally, detailed technology knowledge, which is typically only available at the detailed design level [9], becomes 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. Therefore, first, the term "technology" in the context of systems architecting requires a clear definition, particularly regarding the level of detail at which it is described. The term is multifaceted and is often employed in diverse ways [6], ranging from aircraft and engine types to components and modeling tools. Second, it is necessary to capture both quantitative and qualitative knowledge about existing and emerging technologies unambiguously. This knowledge repository should also highlight potential incompatibilities between technologies. Third, given the diverse nature of technologies required for OBS architecting with unique characteristics and parameters, a generic yet formalized and standardized approach is essential for the effective conservation and retrieval of knowledge. Fourth, structuring and presenting this knowledge concisely, with a focus on the most relevant information, is paramount for assisting engineers during design space exploration [11, 56]. It facilitates the identification and exclusion of infeasible technology variants early in the architecting process. Therefore, 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, serving as a "technology map": the *Technology Management for Architecting Process of on-board Systems* (*TechMAPS*) method, which is being developed and presented in this paper.

To develop this method, Section 2 serves as a foundation by offering background information on existing knowledge management approaches. Additionally, it provides a literature overview of existing technology navigator and radar methods. The chapter proceeds to introduce the OSD framework of

TUHH for aircraft conceptual design. Moving on to Section 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. Afterwards, *TechMAPS* is exemplarily applied to a fuel cell, an existing electric motor, and battery technologies in Section 4. The paper concludes in Section 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.

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, providing also information regarding current knowledge and technology management approaches.

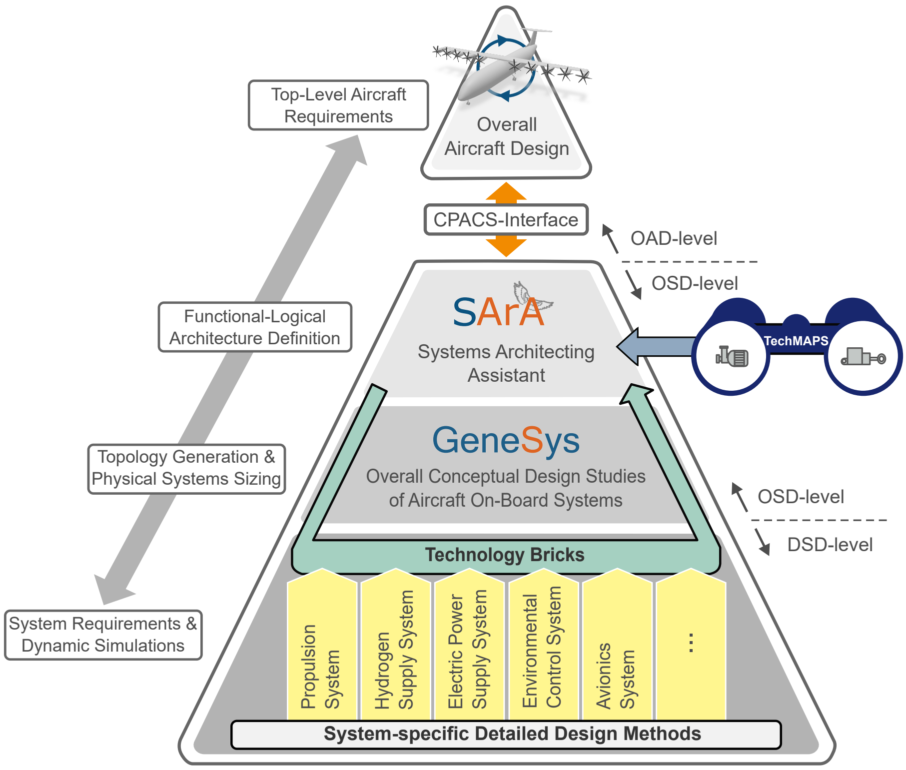


Figure 1 – Overall systems design framework for aircraft conceptual design phase from the perspective of system engineers [38]

The OSD framework, as illustrated in Figure 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. It includes a CPACS [4] interface for importing relevant parameters from OAD performed by external organizations. The CPACS file contains, amongst others, high-level aircraft requirements and a parametric representation of the aircraft geometry.

Utilizing the OAD input, the two methodologies *SArA* and *GeneSys* developed in-house are applied at OSD level [9, 10, 31, 32, 36–39]. With *SArA*, the OBS architecture is defined at a functional-logical level using model-based systems engineering methods [38, 39]. To enhance the efficiency and effectiveness of this process, the *TechMAPS* method is developed to extend and facilitate *SArA*, giving the engineer an extensive overview concerning relevant system technology variants. These technologies need to be instantly available in the process of model-based OBS architecture definition. Subsequently, the *GeneSys* methodology is employed. System components are first 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. In the third step, 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.
The OSD framework as a whole accelerates the setup of OBS architecture trade studies, allowing for a quick evaluation of various architectures in comparison 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, deriving from experiences and data [66]. Consequently, a structured approach to its management is essential for its effective utilization [16]. In engineering, managing knowledge poses specific challenges, notably incorporating intellectual property (IP) constraints [44]. Typically, knowledge exists in diverse forms, including databases, product data sheets, design specifications, process guidelines, heuristics rules, literature, or human expertise [37, 55].
Technology is often viewed as applied knowledge, closely linked to and dependent on it [1, 6, 40, 51]. While there is no universal definition for technology, it is generally understood as a means to fulfill objectives and functions [6, 35]. 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 [6, 51]. 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 [34, 51]. In addition, knowledge about technologies can be either explicit, knowledge documented in a report, or tacit, representing qualitative skills [51]. In the context of this paper, technology knowledge is defined as information, data, and experiences about technologies but in an unstructured, non-standardized form. Formalized technology knowledge denotes organized and standardized technology knowledge [37].
To use formalized knowledge, knowledge-based engineering (KBE) can be applied [37]. KBE as well as associated methods, such as design patterns, are not direct methods to increase creativity but rather optimize tasks by automating repetitive processes and expediting development [47, 50]. It facilitates a rationalized and less biased design space exploration, especially if an exhaustive search is impractical [37, 49, 67]. Implementing KBE allows for the effective collection, storage, and formalization of knowledge, providing engineers with more time for creative design tasks during conceptual design [66]. However, it is important to note that formalizing technology information is time-consuming and therefore most beneficial for complex systems with extended development times, such as aircraft [67].

2.2 Review of Existing Technology Navigator and Radar Concepts

This paper builds upon existing knowledge and technology management approaches as a foundation for *TechMAPS* method. Zheng et al. [71] present a method for handling knowledge and exploring the design space. Fuchs et al. [25] describe a method to automatically design aircraft cabins based on knowledge, requirements, and system interrelations, extending it in [24] with a knowledge database. Pfennig [48] developed an approach for using knowledge about physical laws and geometrical information stored in a database for detailed systems design. Meanwhile, Sanya et al. [57] focused on a platform-independent framework to ensure knowledge conservation for an extended period. Younse et al. [69] present a method for managing architectural knowledge, whereas Fitzsimmons et al. [23] describe a user-oriented knowledge management approach to enable a map for knowledge accessibility.
Presently, there are open-source as well as commercially available technology navigator or radar concepts 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* [46], Technology Radar [62], *Zalando Tech Radar* [70], or *BMW Group Technology Trend Radar* [8]. 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* [28], 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.

Similar concepts are discussed in the literature. Koops et al. [34] focus on aviation technologies by filtering websites, journals, and gathering experts' knowledge as key elements for the 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 works as an indicator for technologies with significant innovation potential for aviation and their physical limitations [7]. Technologies that can be adapted for the next aircraft with a strong focus on low-emission flight are highlighted [7].

Rohrbeck et al. [56] describe their technology radar as a tool to identify and visualize emerging technologies, assess their potential and risks, and provide valuable knowledge. This involves the steps of technology identification, assessment, and dissemination. Moreover, engineers are offered concise and tailored information, ranging from key statements to more detailed information. In addition, each piece of information is accompanied by its respective source. Boe-Lillegraven et al. [11] extend the radar approach from Rohrbeck et al. [56] by introducing scouts who identify emerging technologies, experts who regularly assess these identified technologies, and a quarterly dissemination process. They emphasize the concept of a concise one-page technology profile describing technology novelty and impact on the reader. Choi et al. [14] present a fact-oriented technology database for efficient technology management. A function-based approach directly links a technology to its functions, enabling search capabilities. Judt et al. [29] present an approach for architecture generation based on a component database using experts' knowledge, extending it in [30] to allow knowledge to be provided to multiple engineers.

The presented existing technology navigator and radar approaches serve as the foundation for the *TechMAPS* method. It is evident that the concept of utilizing a radar to identify and visualize emerging technologies warrants further consideration. Additionally, the provision of more detailed technology information in a concise technology profile document appears to be a viable approach for communicating technology information to engineers. However, it is notable that the majority of the approaches are not specifically focused on aircraft OBS technologies and tend to encompass rather high-level technologies. Consequently, the objective of the *TechMAPS* method is to integrate these aspects and to facilitate the systematic and structured documentation of knowledge about system and subsystem technologies. This approach ensures that the knowledge is readily accessible and can be leveraged by engineers during the conceptual design phase.

3. Technology Management for On-board Systems Architecting

Based on the foundation from the literature, the *TechMAPS* method is being developed. Key concepts, including the utilization of document-based concrete technology information profiles and the incorporation of a database for conserving and managing knowledge, are integrated into the *TechMAPS* method.

3.1 Developed *TechMAPS* Method

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 [16]. In response to these challenges, the *TechMAPS* method is being developed. The primary goal of *TechMAPS* is to manage and map out known and emerging technologies not on aircraft or system level, but rather with a specific focus on the subsystem level. Depending on the selected application case, the subsystem level may represent a single or multiple components or equipment working together to fulfill a certain function [13, 15]. 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 the provision of 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. This is exemplified by a proton-exchange membrane fuel cell (PEMFC) 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 [64].
- *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 for an STV for a PEMFC are the low-temperature and the high-temperature proton-exchange membrane fuel cell.
- *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' [19]. 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 Figure 2, depicting vertical dependencies. The tree-like structure visually represents the variations from one level to another. The blue arrow highlights horizontal interdependencies between technologies from different technology trees.

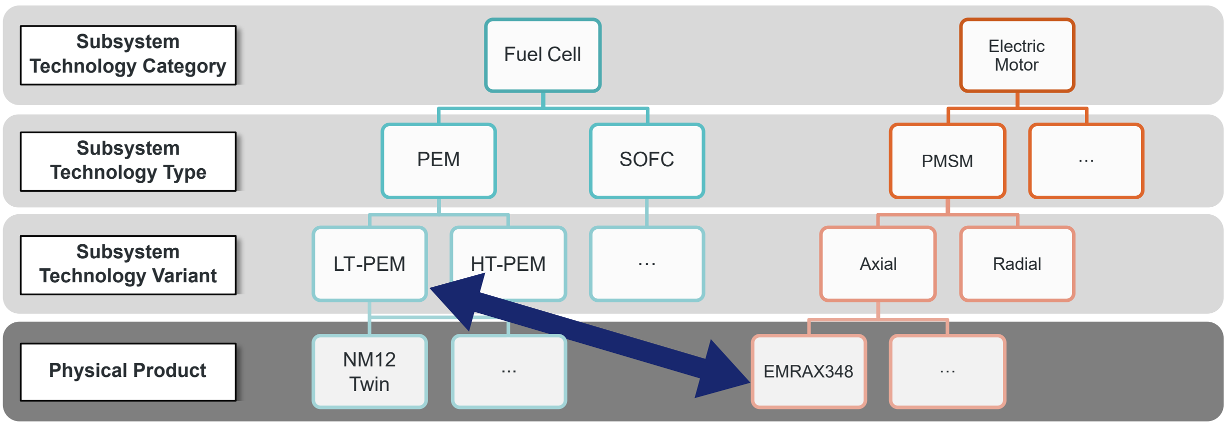


Figure 2 – Schematic representation of the defined technology levels of abstraction including their vertical and horizontal dependencies

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. [37].
As shown in Figure 3, *TechMAPS* comprises three main parts designed to effectively manage and navigate technology knowledge. First, the aspect of a technology radar is integrated, which serves the purpose of identifying new technologies and determining which ones should be conserved with *TechMAPS*. As discussed in Subsection 2.2, various approaches for a technology radar already exist. The aforementioned techniques appear to be suitable for identifying emerging technologies at a high level of abstraction, such as digitalization. However, their applicability to system, subsystem, and component level remains unclear. The technology radar method of *TechMAPS* is currently carried out manually by the engineer within the scope of workshops in collaboration with engineers from the

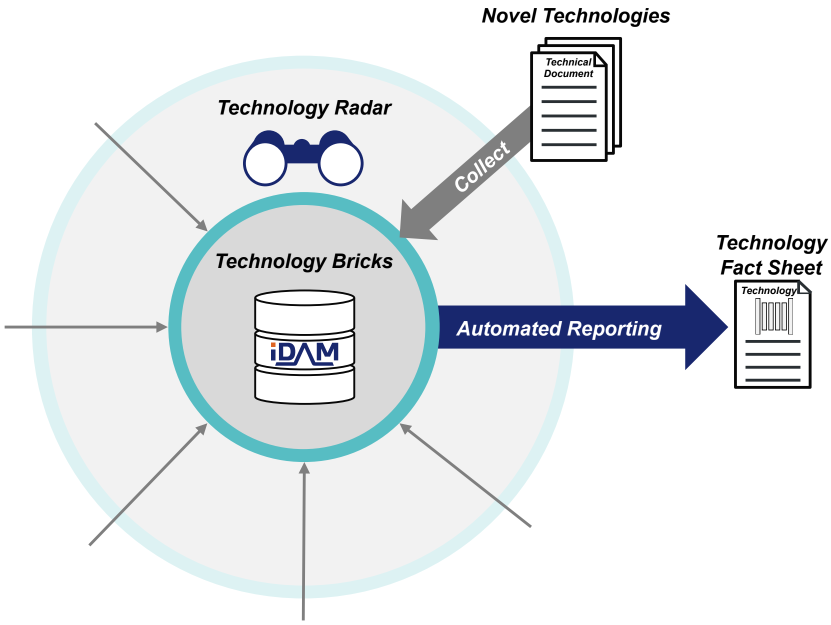


Figure 3 – Schematic overview of the *Technology Management for Architecting Process of on-board Systems* (*TechMAPS*) method

specific design disciplines of DSD. The development of a partly automated and formalized technology radar, as described by Koops et al. [34], for *TechMAPS* has been deferred to future research.
Second, *TechMAPS* incorporates a database concept to conserve, investigate, and reuse knowledge about existing and novel technologies. In this work, the relational database *intelligent Data Analytics and Management* (*iDAM*) is utilized. *iDAM* has been previously introduced for systems architecture pattern knowledge management by Kuelper et al. [37]. Built on the open-source, object-oriented *PostgreSQL* [52] 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 model-based systems architecting tool of the *SArA* methodology: MATLAB System Composer [37, 60]. The schema for formally storing technology knowledge in *iDAM* is presented in Subsection 3.4. Storing formalized technology knowledge within a relational database offers several advantages, including the ability to relate, categorize, query, and reuse knowledge in a machine-readable format [17].
Third, *TechMAPS* includes formalized *Technology Fact Sheets* (TFS), which are inspired by the concept of technology profiles as described by Boe-Lillegraven et al. [11]. A TFS offers engineers compact, document-based information and key data about technologies for OBS architecting (cf. Subsection 3.3). The intent is to automatically generate the TFS based on the information stored in *iDAM* to ensure traceability and reconciliation of document and machine-readable data, as well as to reduce manual repetitive tasks.

3.2 TechMAPS process for preserving 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 Figure 4. The process comprises two main parts: 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 non-standardized forms. This includes but is not limited to technical documents, reports, product data sheets, patents, literature, and human experiences [37, 55]. The non-standardized information regarding a certain technology is initially identified and collected. Subsequently, the information is formalized and standardized by employing a relational database (cf. Subsection 3.4) and entering the information and data into a MATLAB graphical user interface (GUI). Currently, the data

is entered manually by the engineer. Further research is necessary to automate and standardize this interface. The inputs required by the interface are strongly influenced by the information shown in the TFS (cf. Subsection 3.3) and the additional information stored in *iDAM* (cf. Subsection 3.4). Subsequently, the formalized and standardized technology knowledge is conserved in *iDAM*.

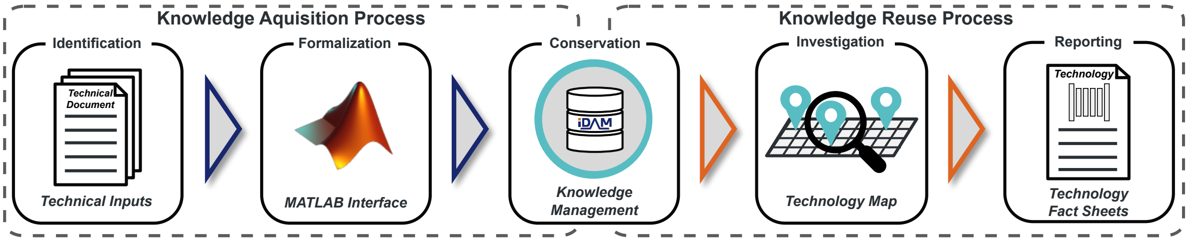
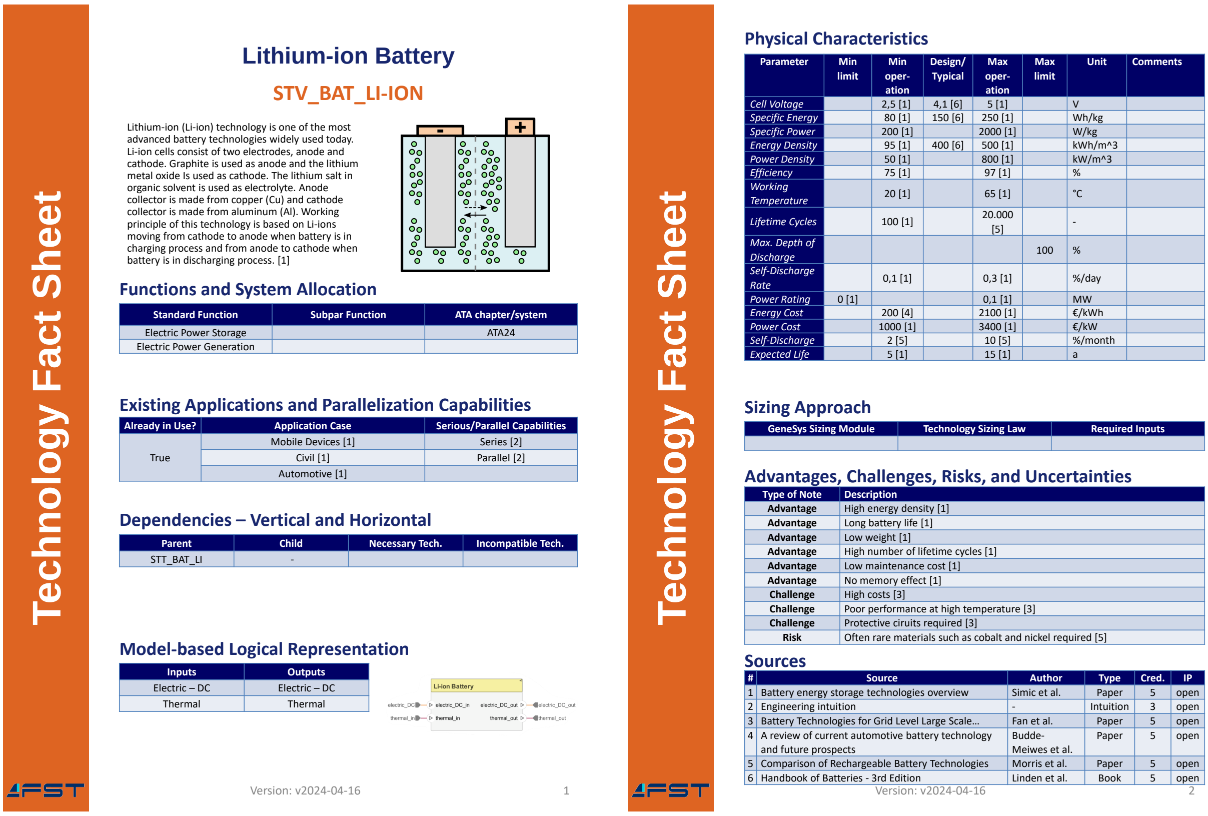


Figure 4 – Underlying process to conserve and provide knowledge with the *TechMAPS* method [61]

In addition to conserving knowledge, *TechMAPS* focuses on investigating and reusing technology knowledge. 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 [5, 38]. Therefore, the technology knowledge within *iDAM* is investigated using queries. Currently, this involves creating individual queries using SQL directly or MATLAB to investigate, for example, all conserved STVs for a certain STT and mapping out their characteristics and performance. Based on the investigated knowledge, formalized reports (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 Technology Fact Sheets

As mentioned earlier, a crucial element of *TechMAPS* is the definition of a formalized and standardized TFS as it encompasses the essential information required for model-based systems architecting when following a knowledge-driven approach. Furthermore, the TFS provides the technology knowledge in a concise, formalized, and standardized format to the engineer. Additionally, the structure and content of the TFS plays a substantial role in designing the database schema of *iDAM*, as the structure and information in the database need to comply with the TFS so that it can be generated seamlessly and automatically.
The standardized TFS comprises two pages, double-sided oriented. The decision to include two pages, rather than a single page as proposed in [11] is intentional. This format allows more relevant information to be provided to the engineer clearly and concisely. Additionally, physical product data sheets, such as those presented in [19] and [20], often consist of two pages as well. The TFS structure is exemplified by a lithium-ion battery as an example of an STV in Figure 5.
As shown in Figure 5a, 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 directly identify the technology presented in the TFS. The unique code includes the characterization of the type of technology (cf. Figure 2). Below, a brief technology description is provided. Additionally, a schematic icon or image of the technology is presented, as shown here for a battery. Subsequently, normal and subpar functions, as well as typical system allocations, are listed to demonstrate which functions a selected logical or physical technology fulfills. This approach can facilitate the generation of architectural designs and consequently reduce 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. Furthermore, the TFS provides information on whether a serial or parallel



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

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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	

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

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(a) Front page of the TFS

(b) Back page of the TFS

Figure 5 – Formalized and standardized structure of the technology fact sheets exemplified by a lithium-ion battery. Content taken from [12, 22, 42, 45, 58]

connection of a technology variant within a system is feasible. This information is of particular importance during the systems architecting process with *SArA*, as it enables the fulfillment of 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. Subsection 3.2). Horizontal dependencies describe the technological interrelations between separate, independent technology trees, as shown in Figure 2: '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 as well as an image of the model-based representation is included enabling a direct link between technology knowledge and model-based architecting. Additionally, at the bottom of the TFS, the present version in a date format is shown and automatically stamped to enable version handling.

As shown in Figure 5b, 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. Furthermore, physical parameters and limits, such as specific weight, specific power, efficiency, and temperature, are provided. 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 real value [10, 33]. 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, as well as the information whether parameters are confidential, is provided. Additionally, qualitative characteristics such as technology advantages and challenges [64], 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 as well as overall systems design.

3.4 Implementation of the Technology Fact Sheets in iDAM

To preserve and reuse technology knowledge while automatically generating TFS, it is imperative to store the knowledge in a machine-readable, standardized format. A feasible approach for that, as outlined in Subsection 3.2, involves employing the relational database *iDAM* [37]. This approach ensures accessibility, updateability, traceability, query capabilities, and reusability [29, 47, 57]. Additionally, the utility of a concurrently and widely accessible database, extending beyond a single institution, is beneficial [29]. Moreover, a generic design ensures adaptability across diverse systems characterized by significant differences [37]. Furthermore, the database is intended to facilitate straightforward modifications and updates, particularly to incorporate novel technology knowledge, such as that of hydrogen system technologies [37, 47].

3.4.1 Database Schema for Managing Knowledge about Technologies

To meet the aforementioned requirements, a generic database schema is devised within the context of *iDAM*, utilizing the open-source, object-oriented PostgreSQL database language [52]. In general, a database schema functions as a type of ontology. The schema is designed to facilitate the creation of analyzable, machine-readable knowledge through the use of SQL queries. It defines the structure, patterns, and interrelations inherent in the conserved technology knowledge [37, 65].

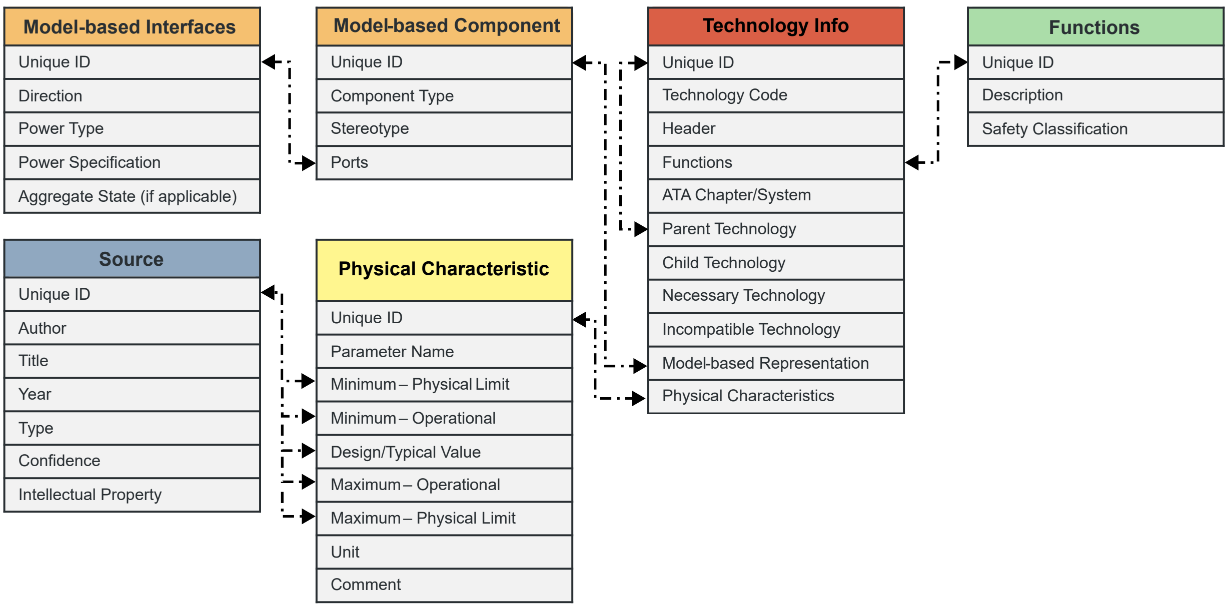


Figure 6 – Database schema for conserving and reusing formalized knowledge about technologies

As illustrated in Figure 6, the database schema comprises multiple tables, each featuring a column of unique identifiers ('Unique ID'). The presented schema shows a simplified version, emphasizing core characteristics and interrelations of the ontology. The schema consists of five distinct table categories, denoted by different colors, delineating varied information stored within the tables: *technology info*, *functions*, *model-based information*, *parameters*, and *source*.
The *technology info* category encompasses a compilation of pertinent data (columns of the table) for each technology entry (rows of the table). Each row entry in the *technology info* category is identical

to a technology described in a TFS. The *functions* table enumerates system functions associated with each technology [43], along with their safety classification. This highlights that *iDAM* conserves and provides access to more extensive technology knowledge than explicitly depicted in the TFS. The orange-colored tables pertain to the *model-based information*, crucial for modeling logical systems architectures. This information includes elements such as the 'direction' of interfaces, denoted as either 'input' or 'output'. To ensure that only valid entries are entered, namely 'input' or 'output', enumerations are defined for each applicable column. This approach minimizes erroneous entries. Enumerations are either directly specified or implemented through separate 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 schema complexity. These tables are not shown in Figure 6 for reasons of simplification, clarity, and understandability of the schema. The yellow table *Physical Characteristic* delineates typical characteristics and physical parameters essential for the TFS. In addition, the *source* table demonstrates the origin of a given value or information ensuring traceability of data and information.
Rows from one table can establish connections to rows of other tables (1-n or n-n connections) by linking unique entries [37], as presented by the arrows in Figure 6. This enables the linking of more detailed information and enumerations to broader tables. For instance, the table *Physical Characteristic* is linked to each row entry of the column 'Physical Characteristics' of the table *technology info*. Consequently, the engineer can search for a specific mass and retrieve all corresponding technologies, enhancing accessibility and query capabilities of stored technology knowledge. This approach ensures that the data in the database is 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 design also ensures that new, even unknown technologies with unknown characteristics can be conserved and navigated. Furthermore, 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 [37]. In essence, the database contains a wealth of technology knowledge beyond what is explicitly presented in the TFS, representing a comprehensive '150%' knowledge conservation approach. However, it is crucial to emphasize that, while *iDAM* has the capacity to store this additional information generically and uniquely, the conservation of required information for the TFS remains paramount.

3.4.2 Considering Intellectual Property Constraints

In the realm of knowledge management, particularly within the context of technology management, a crucial consideration is the handling of intellectual property (IP) rights [59]. 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 [59]. 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 IP management within *TechMAPS* is imperative. Given that knowledge is both conserved in and accessed from the database, the IP management approach needs to be implemented in *iDAM*.
Various approaches for enabling IP management have been evaluated, including employing independent 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. RLS is supported by PostgreSQL allowing the database schema administrator to define additional security rules per row, complementing the SQL-standard privilege system [53]. When RLS is enabled for a table, access to the table 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 [53]. This approach offers the advantage that, in the worst-case scenario, such as for a new user awaiting rights allocation, no IP-protected knowledge is visible or modifiable. 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 specifically for information related to a designated project xy.
- *Administrator*: This user holds full access and the capability to modify RLS rules.

As shown in Figure 7, 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.

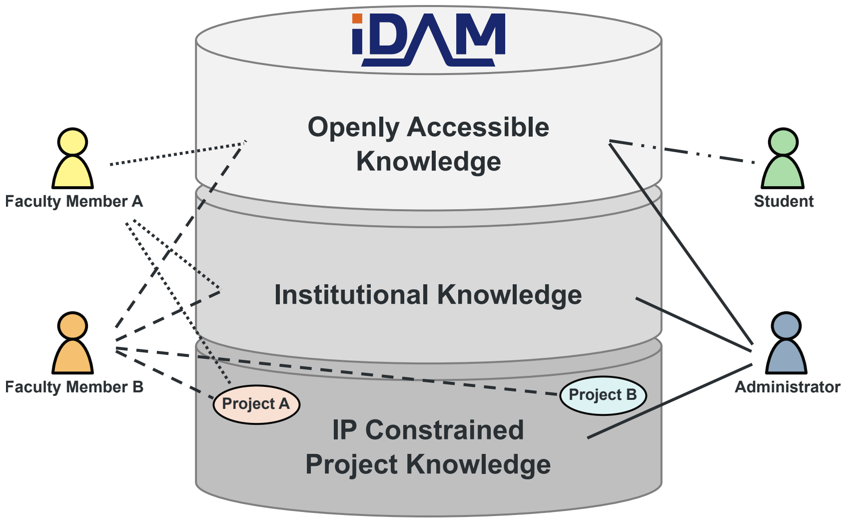


Figure 7 – User access rights shown for different user groups of *TechMAPS*

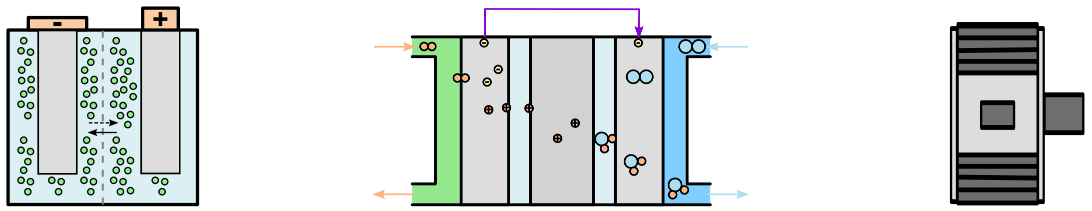
It is noteworthy that engineers with low privileges cannot definitively know whether detailed knowledge for a certain technology is already listed in the database due to the RLS security rules. However, it is essential to acknowledge and address this challenge to establish effective knowledge management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

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. Given that the process of *TechMAPS* (cf. Figure 4) 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 design of *TechMAPS* and its underlying TFS, *TechMAPS* is applied to three distinct technologies, shown in Figure 8, associated with different systems and situated at different technology levels (cf. Subsection 3.2).
First, the lithium-based electric battery is an example of a *Subsystem Technology Type* (STT) and is shown in Figure 8a. This STT includes some technology variants such as 'lithium-ion' or 'lithium-sulfur' batteries [45]. Lithium-based batteries are widely used, even in high-power applications, such as electric vehicles [45, 58]. Second, the LT-PEMFC, depicted in Figure 8b, serves as an illustration of a *Subsystem Technology Variant* (STV). LT-PEMFCs are presently under investigation as part of future hydrogen-based aircraft power trains, offering a potential to achieve low-emission aviation [39, 68]. This FC variant uses 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 [39, 54, 63, 68]. Third, the 'EMRAX 348' electric motor from EMRAX d.o.o. [20], shown in Figure 8c, is an example of a *Physical Product* (PP). 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 [20].



(a) Lithium-based electric battery

(b) Low temperature proton exchange membrane fuel cell

(c) 'EMRAX 348' axial flux PMSM.

Figure 8 – Schematic representation of the selected three use case technologies

To identify, gather, conserve, and provide the knowledge required by the TFS, diverse literature sources are employed for the lithium-based battery as well as 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 technologies at the physical level (PPs). 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 IP constraints.

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-Level (TRL)	-	Maturity-Level (TRL)	-	Maturity-Level (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

Significant distinctions between STTs, STVs, and PPs become evident when focusing on the required parameters, as shown in Table 1. All three of them 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' requires the inclusion of 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 focussing 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. Figure 1), by offering typical technology parameter ranges and physical limits streamlining the model-based systems engineering process. Thereby, 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.

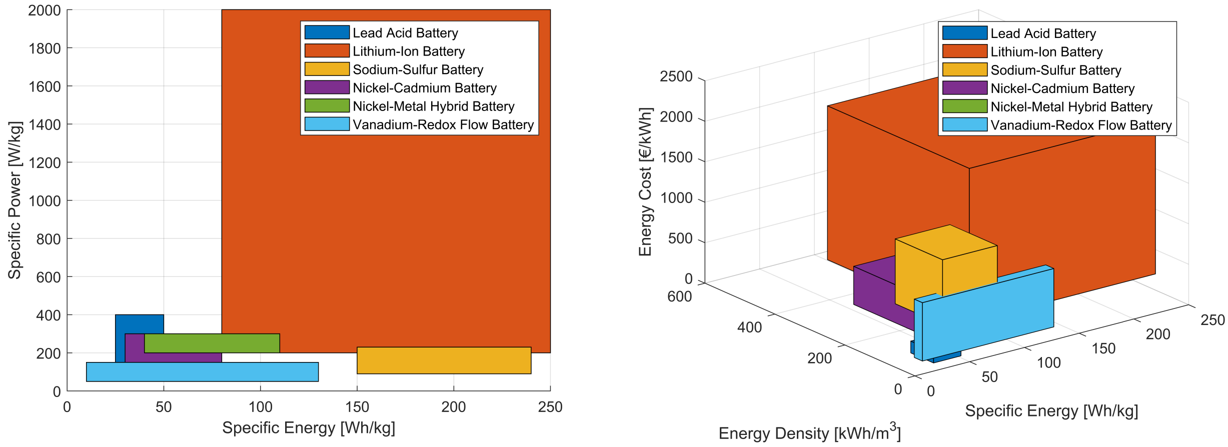
4.2 Comparison of Physical Characteristics of Conserved Technology Variants

In general, during the conceptual design phase, the engineer is not only interested in obtaining information regarding a single technology; rather, they are engaged in the process of comparing different technology variants to identify the most suitable technology for a specific application case. To illustrate this capability of *TechMAPS*, as previously stated in Figure 4, 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 [45, 58]. 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 the purpose of comparison.

As illustrated in Figure 9, physical attributes of technology variants can be visualized 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 Figure 9a) or three parameters (3D visualization in Figure 9b). Although it is possible to contrast technologies based on more than three parameters, this is a challenging task that 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. Any updates or modifications to the data within *iDAM* are automatically reflected in the plots since the information is stored in a machine-readable format. This provides further assistance to the engineer. Furthermore, the conservation of not only a single value for each parameter but also intervals and design values enables the comprehensive representation of complex data, including technology uncertainty and variations. This is demonstrated in Figure 9a and Figure 9b, respectively. In Figure 9a, areas are shown, while in Figure 9b, cuboids are presented. 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 pro-



(a) 2D comparison

(b) 3D comparison

Figure 9 – Visualization maps of physical attributes for different battery STV using *TechMAPS*

cess of OBS architecting. Currently, creating the physical attribute maps for the relevant parameters of the technologies needs to be specified in the code. In the future, this step can be enhanced with the incorporation of a user interface, thereby enabling engineers to select which parameters shall be used for comparison in a flexible manner directly in the interface.

5. Conclusion and Future Work

To assist the engineer in navigating extensive technology design spaces and selecting viable subsystem technology variants during systems architecting within the aircraft conceptual design phase, the *Technology Management for Architecting Process of on-board Systems* (*TechMAPS*) method is developed. It facilitates navigating a "map" of available and emerging technologies and also standardizes the conservation of technology knowledge. Following a literature review of existing technology navigators and radars, the process of *TechMAPS* is delineated, encompassing the formalization of new technology knowledge for conservation in a database, enabling query capabilities, and automating report generation. The created standardized report is the technology fact sheet (TFS), offering engineers concise and pertinent information about technologies on two pages. The TFS structure defines not only the necessary information about technologies required for conceptual design but also guides the database schema and structure. To ensure confidential data processing by *TechMAPS*, the database *iDAM* incorporates a row-based security policy for intellectual property management. Subsequently, *TechMAPS* is applied exemplarily to a low-temperature proton exchange membrane fuel cell, an axial flux permanent magnet synchronous electric motor, and battery technologies assessing its efficacy across different systems and technology abstraction levels.

A key finding is that *TechMAPS* effectively represents formalized technology knowledge, demonstrating clarity even across different systems and levels of abstraction. The method proves beneficial for abstracted logical technology variants but is less suited for directly mirroring existing technical data sheets. Furthermore, the direct linkage of a parameter to its source enhances traceability and facilitates the assessment of the parameter's trustworthiness. This feature of *TechMAPS* significantly increases the confidence in the method. Moreover, employing a database for knowledge conservation and access proves advantageous, enabling the conservation of substantial data volumes and offering flexible query capabilities. However, adding access privileges adds to the administrative workload, requiring management efforts. Nevertheless, this approach enables and facilitates the storage of multi-institutional technology knowledge while considering IP constraints. Furthermore, by visually comparing the physical attributes of technology variants, a map of the performance of the variants is created, which assists the engineer in technology selection.

While the *TechMAPS* method outlined in this paper establishes a foundation for technology knowledge management, further research is necessary to ensure its applicability across a broader spectrum of components and systems technologies. Additionally, there is a need for the development of a standardized, graphical, and user-friendly interface to the database to automatically conserve newly gained knowledge, minimizing the necessity for proficiency in SQL for interaction with the database. 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.

6. Contact, Acknowledgement, and Disclaimer

To contact the authors, please send an email to nils.kuelper@tuhh.de, vivian.kriewall@tuhh.de, kai.beschorner@tuhh.de, or frank.thielecke@tuhh.de. The results of the presented paper are part of the work in the research project *FASTER-H2* (project number: 101101978) which is the acronym for 'Fuselage, Rear Fuselage and Empennage with Cabin and Cargo Architecture Solution validation and Technologies for H2 integration'. *FASTER-H2* is supported by the Clean Aviation Joint Undertaking and its members. The project is co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The authors express their thanks to the European Union and the Clean Aviation Joint Undertaking for funding the research.

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7. Copyright Statement

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