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Procedia CIRP 136 (2025) 856–861

www.elsevier.com/locate/procedia

35th CIRP Design 2025

A design framework for the development of an innovative water-electrolysis space propulsion system

Daniele Ferrara[a,b,*], Paolo Cicconi[a], Angelo Minotti[b], Michele Trovato[a], Michele Amicarelli[a], Antonio Casimiro Caputo[a]

[a] *Università degli Studi ROMA TRE, Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Via della Vasca Navale 79, Rome 00146, Italy*
[b] *MIPRONS S.r.l., Via Ing. Riccardo Morandi snc, Colleferro (RM) 00034, Italy*

* Corresponding author. *E-mail address:* daniele.ferrara@uniroma3.it

Abstract

The space industry represents a thriving yet challenging environment for developing innovative solutions. Small companies may struggle to succeed due to time limitations, budget, resources, and the sector's inherent complexities. Design methods are essential for managing the design complexity while considering constraints, requirements, and standards. However, the applied methodologies must support the designer in finding innovative solutions. The present work proposes a streamlined design framework tailored to meet the needs of small and micro enterprises engaged in engineering and developing innovative high-tech products for the New Space economy. The proposed methodology is applied to support the design of an innovative water-electrolysis space propulsion system for satellites.

Keywords: Design Structure Matrix; Systems Engineering; New Space economy; Space Satellites

1. Introduction

The space sector represents a thriving ground for innovation and economic growth for companies of all sizes. Compared to previous decades, when space was dominated by national agencies and government institutions, today the space economy has become more accessible and cross-sectoral. Forecasts are more than promising for the coming years; an average growth of about 9% per year is expected, up to $1.8 trillion in 2035 [1]. In this context, private small and medium-sized enterprises (SMEs) are providers of innovative technologies and solutions (subsystems or equipment) for large space producers. This scenario is known as the New Space economy [2].

Today's global interest in the space sector leads to substantial investments, creating a new competitive and challenging landscape for SMEs. Space technology presents high intrinsic complexities due to the demanding conditions related to the definition of pre-launch and launch activities, orbit lifetime, and disposal evaluation; moreover, space systems require high reliability and strict adherence to space standards, processes, and regulations [3].

SMEs can fail to address these issues adequately due to a lack of a systematic approach to tackling challenging design tasks and optimizing resources, time, and cost. The systematic approach should be applied from the early phases because the requirements analysis, the function study, and the concept definition are the most important design activities while developing new systems [4].

The development of space systems requires methodologies that minimize rework by anticipating possible design issues (e.g., space qualification and export control), integrating sustainability and safety, and fostering innovation in advanced complex technologies. This approach would help SMEs increase their competitiveness in the space sector, accelerating their market growth.

This work proposes a methodological approach to support SMEs engaged in the design of innovative space solutions from the initial development stages. The research background is

10.1016/j.procir.2025.08.146

focused on design tools and methods for startup companies in the context of the New Space economy. In this context, understanding stakeholder expectations and conducting a state-of-the-art analysis is essential for designing a new system that must successfully reach the market without prior heritage. The proposed approach aims to fill the gap between the requirements study and the definition of the early product structure. The provided design framework includes the Design Structure Matrix (DSM) analysis. Thanks to its features of conciseness, problem visualization, situation awareness, and intuitive understanding [5], the DSM method effectively supports SMEs in guiding the engineering of ideas, particularly when integrated with complementary tools.

The case study concerns the early design of an innovative space propulsion system based on water electrolysis [6]. This propulsion system is innovative because water electrolysis represents a disruptive technology that can potentially introduce significant benefits in the satellite market, impacting system architecture, complexity, operativity, and sustainability [7]. Testing and validation of the method are in progress in collaboration with MIPRONS S.r.l., an Italian SME operating on space propulsion solutions.

The paper continues with a research background on product development and related methods, focusing on SMEs and space applications. The third section describes the proposed methodology, and the fourth section presents initial results and insights drawn from its application to the case study. The final section concludes with a summary of the findings and considerations on the potential of the developed methodology.

2. Background

2.1. Product development and Systems Engineering in SMEs

It is generally recognized that organizations of all sizes benefit from adopting methods and tools that optimize product development, ideally in alignment with their unique strategies and characteristics. This is especially true for SMEs, whose New Product Development (NPD) processes are often characterized by low formality, close customer relationships, limited resources, and a preference for flexible, easy-to-use design methods [8].

Systems Engineering (SE) offers guidelines and procedures to support the development of multidisciplinary, complex, and successful engineering systems [9]. It is easy to find SE processes applied to big projects in large, well-structured organizations such as space agencies. For example, NASA developed their own handbook to guide the application of SE in its projects [10]. In Europe, ECSS (European Cooperation for Space Standardization) dedicated one of their engineering standards to SE [11]. This document describes the requirements and provides the tools for its implementation for developing space systems. Other existing standards which specify a formal SE framework are the standard ISO/IEC 15288 [12] and its more recent adaptation, introduced for Very Small and Medium-sized Enterprises (VSMEs), and the standard ISO/IEC 29110 [13,14] for organizations of less than 25 people. Although they might extend to hardware and larger organizations, these ISO standards have been designed for software systems.

Several authors have analyzed the effects of adopting SE in SMEs. Some points of concern have emerged related to the additional workload and documentation required by traditional approaches, the extensive tailoring needed to meet individual company's needs [15], and the absence of high-level tools to support the design process in available SE standards [16].

Although still rarely used by SMEs [8], the implementation of SE, when carefully assessed, has the potential to lead engineering projects to success [15,17]. The need to improve costs and lead times to accommodate the current fast-paced growth of the space economy has led SMEs to seek more efficient alternatives to embracing SE.

The traditional document-based SE approach has been progressively replaced by Model-based Systems Engineering (MBSE). MBSE is an advanced methodology that utilizes predefined models to efficiently support and accelerate product development across the entire product life cycle [18]. Over the past fifteen years, many major space organizations have been implementing MBSE, from NASA [19] to ESA, which are putting effort into digitalizing their complete project management by 2025 [20].

The research analysis concluded that MBSE, like traditional approaches, can provide significant process improvements for SMEs. MBSE requires a great learning effort and time before yielding positive results. Consequently, the decision to adopt MBSE varies on a case-by-case basis [21], and efforts to streamline the adoption in SMEs are still ongoing [22].

2.2. Conceptual design modeling

MBSE models are not the only SE techniques present in the literature. Many design frameworks combine one or more techniques to address specific design problems throughout the product lifecycle, such as managing requirements, functional analysis and allocation, managing changes, and analyzing risks.

To support architectural and conceptual design, a wide range of methods and tools can be selected to guide specific stages or development processes depending on the engineering field, the organization, and so on [23].

By analyzing Architecture Frameworks, complex systems and processes can be effectively managed by selecting a subset of multiple "views" (or representations, such as flow charts, DSMs, IDEF0, etc.) that are easy to manipulate, effectively organize and convey information and work together to offer a comprehensive and holistic model of the system [24].

To address the early stage of the design, considered the most critical for decision-making, several researchers have proposed the combination of the Design Matrix (DM), the core of the Axiomatic Design theory, with the DSM method [25,26]. At the same time, the limitations of building the DSM for a new product using the traditional method (e.g., through expert interviews and existing documentation looking at the "as-is" system) are argued.

However, recent evolution in DSM theory introduced Multidomain Matrices (MDMs) together with Domain Mapping Matrices (DMMs). The matrices are an extension of the DSM and allow this method to evolve with the product from its early life and to interconnect multiple project domains, from system goals to product architecture [27]. MDM is a contemporary research topic, and its application as a tool to enhance innovation management is gaining increasing interest in the scientific community [28].

In this paper, the DSM is chosen as the primary design tool, distinguished by its capability to analyze interactions within and across design domains. The DSM supports SE phases of requirements management and functional analysis, playing a pivotal role in characterizing the conceptual design. To facilitate functional decomposition, the DSM study is supported by the IDEF0 diagram [29]. This visual tool provides the formalism to achieve concise, precise, and flexible functional modeling. The integration of DSM and IDEF0 can effectively guide process analysis, offering complementary perspectives of the same system [30].

2.3. The design scenario in the space industry

DSMs and DMMs are used as static matrices, representing relationships that are not time-dependent. Through clustering analysis [31], products are designed with a modular approach, which offers both technical and economic advantages. These benefits include the management of design changes, product variants, and reductions in development costs and time [4].

The modular approach aligns well with the current needs of the space industry, which is driven by intense competition and growing market demands. This sector requires design methodologies that prioritize adaptability and flexibility, as well as reliability and performance, to address the challenges of the space environment [32]. These requirements are often achieved through modularity and miniaturization, key innovations introduced by CubeSats. This class of satellites has revolutionized the sector, introducing faster, more streamlined procedures and more accessible pathways to space [33].

The need for highly reliable systems arises from the harsh conditions encountered throughout a system's lifecycle (e.g., vibrations, shocks, high vacuum), the impossibility of repair, and the high costs of space programs. As a result, space products must undergo rigorous design and testing processes to ensure they meet mission requirements and minimize customer risks. Moreover, European space companies develop products that conform to non-mandatory ECSS standards [34]. Compliance with international regulations is essential to avoid potential legal and operational challenges [35]. Among these, export control regulations impose strict technical requirements that must be carefully understood and addressed during the design process [36]. Furthermore, sustainability and space debris mitigation have emerged as key drivers in space system design, encouraged by current international space policies [37]. All the introduced aspects increase the complexity of the design phase and highlight the importance of achieving the right choices in the concept analysis. Advanced engineering design methods are well-established in large companies, enabling them to address complex challenges effectively. However, SMEs require adaptable, flexible, and agile approaches to be competitive and cost-effective in the demanding New Space economy.

3. Approach

This research proposes a design framework to support the early development of innovative products for small and micro companies in high-technology sectors, such as the New Space economy. The objective is to create a streamlined and modular methodology tailored for SMEs, enabling them to introduce the benefits of SE and engineering design in their NPD processes to meet the demanding requirements of today's space market.

The stages of the proposed approach, from the system input analysis to the creation of a modular functional architecture, are shown in Fig. 1. The scheme goes into more detail than the general setup of the conceptualization phase proposed in [6]. Insights derived from its application to the case study are reported in the next section.

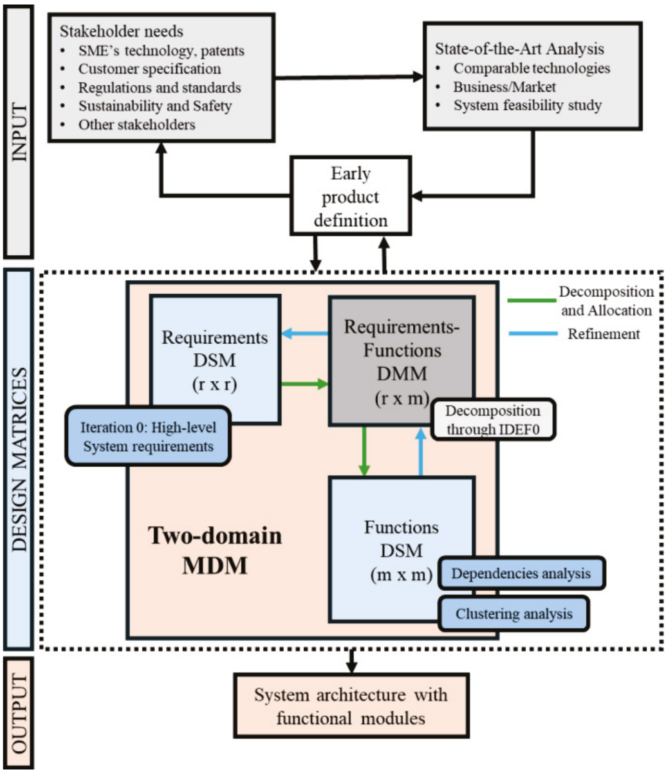


Fig. 1. The proposed approach for defining the system architecture with functional modules. The approach considers stakeholder expectations, requirements, and functional analyses. The macro-phases of the scheme are Input, Design Matrices, and Output.

As in any SE process, the initial activity is to understand the stakeholder expectations. Stakeholders include all entities interested in the development of a specific product. The stakeholders vary depending on factors like industry, type of technology, and the project's scope and potential.

In high-technology projects, the design drivers originate internally within the company. Many startups are built around patents, the company's key asset in a competitive market. Additional input comes from the external environment. This input is not necessarily technical and spans diverse areas, including standards, regulations, international policies, shareholders, potential customers, and market trends.

In parallel with stakeholder analysis, it is crucial to recognize that technology without heritage lacks a design reference point. This absence necessitates alternative methods to support the early stages of development. Conducting a state-of-the-art analysis of comparable systems and pieces of equipment, even from other engineering domains or designed for different purposes, can be functional in gathering design strategies, performance data, and current technological benchmarks applicable to the ongoing product development. Simultaneously, a preliminary feasibility study at the system level can provide an overall assessment of the physical limits achievable by the specific technology, including commercial solutions necessary for system integration and not developed in-house (materials, manufacturing techniques, commercial-off-the-shelf components, etc.).

Through several iterations, this initial analysis provides a solid baseline, referred to as the “Early product definition”, for the subsequent system conceptualization, during which the more evident potentials and limitations are defined, and a balanced set of high-level system requirements is formulated.

At this stage, design matrices are used to drive the design process. As shown in Fig. 1 above, iteration loops are included in the process. These loops reflect traditional SE practices that foster efficient information exchange between design domains supporting decomposition and requirement allocation.

The initial DSM, “Requirements DSM”, is derived from the high-level system requirements analysis (r x r matrix). Its elements represent the dependencies between the different requirements. “Requirements DSM” can be analyzed in other ways, according to the designer’s objectives. It helps identify potential redundancies in requirements that can be removed to simplify the information content. Additionally, it shows how requirements affect each other, functionally or in terms of performance and resources. This visibility allows designers to detect and resolve potential conflicts upstream, reducing the likelihood of rework. In successive iterations, parent-child relationships can be highlighted following the requirement cascading to lower levels.

Requirements are allocated to system functions through the “Requirements-Functions DMM”, a rectangular matrix linking requirements (rows) to functions (columns) (r x m matrix). This mapping process ensures that each requirement is assigned at least one function. By applying simple matrix operations on the DMM, the “Functions DSM” is derived, a square matrix that enables dependency analysis between functions (m x m matrix). This analysis supports clustering to identify functional modules, promoting architecture development and optimization. For functional decomposition from the system to the component level, the IDEF0 method is implemented to define functions and their relationships by gaining a complementary view.

For a new product development, capturing all functional relationships poses a significant challenge. Many connections may not be immediately apparent, and unanticipated emergent behaviors can be even more difficult to foresee. Adopting a high-level preliminary analysis, iterative design loops, and robust tools helps mitigate the risk of overlooking critical relationships, leading to unintended behaviors, notably when cascading from high levels down to components.

Iterative loops support the refinement of the system design. As new information is uncovered, it is fed back into the process. Once the refining process reaches the desired level of granularity, the functional architecture of the system is finalized. The relationships between requirements and functions, established through the design matrices, ensure the traceability of requirements back to the original high-level specifications. Traceability supports later phases, including trade-offs between design variants, change management, and requirements verification. It also facilitates more precise communication with stakeholders, allowing them to connect design elements to their initial inputs.

The methodology supports innovation in engineering new solutions and managing changes related to materials, stakeholders, and the market. This is continuously captured through an additional feedback loop from the design matrices to the inputs.

The resulting two-domain MDM can be extended into the product domain to complete the conceptual design, resulting in a comprehensive system architecture. By manipulating the matrix, the model supports a range of analyses, including dependency mapping and modularization, while facilitating project management tasks like cost estimation, personnel allocation, and resource and time planning.

4. Case study

This methodology is built upon the case study of a patented water electrolysis space propulsion system for satellites characterized by its miniaturized size and high performance [38]. The proposed approach supports the early design phases of this innovative propulsion system.

Nowadays, one of the most common propellants for spacecraft propulsion is hydrazine, which shows safety issues [39]. Water-electrolysis propulsion is a cutting-edge technology that can revolutionize the world of space propulsion. Water is the safest propellant, and its large availability and intrinsic safety can offer significant procedural and cost advantages. The idea of developing this solution for satellite space propulsion is not recent, but it goes back to more than 50 years ago [40,41]. Recent advancements in materials and manufacturing and a growing emphasis on sustainability, safety, and cost reductions have renewed interest in this technology.

The early product structure is defined through an analysis that assesses potential customer needs and identifies the involved stakeholders while considering the central role of the company’s intellectual property. Simultaneously, a state-of-the-art analysis focuses on comparable existing technologies alongside a preliminary system architecture study. The patented water electrolyzer [38], engineered in the proposed case study, was compared with similar terrestrial applications [42] to define requirements and functions.

As is typical in SE, stakeholder expectations are translated into high-level system requirements, which are classified as shown in Table 1. This classification derives from the analysis of guidelines, customer technical specifications, and similar works. It aims to be comprehensive, covering all areas influencing the product development [3,10,34,43,44].

Table 1. Identified high-level system requirement classes for space systems.

Code	Class	Description
H	Stakeholders	Non-technical and transversal (geopolitical strategy, satellite profitability, etc.)
M	Mission	Aspects related to the specific space mission and customer specification
R	Regulations and Standards	ECSS standards, export control, MIL standards, ASTM standards, etc.
S	Safety and Sustainability	Operator safety, elimination of hazards, reusability, etc.
T	Technical	Detailing of measurable system attributes
Te	Technology	Specific to the technology underlying product development (patents, technical solutions, etc.)

The system's requirements can be grouped into technical requirements and general requirements. The former are purely technological and initially derived from similar systems and the space environment, while the latter stem from diverse stakeholders but still have a significant impact on the system's technical design. Throughout successive iterations in the development process, all high-level requirements will be refined into validated technical requirements associated with specific subsystems and components. Technical requirements are further divided into subclasses, each covering different design areas. Different classifications emerge depending on the context, organization, and project. The commonly adopted subclasses, which try to cover all design areas exhaustively, are outlined in Table 2.

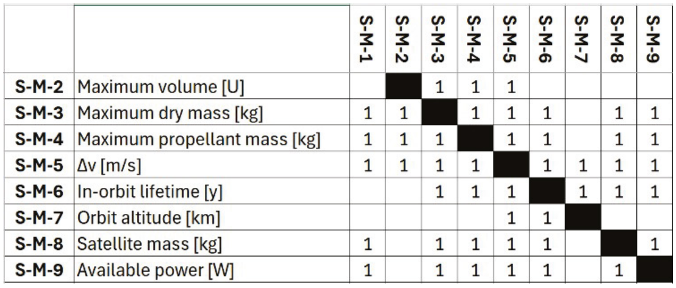
Table 2. Typical technical requirement subclasses in space product design.

Code	Subclass	Description
D	Design and Manufacturing	Material properties, manufacturing techniques, structure, cleanliness, resistance, etc.
E	Environmental	Operating and non-operating conditions during the system lifetime (launch, orbit, etc.)
F	Functional	Functions, lifetime, media compatibility, operational modes, etc.
I	Interface	Mechanical, fluid, electrical, logical, and thermal interfaces
P	Performance	Quantify specific system attributes (e.g., thrust level, maximum operating pressure, leakage)
Re	Reliability	Robustness, redundancy, single failure mode reduction, and other "-ilities" requirements [10]
V	Verification	Testing, analysis, review, inspection [34]

In different scenarios, more subclasses may be proposed or even combined based on the variety of requirements identified (for example, performance and safety requirements may fall under the functional subclass).

An excerpt from the resulting high-level system Requirements DSM is shown in Fig. 2. The coding system, essential to ensure requirement traceability, follows the format "Level – Requirement class – Sequential number". "Level" refers to the system, subsystem, or equipment.

An example of the hierarchical structure diagram, derived from the first functional decomposition through IDEF0, is shown in Fig. 3. The relationships between the functions are classified into fluidic, energy, and data & control.



		S-M-1	S-M-2	S-M-3	S-M-4	S-M-5	S-M-6	S-M-7	S-M-8	S-M-9
S-M-2	Maximum volume [U]		■	1	1	1				
S-M-3	Maximum dry mass [kg]	1	1	■	1	1	1		1	1
S-M-4	Maximum propellant mass [kg]	1	1	1	■	1	1		1	1
S-M-5	Δv [m/s]	1	1	1	1	■	1	1	1	1
S-M-6	In-orbit lifetime [y]			1	1	1	■	1	1	1
S-M-7	Orbit altitude [km]					1	1	■		
S-M-8	Satellite mass [kg]	1		1	1	1	1		■	1
S-M-9	Available power [W]	1		1	1	1	1		1	■

Fig. 2. Excerpt of the high-level system "Requirements DSM".

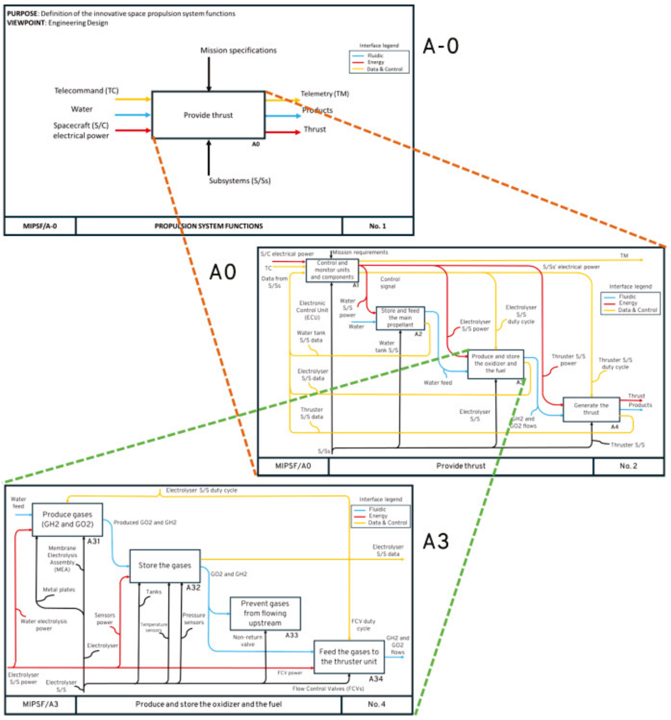


Fig. 3. Example of the IDEF0 hierarchical structure diagram.

5. Conclusions

The work presents the first insights gained from applying an SE methodology tailored to SMEs involved in developing space technology products. Innovation can be significantly enhanced if effectively integrated throughout the system design process, particularly when the initial phases are well-defined. Ensuring a robust conceptual design phase can effectively support the subsequent critical development phases of detailed design, verification, qualification, and market acceptance.

Acknowledgements

Doctoral project activated under The Italian Ministry of University and Research - Ministerial Decree 117/2023, resources based on PNRR, Mission 4, component 2 "From Research to Business" - Investment 3.3 "Introduction of innovative doctorates that meet the innovation needs of businesses and promote the hiring of researchers from businesses", with the contribution and involvement of MIPRONS S.r.l.

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