The Role of the Design Structure Matrix in a Streamlined Innovative Product Design Approach

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1 Introduction

In recent years, the space industry has radically changed, moving toward a democratized service economy. The term "NewSpace Economy" has been adopted in everyday life. Everything started with the CubeSats innovation, which aimed at exploiting modular space architectures (cubes of 2 kg of weight and 1 liter of volume) characterized by faster, cheaper and lighter procedures, maintaining, at the same time, safety and performance (Munakata, 2009). Since then, new entrepreneurial space companies and start-ups, which embrace innovation and tend to move away from classic, cumbersome state-centric models associated with big government agencies, rather adopting simpler and faster approaches for their development, have been set up globally (Brockmann and Raju, 2022).

The space industry consists of large producers and small-medium providers. While the first companies are big, structured organizations with often slow and costly processes, the others tend to be non-layered organizations to support the big players. The category of small-medium providers also includes start-ups that have to face issues such as reduced budget, resources, and time. However, the design of high-tech space features includes constraints that should be considered from the early stages of system development to reduce the risk of rework and avoid incongruence. Therefore, in addition to the NewSpace peculiarities, which are beneficial to companies of any size, the adoption of efficient design tools and methods may simplify the acceptance of small-medium providers by large players as well as provide support to the requirements and design management of complex projects. Such complexities arise due to the requirement of compliance with international regulations, such as the dual-use export control regulations for emerging and sensitive technology areas, and international standards, such as the European Cooperation for Space Standardization (ECSS). Though not binding, the ECSS standards are widely used by the European space industry and cover the whole product lifecycle (ECSS, 2020). Together with regulatory aspects and innovation features, the space field introduces complexity due to the demanding thermomechanical mission environment, high costs, low to zero risk tolerance (due to the impossibility of intervening in case of failure), numerous and diverse stakeholders, and a highly competitive market (Seifert, 2017).

In this context, the objective of this research is to propose a comprehensive streamlined and easy to manage Systems Engineering (SE) approach to support the design management of innovative companies dealing with high technology and operating in the space field (but not limited to), which can manage the complexities stemming from the specific technology under development and the inputs and constraints given by the external environment, while synergistically integrating with the company's resources, growth objectives, culture, and size (Chapuriat and Nastov, 2020). In particular, the presented work is motivated by the need of streamlining the design management of an innovative water-electrolysis space propulsion system for satellites (Minotti, 2018), which is under development by the Italian Small Enterprise MIPRONS and is characterized by sustainability, high efficiency, miniaturization, and reduced time-to-market.

Among the different system modelling tools in literature, the Design Structure Matrix (DSM) and its related approach were chosen as the foundation to the proposed methodology. The DSM is a tool to model networks of interactions and support decisions in engineering systems. It was first introduced in the process-based form for engineering work planning and communication applied to the example of an electric car project (Steward, 1981), but then it evolved and broadened in types, fields and range of application. This evolution is given by the fact that DSM provides a concise and straightforward tool to represent and analyze complex systems and, to achieve wider and better results, it has been lately accompanied by greater use of two of its inter-domain extensions, which are Domain Mapping Matrix (DMM) and Multidomain Matrix (MDM) (Browning, 2016).

This work introduces an approach to support the product design by the use of DSMs and DMMs. The traditional SE product and system design process receives the stakeholder needs as an input, which are transformed into system requirements, from which functional analysis and allocation are derived, finally bringing to design synthesis (Bhise, 2022). Following these typical design stages, several loops (requirements, design, control and verification) ensure the achievement of a balanced product design by fostering periodical communication and exchange of information between the design areas, enhancing decision making and tradeoff analysis, in order to meet the project budget and constraints.

At the current research stage, the focus will be on the product architecture DSM (component-based DSM), which is generally a square matrix, and DMMs, which generally are rectangular matrices, related to requirement, functional and physical domains. Both matrices are usually treated as time-independent, therefore static analysis is carried out. The usual approach is the analysis through clustering, which provides insights on the system architecture (DSM) and relationships between different domains (DMM) by identifying the so-called chunks, or modules, made up of highly interdependent items and that form the core from which significant understanding of the system can be derived.

2 Proposed Approach

The goal of this research is to address the product design of complex systems to the specific needs of high-tech small enterprises operating in challenging environments. The aim is to provide a tool to manage the system's inherent complexity, minimizing the risk of information loss and the consequent necessity of rework, which could occur in poorly structured organizations. The proposed methodology is depicted in Figure 1. This paper details the initial setup of the proposed approach, investigating the role of the DSM in supporting a specific set of stages in the product design process. The proposed approach is in the early stages of the study, and it may undergo various modifications and improvements based on the initial feedback resulting from its application to the case study. Given the innovative nature of both the approach and the system, such possible changes align with the research expectations.

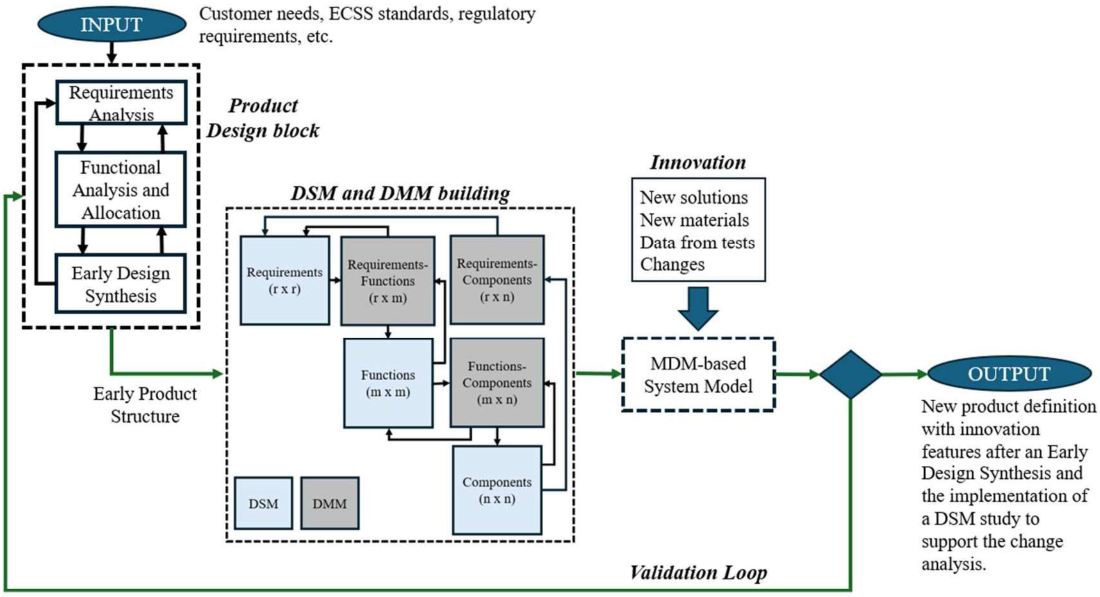

Figure 1. Role of DSMs and DMMs in the proposed product design approach.

Figure 1 shows the flowchart of the presented work. It includes the input to the product design process, which is analyzed into the product design block. This block represents the specific set of the traditional SE process. Representing a well-established base process, this block is used as a means for the subsequent validation of the matrix-based proposed approach. Initially, it supports the early structure definition of the system under development, which, being a new product, has no heritage and can be based mostly on literature analysis of comparable systems. The goal of achieving a streamlined approach is realized by adopting DSMs and DMMs to structure the product design process through the mapping of requirements, functions and components. The approach then provides, as the output, a detailed domain model representing the developed system. The resulting MDM can be used to perform the innovation process when input as new solutions, materials, and test data are introduced, demanding possible changes in the matrix structures. The proposed matrix-based design process is validated through a validation loop that goes back to the initial reference block. At the end of the whole process, the main output is the new product definition, characterized by innovative features, but also insights and experience on how to improve the proposed method are gained.

Focusing on the matrix building box, the information flow through the identified matrices is highlighted. This architecture, based on the joint use of DSMs and DMMs, combines DSMs on the diagonal and DMMs off-diagonal (Danilovic and Browning, 2007). The sequence of arrows in Figure 1 gives the idea of looping and iterations that align to the traditional approach. Through every iteration, each matrix evolves with the system, following the tradeoffs and decisions made during the product design development. Requirement, functional, and physical decompositions are also aided by iterations among the different domains.

The initial input to product design is given by the stakeholder expectations definition. In space projects, it consists in the identification of the stakeholders and the mission objectives, usually through use case scenarios as a Design Reference Mission (DRM) (NASA, 2016). The technology analyzed in this research project, focused on an innovative propulsion system, is still under development and no commercial contracts have been signed to date; therefore, the key stakeholders identified for the specific case study are the international standards and regulations, the shareholders and the few direct competitors.

The Requirements DSM is a requirement-based square matrix. At the beginning of the development, it is initially composed of system-level requirements, obtained by analyzing the DRM and the stakeholder expectations. Following successive design iterations in a top-down approach, it will extend and include more detailed, lower-level requirements following the so-called requirements cascade process. It helps visualize all the requirements and highlights the dependencies among them, particularly the parent-child relationships, of paramount importance during functional allocation and product verification. Clustering analysis can identify requirement chunks, which can assist the modular analysis.

The Requirements-Functions DMM is a non-square matrix that helps decompose the system requirements into system functions. This matrix is a powerful tool since it ensures that no requirements are left unassigned to functions, preventing them from being overlooked and avoiding unnecessary iterations.

The Functions DSM, together with the Components DSM, represent the classic square design matrices providing, respectively, the interactions between the system functions and the systems elements. Through clustering analysis, optimized system modularization and integration is achieved. The interface analysis carried out with these matrices represents a key aspect to support design synthesis in the detailed engineering phase. From the first application to the case study, it has been observed that the related interdomain DMM (Functions-Components mapping matrix) provides a tool to explore the product design architecture space. In fact, different architectures can be developed to meet the functional requirements by incorporating, for example, redundancies, COTS (Commercial Off-the-Shelf) or customized parts in the design.

Finally, the Requirements-Components DMM (with size r x n) is easily obtained by performing simple matrix operations from the Requirements DSM (r x r) to the Components DSM (n x n). Like the Requirements-Functions DMM, it offers a rapid solution to the product decomposition and requirement cascade to subsystems and components. This is particularly important for new products with no heritage, for which only the high-level system requirements deriving from the fixed DRM and external environment are initially known, and sub-systems or components can be few and only conceptually defined. Furthermore, the Requirements-Components DMM guarantees requirements traceability, which is fundamental for the verification loop. For space projects, this DMM would simplify the creation of the verification matrix, required by ECSS standards, and, therefore, by customers, as proof of design requirements verification.

It is clear that, particularly through DMMs, each matrix is interdependent, and this brings a similar benefit as the numerous loops required in the traditional product design process. The proposed architecture might facilitate control over the information flow and the interaction among the different design stages.

The main advantage observed by applying the proposed approach from the very first phases of development of a new complex product is that the amount of needed information to describe the model is the minimum possible, and it grows together with the system itself. Therefore, the flow of information is appropriately integrated, organized and managed along with the system evolution, and the data collection efforts are minimized, unlike what happens in already existing complex systems and static organizations (Browning, 2001). On the contrary, the complexity introduced by the inherent multidisciplinary feature of the high-tech system design still plays a critical role in the information gathering, in particular for requirements and interface analyses.

At the end of the product design phase, the system will present a matrix-based model which describes aspects such as requirements on which the system was designed, functions, sub-systems and components, and system architecture and interrelationships. If a new configuration is required, this model can support the redesign process, being all the dependencies between the aspects traced, and so the impact of each proposed change can be anticipated, quantified, and evaluated.

3 Closing Remarks

The role of the DSM in a streamlined approach to address the product design phases of an innovative high-tech system has been introduced. The DSM appears to be well suited to the needs of an innovative small enterprise facing the complex space environment. The initial analysis of the case study highlights several benefits and paves the way for further ones. The proposed approach provides ease of implementation, manipulation and visualization. It can offer efficient requirements management, supporting requirements traceability and cascade to lower system levels, and assist in defining and comparing alternative architectures, facilitating tradeoff analyses throughout the development process. Lastly, it offers a detailed domain model of the system, serving as a valuable resource for conducting design change analyses for different mission scenarios. However, DSMs and DMMs are not sufficient to address all the aspects of the product design, where specific tools and documents are needed such as Computer-Aided Design models, technical drawings, block and flow diagrams, Computer-Aided Engineering simulations, materials and manufacturing specifications, verification tests, etc.

In future work, the proposed approach will be implemented and tested, focusing on the case study related to the design of an innovative propulsion system. Clustering techniques, design tradeoff methods, and methodology architecture will be defined and improved according to the received inputs.

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