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Methodology for requirements definition of complex space missions and systems

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ABSTRACT

The paper deals with the description of a methodology to properly perform space mission design, with particular attention to derivation of requirements.

Several tools are usually adopted to support the design of complex missions and systems, but no very rigorous processes are available for the derivation of requirements. The methodology proposed in this paper aims at providing a general approach to exploit the main system engineering analyses and tools for a thorough assessment of the requirements. Specifically, it addresses how each category of requirements can be derived by appropriate analyses and what is generally the sequence of derived requirements categories.

The very first design step is mission statement and objectives definition. A parallel activity is the stakeholders' needs' analysis, mainly based on identifying all mission's actors and their expectations, thus deriving additional objectives. Once the broad objectives of the missions have been established, the following step of the design methodology is the Functional Analysis, which allows identifying the major functions to be performed for the mission's accomplishment, as well as the needed physical components. Another important analysis is related to the Concept of Operations, which has the scope of describing how the system is operated during its life-cycle phases to meet stakeholders' expectations. The overall process relies on the use of specific software tools, which provide useful means for the analyses integration giving also the chance to easily track and verify the results.

The paper reports a detailed description of the methodology, as well as an example case study in order to provide a clearer understanding of the entire process. The analyzed case refers to in-orbit validation of inflatable technology, which is one of the most significant technologies to be developed for future human space missions to deep space targets. Future human exploration programs point towards new and more challenging objectives, which require the development of new advanced systems and technologies, and their demonstration in space environment. Indeed a system is considered flight-qualified, once it has completed a demonstration mission in space environment. Accordingly, there is a great interest in the definition and analysis of dedicated missions for the in-orbit demonstration of advanced technologies.

The developed design methodology and the results obtained by applying the methodology have been obtained in the framework of STEPS-2 (Sistemi e Tecnologie per l'EsPlorazione Spaziale-Phase 2). STEPS-2 is a research project co-founded by EU on the "Misura Piattaforme Innovative"-Phase 2 of POR FESR 2007/2013.

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1. Introduction

In the last decades, there has been an increasing desire in studying and developing innovative space systems for different purposes applying new technologies [1–3]. For this reason, many recent research programs deal with the development of specific validation/demonstration missions to increase the TRL (Technology Readiness Level) of crucial technologies for space exploration [4,5]. The design of complex space missions and systems is not an easy task, and may require brainstorming and iterations to analyze several alternatives and gradually refine both the requirements and methods of achieving them.

The paper deals with the description of a versatile methodology with particular emphasis on requirements definition to support space mission design, taking specifically into account innovative technology demonstration/validation missions. The work has been developed in the framework of STEPS-2 (Sistemi e Tecnologie per l'EsPlorazione Spaziale-Phase 2). STEPS-2 is a research project co-founded by EU on the “Misura Piattaforme Innovative”-Phase 2 of POR FESR 2007/2013.

Several tools are available to support the design and specifically the definition of requirements, but no generally applicable rules or processes do exist. Design methodologies are discussed by a considerable number of authors [6–8], who consider both Functional Analysis (FA) and Concept of Operations (ConOps) as fundamental activities to capture requirements. The approach that we pursue within the present methodology specifically for requirements definition is the typical approach of Systems Engineering, which starting from the mission statement proceeds with the mission objectives through the stakeholder analysis and eventually to the definition of requirements through Functional Analysis and ConOps, as reported in [6–8]. However, unlike the design methodologies presented in [6–8], the proposed method aims at addressing how each single category of requirements (mission, functional, configuration, interface, environment, operational, logistic support, performance, design, physical and product assurance and safety) can be derived by appropriate analyses and what is generally the sequence of derived categories of requirements.

Section 2 describes the methodology, discussing the various steps that shall be performed. In Section 3, an in-depth description of the methodology is provided through the analysis of the major results for the inflatable technology case study. In particular, starting from the assessment of the mission statements and objectives, the process has gone through the Functional Analysis and Concept of Operations evaluation, with the final aim of producing a detailed and organized list of requirements.

Eventually, last section summarizes the main conclusions and proposes possible future applications of the methodology.

2. Methodology overview

Space mission analysis and design shall be regarded as an iterative and recursive process, permitting a continue refinement of requirements and constraints leading to a deeper component definition level.

Typical steps of the design process of a space mission are schematically illustrated in Fig. 1. The very first step is the definition of the mission statement. This activity shall be properly executed in order to obtain a complete, clear and concise statement that represents mission purpose for existence. This statement, as well as mission objectives, shall be fixed early because they represent mission foundation and for this reason they shall not be modified or readapted during following iterations. Primary mission objectives are directly derived from the mission statement. Simultaneously, the stakeholders' expectations shall be analyzed; this analysis mainly consists of two steps: identifying all the actors of the mission and determining stakeholders' expectations. As a consequence, secondary objectives can be derived.

Once the broad objectives of the mission have been fixed, it is necessary to proceed with the assessment of requirements. The requirements' definition is not quite an easy task, as no general rules do exist to derive them.

Two main analyses can be exploited to support the process: the Functional Analysis and the Concept of Operations (see Fig. 1).

The overall process is recursive, meaning that it shall be repeated starting from the highest level (system of systems) and going through successive lower levels (system, subsystem, …), as schematically illustrated in Fig. 2. Within this paper, the system-of-systems (SoS) and system levels are discussed in detail, in order to better highlight the recursive nature of the process.

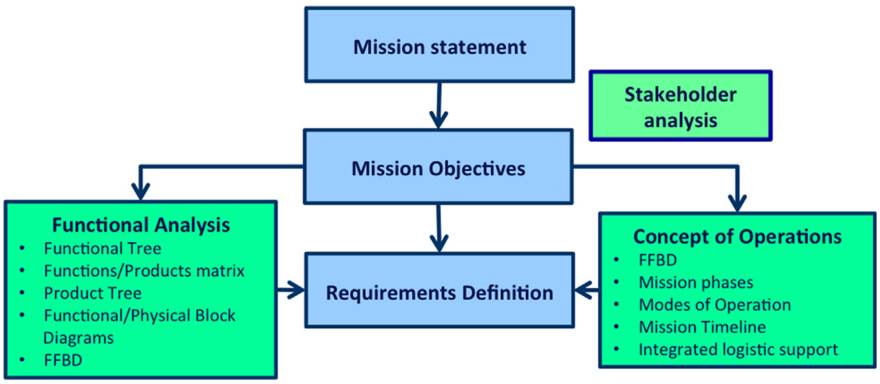

Fig. 1. General methodology overview.

The Functional Analysis includes several tools, which allow defining the systems needed for the mission accomplishment, the so-called building blocks, and how they are interrelated to build up the functional architecture of the future mission. Moreover through Functional Analysis functional, configuration and interface requirements can be defined (see Fig. 3).

As first step, the functional tree is built; it expresses the functions to be performed for the execution of the mission. The functional tree allows splitting the higher level and complex functions, which stem from the mission objectives, into lower level functions, through a typical breakdown process, and eventually it allows identifying the basic functions that have to be performed by the future product. Therefore, starting from the so-called top level functions, the functional tree generates various branches, which move from the most complex function to the basic functions, i.e. those functions at the bottom of the tree that cannot be split any further. The basic functions help defining the functional requirements of the future product, as each basic function can be rewritten as a functional requirement.

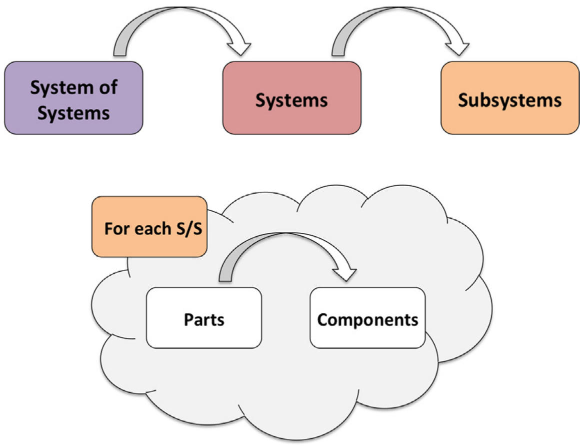

Fig. 2. Recursive nature of the methodology.

Starting from the functional tree, the functions/products matrix is created, with the scope of identifying the elements or building blocks needed to accomplish the functions. Specifically, the matrix's rows contain the basic functions coming from the functional tree, while the columns report the products, i.e. the space mission elements capable of performing those functions. Starting from the analysis of the first basic functions, new elements progressively fill in the columns. Eventually all basic products are determined. As a result, the elements to be involved in the missions are identified, by mapping all basic functions to products. Eventually by simply grouping together the elements, the product tree of the new product can be generated. Unlike the functional tree, which has a typical top-down approach, the development of the product tree follows a straightforward bottom-up process. On the basis of the function/products matrix and the product tree, functional requirements can be refined and configuration requirements can be defined (see Fig. 3). It is worth remembering that, depending on the level of the analysis, a "product" can be a system of systems, a system, a subsystem, etc. As part of the functional analysis, other tools have been used within the proposed methodology for the requirements definition: the connection matrix and the functional/physical block diagram. The connection matrix

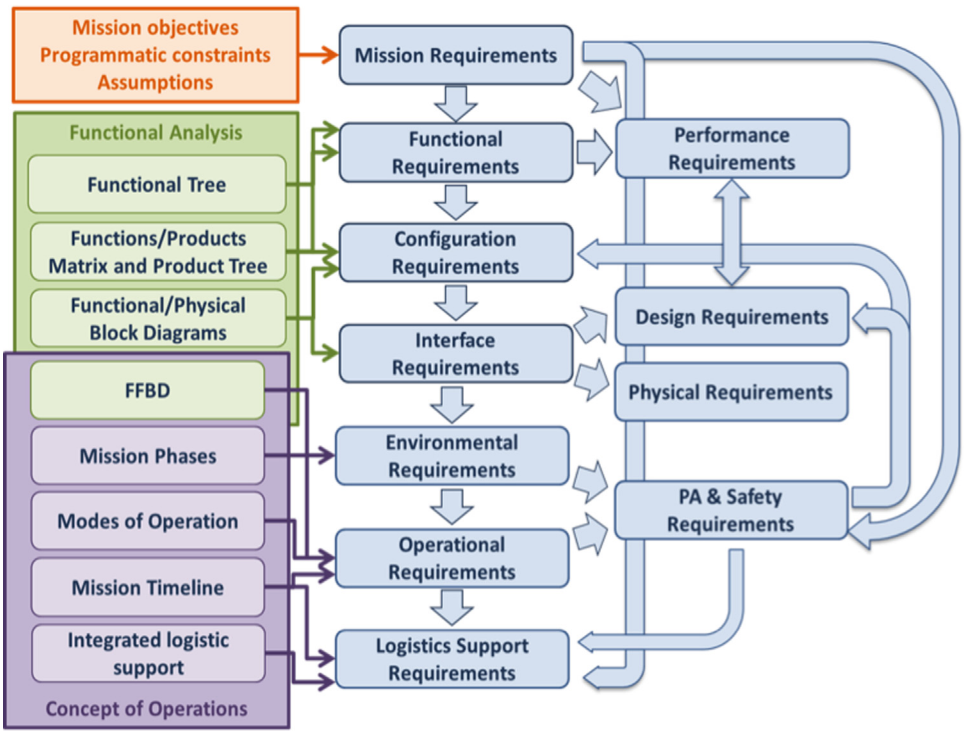

Fig. 3. Requirements definition methodology.

can either be a triangular or a square matrix, where both rows and columns have the same elements. The connection matrix highlights connections among all building blocks. Unlike the connection matrix, the functional/physical block diagram represents the building blocks linked through point-to-point connections. The block diagram provides the designer with further information, if compared to the connection matrix, about the links' directionality. Moreover it gives evidence of the link type (e.g. mechanical, electrical, etc.). From these diagrams, configuration requirements can be refined and interface requirements can be derived.

Functional Analysis as a fundamental analysis of the design process is discussed by a number of references. Wertz and Larson [8] present the Functional Analysis to decompose the functional requirements and focus only on one single tool of the Functional Analysis, i.e. the functional tree. NASA [6] and ESA [7] consider Functional Analysis as the systematic process of identifying, describing, and relating the functions a system has to be able to perform, in order to be successful, but do not consider it as a design tool to address how functions have to be performed, i.e. to map functions to components. Emphasis is given to the possibility of capturing functional requirements by performing Functional Analysis [6]. In contrast within the proposed methodology, the main outputs of the Functional Analysis are

- the definition of the building blocks of the system functional architecture, through the development of the functions/products matrix, the product tree and then the functional/physical block diagram;
- the identification of configuration requirements through the functions/products matrix, the product tree and the identification of interface requirements through the functional/physical block diagram, besides the identification of functional requirements through the functional tree.

The following section describes into details the tools of the proposed Functional Analysis methodology.

The Concept of Operations allows describing how the system will be operated during its entire life cycle, in order to achieve the mission objectives. Moreover through ConOps environmental, operational requirements and logistic support requirements can be defined (see Fig. 3).

Typical analyses contained in ConOps include evaluations of mission phases, operation timelines, operational scenarios, end-to-end communications strategy, command and data architecture, operational facilities, integrated logistic support and critical events [6]. The proposed methodology focuses mainly on the analysis of the mission phases, the mission timeline and integrated logistic support, as well as on the establishment of the modes of operations. Future activities will consider more analyses of the ConOps.

The mission phases have been defined in terms of activities and environment that characterize them. Each phase is identified by a well precise state of the system within the mission under consideration. The state of the system is defined by the external environment (natural and induced environments, e.g. radiation, electromagnetic, heat, vibration and contamination environment) within which the system operates. The transition between one state of the system to the next one defines also the transition from one phase to the next one. During each mission phase, the system can enter various modes of operation. The modes of operation can be defined as stable configurations of the system, or, similarly, as a set of functions performed and/or maintained by the system. Unlike the mission phases which are related to the external environment in which the system operates, we define a mode of operation by establishing which subsystems and equipment are active or not active within that specific mode. The analysis of the modes of operation allows having a clear picture of which functions are available simultaneously, which components are required to be active and it represents one of the main inputs for power and thermal budgeting activities. The identification of the modes of operation is therefore a fundamental activity of the system design process. Together with the modes of operations also the transition between the various modes of operations has to be clarified. The present methodology addresses the identification of the transition between modes of operations through the Functional Flow Block Diagrams (FFBD).

FFBDs specifically depict each functional event (represented by a block) occurring, following the preceding function. Some functions may be performed in parallel, or alternative paths may be taken. The FFBD network shows the logical sequence of “what” must happen; it does not ascribe a time duration to functions or between functions. The FFBDs are function oriented, not equipment oriented. FFBDs are in fact drawn starting from the output of the Functional Analysis, specifically the functional tree. They identify “what” must happen and must not assume a particular answer to “how” a function will be performed. FFBDs are developed from the top down, in a series of levels, with tasks at each level identified through functional decomposition of a single task at a higher level. The FFBD displays all of the tasks at each level in their logical, sequential relationship, with their required inputs and anticipated outputs, plus a clear link back to the single, higher level task. The decomposition of high level functions into simpler tasks leads to the definition of sequence of operations, thus providing an understanding of the total operation of the system. FFBDs serve therefore as a basis for the development of operational and contingency procedures, and pinpoint areas where changes in operational procedures could simplify the overall system operation. Moreover FFBDs highlight the transitions between the various system modes of operations, identifying along the overall sequence of system operations when the system enters a certain mode of operations and how it moves from one mode of operation to another. FFBDs are used to develop, analyze, and flow down requirements, specifically operational requirements, as well as to identify profitable trade studies, by identifying alternative approaches to performing each function. In certain cases, alternative FFBDs may be used to represent various means of satisfying a particular function until trade study data are acquired to permit selection among the alternatives.

According to [6] FFBD is a fundamental tool of Functional Analysis. Even though FFBDs are functions oriented and are actually completed once Functional Analysis (in particular the functional tree) has been accomplished, Functional Analysis is just a starting point to develop FFBDs. FFBDs are actually built initially on the basis of the functional tree but they then proceed with a further decomposition of functions into sequence of operations to support mission operations analysis. Taking into account these considerations, the present methodology considers FFBD as a tool that should belong more appropriately to ConOps rather than to Functional Analysis.

ConOps as a fundamental analysis of the design process is largely discussed by NASA [6], which states that ConOps in an important component in capturing stakeholder expectations, requirements and the architecture of a project. However NASA does not provide the reader with specific information about which distinct categories of requirements can be derived by the ConOps and from which specific analyses the various categories of requirements come from. In contrast, the present methodology identifies certain categories of requirements as directly derived from the ConOps and associates each specific analysis of the ConOps with families of requirements.

Fig. 3 reports, as a summary of the proposed methodology for requirements definition, a flow chart which highlights the connections between analyses (Functional Analysis tools and ConOps tools) and categories of requirements, as well as the sequence of derivation of categories of requirements.

On the left hand side of the flow-chart there are the boxes of the analyses that help designing space missions and systems and within each box (Functional Analysis and ConOps) various tools are pointed up. Each tool is useful to derive certain specific categories of requirements that are expressed in the light blue boxes in the center of the flow-chart. It is worth noting that mission requirements stem out directly from mission objectives, programmatic constraints and assumptions. Functional, configuration and interface requirements derive from the Functional Analysis and respectively from the functional tree and the functions/products matrix, the functions/products matrix and the product tree, and the functional/physical block diagrams. Environmental, operational and logistic support requirements derive from the ConOps and respectively from the mission phases, the FFBDs and the modes of operations together with the mission timeline, and from the mission timeline and the integrated logistic support. The categories of requirements in the light blue boxes in the center of the flow-chart are those types of requirements which can be defined on the basis of specific analyses/tools ("primary" requirements), whereas the requirements in the light blue boxes on the right hand side of the flow-chart are those types (performance, design, physical, product assurance and safety) that cannot be defined on the basis of specific analyses/tools but derive from other categories of requirements ("secondary" requirements). For sake of clarity, as an example of primary and secondary requirements, we can think of functional and performance requirements: first functional requirements can be defined or refined on the basis of Functional Analysis, considering the functions that the system shall be able to perform, eventually performance requirements will be established considering how well those functions shall be performed. The light blue arrows in the flow-chart show not only the relationships between primary and secondary requirements but they do also reveal a general sequence of derived categories of requirements. Within primary requirements, first mission requirements can be established, then functional, configuration, interface, environmental, operational and logistic support requirements can be defined in sequence.

A general order between derived categories of requirements is rarely discussed in the literature, apart from the obvious relationship between descriptive and quantitative requirements, i.e. between functional and performance requirements [6,8]. The present methodology addresses this issue and identifies a general sequence of derived categories of requirements, as illustrated in Fig. 3.

3. Inflatable demo mission

In order to provide a clear example of the implementation of the methodology, this section reports a thorough description of the results obtained by applying it to a specific case study, that is the definition of an in-orbit validation mission for the inflatable technology.

3.1. Overview

The inflatable technology is very appealing, when looking at long and far missions, since it allows larger volume/mass ratio than conventional rigid structures, being able to increase the volume once on orbit.

Traveling beyond LEO is the next step in the conquest of the solar system, and so far, a large effort has been dedicated to the investigation of possible strategies for future human space exploration. This is proved by several research activities carried out by the major space agencies, industries and academies, which aim at the definition of opportune mission strategies, as well as at the assessment of the technologies needed to accomplish these types of missions [9–15].

According to these studies, the inflatable is one of the most important technologies to be developed, since long travels will require large habitation modules, also for psychological reasons [16]. As a matter of fact, relying on inflatable modules will allow larger volumes available for the astronauts, without the need of excessive launch masses. Moreover, inflatable technology can be also exploited for other applications, like for example orbital structures as booms, radiators, solar arrays, etc.

Prior to be actually used in operative systems, new technologies need to be "flight qualified", through dedicated demonstration missions in space environment [17–19].

Specifically, the inflatable compatibility with Low Earth Orbit (LEO) and deep space environment is still to be fully understood (i.e. exposure to heat, radiation and debris for long periods of time) and therefore it needs to be demonstrated and validated in relevant space environment before its implementation in a real operational mission. This step would allow the achievement of TRL 7 and 8, which indeed require demonstration in space environment (TRL 7 is reached through demonstration of a prototype system, while TRL 8 is reached through demonstration of the actual system).

Hereafter, the results for the inflatable validation mission case study are discussed, as obtained by applying the steps of the methodology mentioned in the previous section.

3.1.1. Mission statement and primary objectives

As very first step of the design process, the mission statement has been defined. It can be expressed as

> "*To demonstrate and validate inflatable technology to support future human space exploration, exploiting ISS as existing infrastructure, providing ISS with resupplies, experiments and waste management and temporally extending ISS habitable volume.*"

Once the mission statement has been defined, the following step is the mission objectives' assessment: they are broad goals the system must achieve to satisfy a need [8,20]. The primary objectives for the inflatable demonstration mission are directly derived from the just discussed mission statement. They are

- to demonstrate and validate inflatable technology,
- to exploit ISS infrastructure,
- to resupply ISS,
- to provide ISS with experiments,
- to bring back ISS waste,
- to temporary extend ISS habitable volume.

3.1.2. Stakeholders' analysis

Another important aspect to be accounted for when designing a space mission is the analysis of the needs of the main mission's actors. Depending on their role, all the participants can be categorized as sponsors, operators, end-users, customers and/or developers. Especially during first iterations, sponsors' desires shall be considered, because they often establish mission statement, bounds on time schedule and define funds availability. Sponsors' needs should be compared to developers ones, in order to achieve a preliminary agreement between ideas and physical and technological requirements.

According to the definitions provided in [20], the mentioned categories can be described as reported hereafter.

Sponsors are those associations or private who establish mission statement and fix bounds on schedule and funds availability. For the mission analyzed in this paper, Thales Alenia Space—Italy (TAS-I) is the sponsor.

Operators are in charge of controlling and maintaining space and ground assets. Typically they consist of engineering organizations. In the analyzed case, they mainly are TAS-I (Space Segment) and Altec (Ground Segment); furthermore, launcher developers (Transportation Segment) and astronauts (as payload operators) are to be considered.

End-users are those people that receive and use space mission's products and capabilities. They are usually scientists or engineers. In the present case, end-users are structural and systems engineers from TAS-I (inflatable technology), engineers from Altec (Ground segment) and scientists (scientific experiments).

Customers differ from the previous category because they are users who pay fees to utilize a specific space mission's product or service. Since the studied mission is aimed at the demonstration and validation of specific technology, customers would be absent. The possibility to have customers of specific experiments to be carried out on board the module is not excluded.

By analyzing the needs of the identified stakeholders the following secondary objectives have been derived

- to improve TRL of inflatable technology (TAS-I),
- to exploit existing spacecraft design (TAS-I),
- to receive data and transmit commands (TAS-I, Altec),
- to exploit ISS resources (fluids, electric power, communications links) (TAS-I, Altec),
- to exploit existing Ground facilities (Altec),
- to operate inflatable technology (Astronauts),
- to operate experiments (astronauts, scientists).

3.2. Functional analysis

This section discusses the Functional Analysis, which has led to the assessment of the main functions that shall be performed for the accomplishment of the mission and to the identification of the mission architecture. In particular, in the following sub-sections the results of the Functional Analysis performed at system-of-systems (SoS) and system levels are reported, in order to underline the recursive nature of the process.

3.2.1. Functional tree

In the first phases of the design process, the functional tree shall be developed, paying particular attention to maintain high level of abstraction and definition. Starting from the mission statement, the highest-level functional tree has been directly derived. The derived functions describe all the functionalities that the products involved in the mission shall provide.

In particular, the first level functions refer to the system-of-systems (central boxes in Fig. 4) level, which have direct correspondence with the segments involved in the mission.

From the SoS-level functions, answering the "how" question, the lower level functions have been derived (right hand side box in Fig. 4), which have a direct correspondence with the systems involved in the mission. Functional trees are the starting point for the derivation of the functional requirements.

The two trees (SoS and the system levels) have been used to build the functions/SoS and the functions/systems matrices, respectively. The matrices aim at mapping the functions to be performed on, respectively, the mission's segments and systems identified through this analysis (see following sub-section).

3.2.2. Functions/devices matrix

Fig. 5 reports the functions/segments matrix, which has led to the identification of the "segments" to be involved in the mission. Specifically, there will be

- *Launch segment*, in charge of the launch of the spacecraft into orbit,

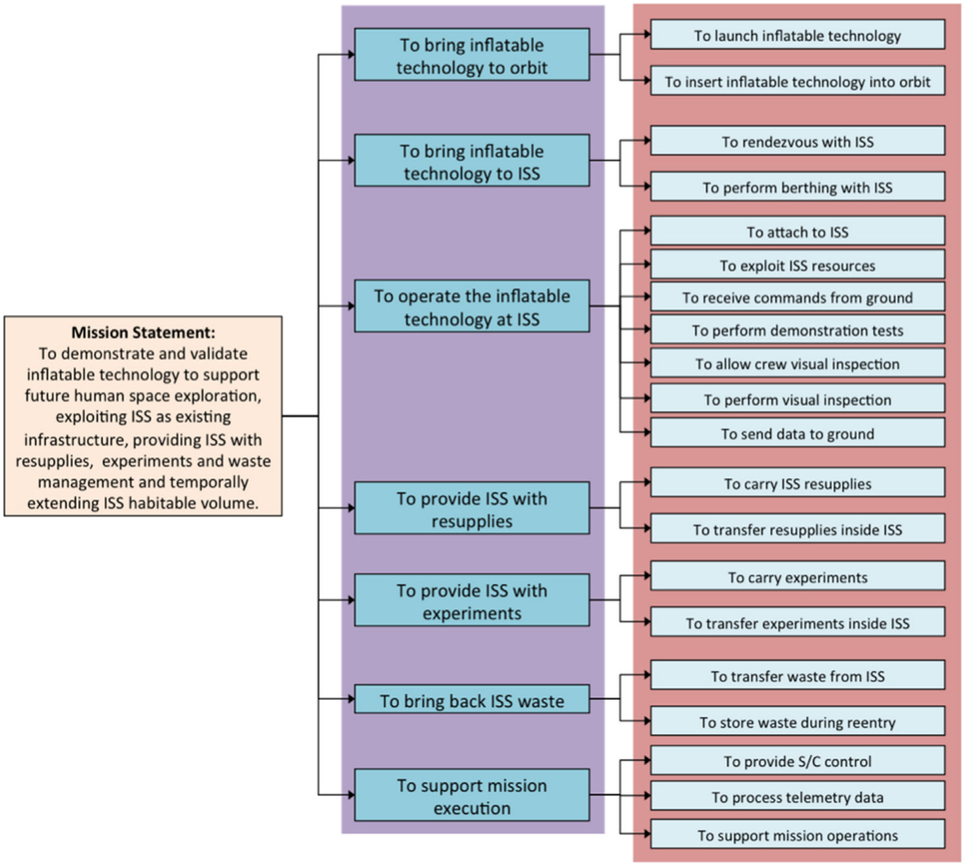

Fig. 4. Functional tree.

- *Space segment*, for all the operations to be accomplished in orbit,
- *Ground segment*, to support mission operations.

Each segment consists of several systems, which have been identified by means of the lower level functions/systems matrix, as shown in Fig. 6.

The main identified systems are

- *Launcher*, in charge of launching and inserting the spacecraft into orbit;
- *Service Module*, needed mainly for the rendezvous maneuvers with the International Space Station;
- *Inflatable Module*, which represents the “payload” of the mission, as it is the module for the inflatable technology validation;
- *Pressurized Cargo Module* (*PCM*), that is a rigid module, in charge of loading resupply and experiments for the ISS; specifically, a Cygnus-like module is considered [21];
- *International Space Station* (*ISS*), to support the inflatable operations, mainly for what concerns the communications with ground;
- *Astronauts*, that will be in charge of operating the inflatable and performing visual inspections;
- *Mission Control Center* (*MCC*), for control and telemetry data processing;
- *Mission Support Center* (*MSC*), in charge of supporting the mission.

All systems listed above may be grouped into launch, space and ground segments to make up the product tree at system level.

The functions/products matrix is exploited to derive configuration requirements as well as to refine functional requirements.

3.2.3. Connection matrix and functional block diagrams

Once the elements have been assessed, in order to complete the functional architecture definition, the relationships among the elements have to be analyzed. Even in this case, the analysis has gone through several levels: hereafter the results obtained for the system-of-systems and the system levels are reported. Specifically, two main steps have been followed which are the development of the connection matrices and the functional/physical block diagrams. The results of this analysis are important to derive interface requirements and refine configuration requirements.

The connection matrix allows identifying the links among the products, even if it does not specify the type of connection. Functional/physical block diagrams provide

FUNCTIONS	PRODUCTS (SoS/SEGMENTS): Launch segment	Space segment	Ground segment
To bring inflatable technology to orbit	X		
To bring inflatable technology to ISS		X	
To operate the inflatable technology at ISS		X	
To provide ISS with resupplies		X	
To provide ISS with experiments		X	
To bring back ISS waste		X	
To support inflatable technology operations at ISS			X

Fig. 5. Functions/segments matrix.

	PRODUCTS							
	LS	SS					GS	
FUNCTIONS	Launcher	Service Module	Inflatable Module	PCM	ISS	Astronauts	Mission Control Center	Mission Support Center
To launch inflatable technology	X							
To insert inflatable technology into orbit	X							
To rendezvous with ISS		X						
To perform berthing with ISS					X			
To attach to ISS				X				
To exploit ISS resources			X					
To receive commands from ground					X			
To perform demonstration tests			X					
To allow crew visual inspection			X					
To perform visual inspection						X		
To send data to ground					X			
To carry ISS resupplies				X				
To transfer resupplies inside ISS						X		
To carry experiments				X				
To transfer experiments inside ISS						X		
To transfer waste from ISS						X		
To store waste during reentry			X					
To provide S/C control							X	
To process telemetry data							X	
To support mission operations								X

Fig. 6. Functions/systems matrix.

additional information about the link's type and directionality.

Fig. 7 shows the connection matrix obtained for the system-of-systems level, which gives evidence of the connections among segments.

From the matrix, it is evident that links exist among all three segments, but no specification about the type of link is provided. To clarify this issue, the functional/physical block diagram has been built (see Fig. 8).

	Launch segment	Space segment	Ground segment
Launch segment			
Space segment	X		
Ground segment	X	X	

Fig. 7. Segments connection matrix.

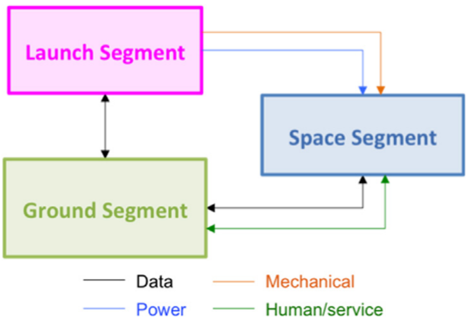

Fig. 8. Segments functional/physical block diagram.

The types of connections are highlighted by using different colors lines: mechanical interfaces are indicated with orange lines, electrical interfaces are indicated with blue lines, data links are indicated with black arrows, and service/human links are indicated with green arrows (operations involving astronauts). Moreover the arrows give evidence of the direction of the links.

Analogously to what has been just discussed for the system-of-systems level, the connection matrix and the functional block diagram have been built to point out the connections among systems.

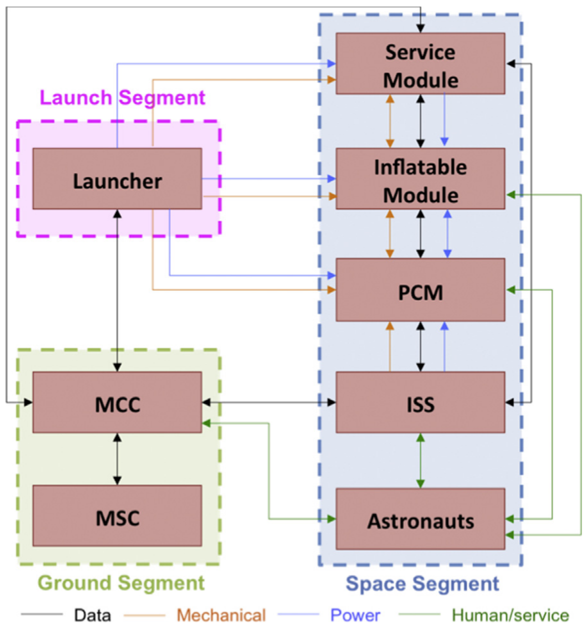

Fig. 10. Systems functional/physical block diagram.

	Launcher	Service Module	Inflatable Module	PCM	ISS	Astronauts	Mission Control Center	Mission Support Center
Launcher								
Service Module	X							
Inflatable Module	X	X						
PCM	X	X	X					
ISS		X		X				
Astronauts			X	X	X			
Mission Control Center	X	X			X	X		
Mission Support Center							X	

Fig. 9. Systems connection matrix.

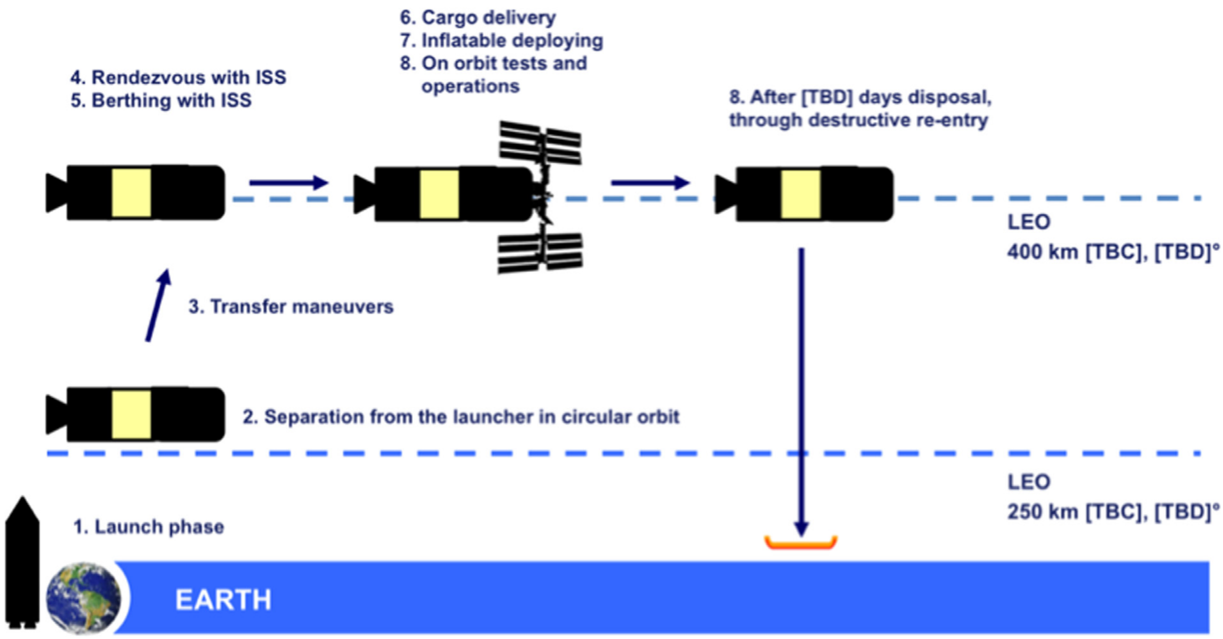

Fig. 11. Inflatable demonstration mission profile.

Table 1
Mission phases.

Mission phase	Start	End
Launch	Lift-Off	Burn out
Separation	Burn out	Transfer orbit insertion
Transfer	Transfer orbit insertion	Cygnus arrival in the proximity of ISS
Rendezvous	Cygnus arrival in the proximity of ISS	Robotic arm grab
Berthing	Robotic arm grab	Cygnus connected to ISS
Cargo delivery	Cygnus connected to ISS	Supplies transferred to ISS
Inflatable deploying	Supplies transferred to ISS	Nominal test mode activity
On orbit tests and operations	Nominal test mode activity	Stand by mode activity
Undocking	Stand by mode activity	Cygnus hatch closing and separation from ISS
Destructive re-entry	Cygnus hatch closing and separation from ISS	Spacecraft destructive reentry

Table 2
Operational modes vs mission phases.

Modes of operation mission phases	Stand-by	Check	Safe	Nominal testing	Nominal crew
Launch	S				
Separation	S				
Transfer	S		S		
Rendezvous	S		S		
Berthing	S		S		
Cargo delivery	S		S		
Inflatable deploying		S/D	S/D	S/D	
On orbit tests and ops		D	D	D	D
Undocking	D		S/D		
Destructive re-entry	D				

Fig. 9 reports the connection matrix, while in Fig. 10 the functional/physical block diagram is shown.

In the functional/physical block diagram illustrated in Fig. 10, the segments (higher level), which each system belongs to, are highlighted as well.

The connection matrix and the functional/physical block diagram are exploited to derive interface requirements and to refine configuration requirements.

3.3. *Concept of operations*

This section discusses the Concept of Operations, which has led to the assessment of how the system will be operated during the life-cycle phases in order to meet stakeholders' expectations. In particular, in the following sub-sections the results of the mission phases, modes of operations, mission timeline and FFBDs with specific attention to the Inflatable Module are reported.

3.3.1. *Mission phases*

The main mission phases for the inflatable demonstration mission are: launch, separation from launcher, transfer maneuver, rendezvous and berthing with the ISS, cargo delivery, inflatable deploying, on orbit tests and operations, separation from ISS and destructive re-entry. The mission is envisioned as a Cygnus-like mission, in which the inflatable

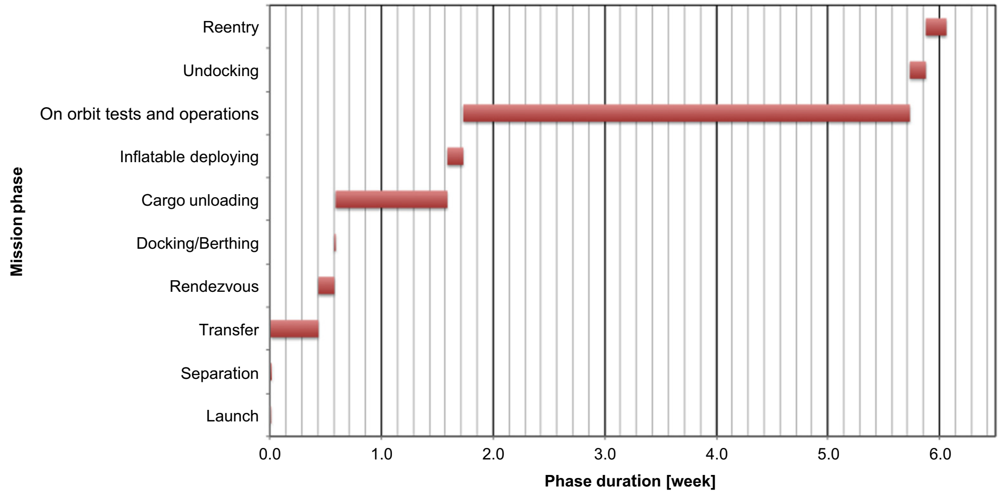

Fig. 12. Mission timeline.

module replaces one of the three Cygnus bays. The overall mission profile is schematically illustrated in Fig. 11. Furthermore, some details about the initial and ending conditions of each phase are summarized in Table 1.

From the analysis of each mission phase, environmental requirements can be derived.

3.3.2. *Modes of operation*

For the analysis of the modes of operation, two possible configurations of the IM have been preliminarily defined, that are

- Stowed, S (unpressurized);
- Deployed, D (pressurized).

The modes of operation identified for the IM are

- *Stand-by mode*: only components necessary to monitor the system and to survive the external environment are active;
- *Check mode*: all components necessary to check system's health before starting the tests are active;
- *Safe mode*: all components are activated at limited level (adopted in case of contingency);
- *Nominal testing mode*: all components necessary to perform tests are active; data are transmitted to SM to be elaborated, then transmitted to ISS and eventually to Ground Segment;
- *Nominal crew mode*: all main functionalities are active and access of the crew to perform visual inspections is allowed.

Table 2 shows all possible modes of operation that IM can enter during all mission phases. The different configurations of the IM are also highlighted.

From the analysis of the modes of operations, operational requirements can be derived.

3.3.3. *Mission timeline*

To proceed with the concept of operations analysis, it is important to define and characterize the mission timeline, which shall contain general indications concerning time duration of each mission phase. The timetable reported in Fig. 12 describes the sequence of mission phases, highlighting their duration. In the first attempt, a period for on-orbit demonstration of one month has been considered. This preliminary timeline shall be developed considering time constraints imposed by stakeholders and typical mission reference schedule.

From the mission timeline, logistics support and operational requirements can be defined or refined.

3.3.4. *Functional flow block diagram*

The purpose of the FFBDs is to indicate the sequential relationship of all functions that must be accomplished by a system. When completed, these diagrams show the entire network of actions that lead to the fulfillment of functions and provide an understanding of the complete sequence of the system operations as well as of the transitions between the system modes of operation.

Starting from the first level, each block is expanded in order to further detail it and identify at lower level the sequence of actions to be accomplished. Specifically, decomposition up to a "third level" has been performed for the functions that directly involve IM. An example of expanded FFBD is illustrated in Fig. 13, with focus on inflatable technology operations. This decomposition can be worked out for all the rest of the functions and also at subsystem level, being these methods recursive and iterative. From the FFBDs operational requirements can be derived.

3.4. *Top level requirements*

As underlined along the paper, requirements have been derived throughout the design process. Specifically, from the analyses/tools previously described, different classes of requirements can be directly deduced (primary requirements),

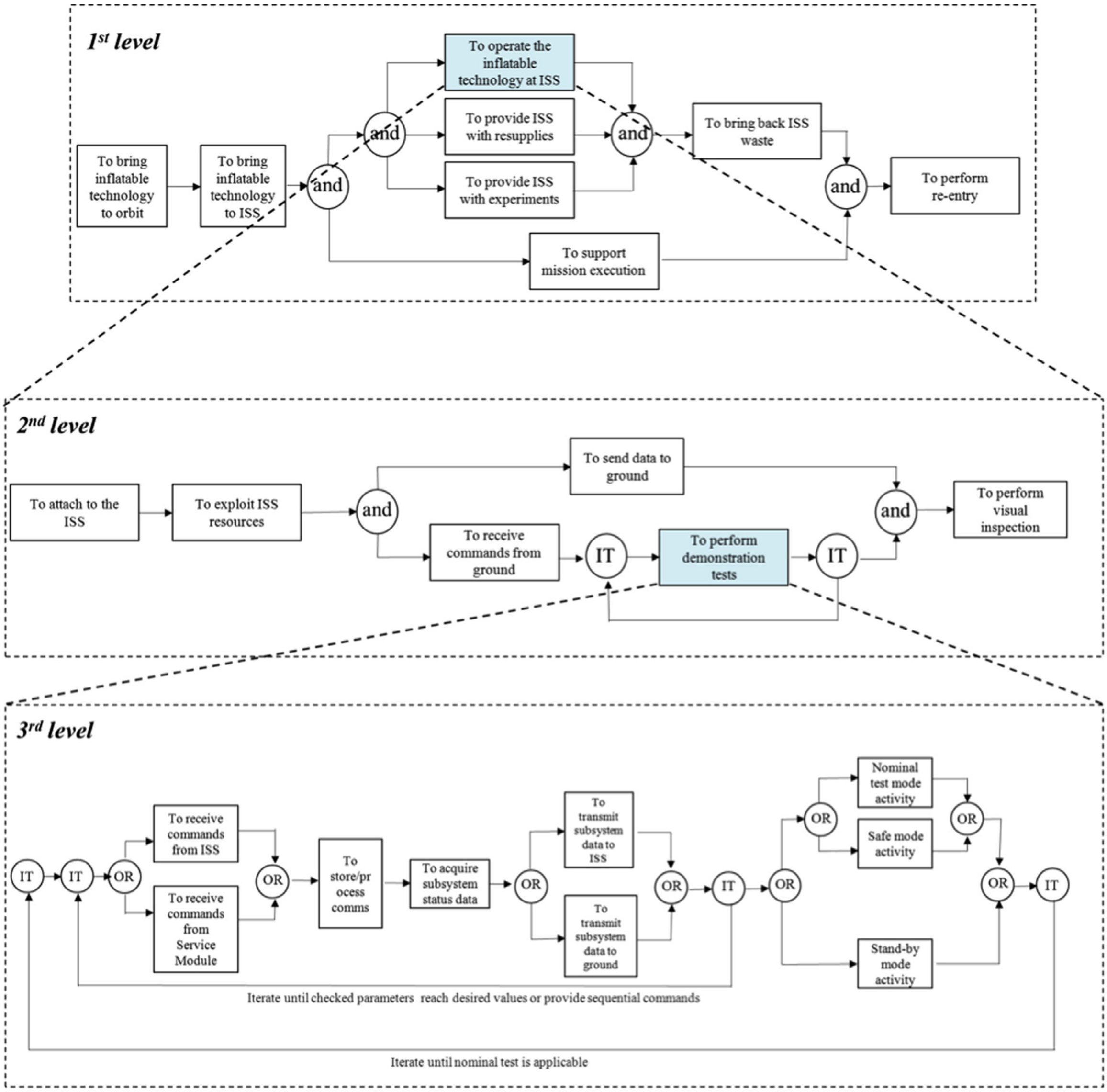

Fig. 13. FFBD–focus on operating inflatable technology at ISS and performing demonstration tests.

Table 3
Examples of primary requirements with associated analyses/tools.

Analysis/Tool	Requirement category	Example
Mission objectives	Mission	Existing spacecraft design shall be exploited
FA/Functional tree (first iteration)	Functional	Demonstration tests shall be performed
FA/Functions/Products matrix (refinement)		The IM shall perform demonstration tests
FA/ Functions/Products matrix	Configuration	The spacecraft shall consist of Service Module (SM), IM and Pressurized Cargo Module (PCM)
FA/Connection matrix and Functional/ Physical block diagram	Interface	The IM shall mechanically interface with the launcher
ConOps/Mission phases	Environmental	The IM shall withstand LEO environment
ConOps/Modes of operations	Operational	In IM stand-by mode only components necessary to monitor the system and to survive the external environment shall be active
ConOps/Mission timeline	Logistics support	The mission shall be performed at TBD time

Table 4
Examples of secondary requirements with associated primary requirements.

Primary requirements	Requirement category	Example
Mission (The TRL of inflatable technology shall be improved)	Performance	The IM shall provide TBD m^3 of habitable volume when inflated
Mission (Existing spacecraft design shall be exploited)	Design	The IM shall replace one Cygnus-like module bay
Interface (The IM shall mechanically interface with the launcher)	Physical	The IM shall have a mass not exceeding 900 kg
Operational (In IM safe mode all components are activated at limited level-adopted in case of contingency)	PA and Safety	The IM shall be isolated in case of contingency
Mission (ISS infrastructures shall be exploited)		

whereas other classes of requirements (secondary requirements) stem out from the previous ones.

The categories that have been considered for the requirements classification are mainly the following (primary requirements)

- *mission*, related to tasks to be accomplished to achieve mission objectives;
- *functional*, defining functions that the product shall perform;
- *configuration*, related to the composition of the product or its organization;
- *interface*, related to the interconnection or relationship characteristics between the product and other items;
- *environmental*, related to a product or the system environment during its life cycle;
- *operational*, related to the system operability;
- (*integrated*) *logistics support*, related to the (integrated) logistics support considerations to ensure the effective and economical support of a system for its life cycle;

Besides the just mentioned categories, other classes shall be considered (secondary requirements), i.e.

- *performance*, defining how well the system needs to perform the functions;
- *design*, related to the imposed design and construction standards;
- *physical*, establishing the boundary conditions to ensure physical compatibility;
- *product assurance and safety*, related to the relevant activities covered by the product assurance, including reliability, availability, maintainability, safety and quality assurance.

Table 3 reports examples of primary requirements for the inflatable mission study-case. The left hand side column shows the analysis/tool that has been considered to derive the requirement. Then the central column report the category of requirement and eventually the right hand side column list the examples of primary requirements.

Table 4 reports examples of secondary requirements for the inflatable mission study-case. The left hand side column shows the primary requirement that has been considered to derive the secondary requirement. Then the central column report the category of requirement and eventually the right hand side column list the examples of secondary requirements.

4. Conclusions

This paper has presented an iterative and recursive methodology in support of the design of future space missions, with particular attention to the derivation of the requirements.

The very innovative aspect of the proposed methodology is that it gives evidence of how each single category of requirements (mission, functional, configuration, interface, environment, operational, logistic support, performance, design, physical and product assurance and safety) can be derived by appropriate analyses and exploiting well known Systems Engineering principles and tools. Moreover, attention is given to what is generally the sequence of derived categories of requirements. These are issues not addressed in design methodologies discussed by several other authors [6–8].

The results obtained by applying the proposed methodology to a specific case study (inflatable technology on-orbit demonstration) have revealed that it is very useful to derive in a rigorous way the requirements driving space missions and systems design.

Moreover it is worth underlying that, the iterative and recursive nature of this method allows applying it to a wide sets of space systems design. For example, it can be used for the detailed definition of the inflatable module (subsystems level and so on).

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