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Towards a formalized Model-Based process for the design of high-speed aircraft and related subsystems

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Abstract

Increasing complexity associated to advanced aircraft concepts for high-speed flight is pushing the limit of engineering practices concerning design phases of products lifecycle. Specific methodologies aimed at managing requirements over the entire vehicle architecture definition shall then be properly formalized and supported by means of standardized processes and languages in order to be effective. The approaches suggested by the Systems Engineering practices, especially when considering the Model-Based environments as main tools for systems design, can be exploited to face this challenges, if properly tailored to suit the specific engineering field considered. This paper aims at proposing a Model-Based process for the design of high-speed aircraft exploiting a formalized methodology and the typical tools of Systems Engineering. A conceptual design exercise, based on the STRATOFLY MR3 hypersonic cruiser case study, is performed from high-level stakeholders objectives to vehicle performance estimations, passing through functional and interface analyses. Additionally, some insights concerning on-board subsystems sizing activities are provided in terms of integration within the high-level design process. The whole work highlights the capability of performing a seamless requirements management and development within the design procedure, particularly focusing on the relationships among the different stages of the workflow.

Keywords: Model-Based aircraft design; Conceptual design; High-speed aircraft; Functional architecture; System Modelling Language; Systems Process Engineering Meta-Model

1. Introduction

1.1 The high-speed paradigm: origin and evolution

High-speed flight has been a recurring topic in aeronautics since the 1950's, when some of the most valuable engineering concepts, currently used as reference, were defined for the first time. During the years, several attempts were made, with various fates and some honourable mentions, as the Concorde case study. Nowadays, high-speed flight is mainly seen, on one side, as the natural evolution of the commercial aviation and, on the other hand, as a mandatory step to exploit a fully reusable access to space architecture based on Single Stage To Orbit (SSTO) technologies for Low Earth Orbit (LEO) payload delivery. Neglecting the research in military fields, which are most of the time classified, the scientific community is investigating the feasibility of the concept for civil applications, to establish a roadmap towards the enhancement of the Technology Readiness Level (TRL) of main critical areas and to demonstrate how supersonic and even hypersonic flight can represent a valuable solution to improve the quality of commercial aviation, basically stable in its paradigm since the entry into service of the first airliners. The number of past and present initiatives in this domain is an evidence of the complexity related to the field of study, mainly associated to the high degree of integration of different disciplines involved. In fact, far from being a simple and mere sum of different ingredients, the System of Interest (SoI) shall be designed looking at multiple aspects. The success of the system will strictly depend on its compliancy with a large set of requirements that, starting from the conceptual design up to operation and end-of-life, shall be managed and traced. The Systems Engineering, especially in its Model-Based approach, is a typical example of "systems thinking" attitudes giving a high priority to requirements management and trace during product lifecycle. This work will analyse several aspects of the design of a high-speed vehicle, at conceptual and preliminary stages, always aiming at keeping trace of the big picture, providing a consistent and as much as possible complete view over the entire design process. The main aim and innovation point of the work consists in proposing a fully integrated Model-Based aircraft design approach for High Speed Transportation (HST), applying a Systems Engineering attitude to the design process, with particular focus on requirements coverage analysis. Functional and performance aspects are presented, trying to provide a reusable approach for the development of this kind of aircraft and related technologies, making benefit of existing standards, languages and frameworks in the field of Model-Based Engineering.

1.2 A research framework to be used as reference

As briefly anticipated, hypersonic flight has been already investigated in the past by different institutions and agencies all over the world. Researches were, at the beginning, mainly driven by military needs and sponsorships, while moving towards civil applications and reusable access to space at the end of the last century. In Europe, besides a set of heterogeneous and independent national initiatives carried out in the 90s, a clearer development trend can be noticed since the beginning of the years 2000, when aerospace community decided to focus on high-speed airbreathing propulsion, pushing the boundaries of hypersonic flight. It is in this context that, in 2005, The LAPCAT project [1] (which stands for Long-term Advanced Propulsion Concepts And Technologies) has been funded by the European Commission under the sixth European Framework Programme (FP6), constituting for the first time a joint multidisciplinary working group in Europe on innovative high-speed aircraft design, specifically tackling the analysis of breakthrough enabling technologies as well as the study of brand-new propulsion systems. Thirteen years later, making benefits of the whole set of European projects on high-speed transportation funded in between [2-6], the STRATOFLY project [7] (acronym of STRATOspheric FLYing opportunities for high-speed propulsion concepts) kicked-off in 2018. The project aimed at proposing a roadmap to demonstrate the possibility of raising the TRL for critical high-speed technologies up to level 6 by 2035. To reach this result, the project assessed: multi-functional integration of propulsion plant, exploitation of cryogenic propellant as liquid hydrogen, airframe and on-board subsystems design, as well as harmonization of different disciplines, aiming at defining and detailing a high-speed aircraft configuration enabling long-haul travels starting from a reference layout proposed in [8-9]. Moreover, the project aimed at assessing the sustainability of the vehicle and its mission concept from several perspectives, such as pollutant and noise emissions, environmental impact, human factors, social acceptance as well as market analysis. It is thus clear how the design focus for such kind of vehicle shall be oriented to use an holistic approach, integrating the different aspects within a unique big picture, as core of a specific analysis process, able to catch the different mutual interactions of the elements constituting the HST. In fact, the efficient integration of aircraft concept and related subsystems is the key for the success of the high-speed paradigm, thus requiring, on the design stage, a seamless process to support the development of the vehicle configuration, from high-level requirements up to architecture definition. Particularly, after this brief introduction, Section 2 presents the overall process applied to the design of STRATOFLY MR3 vehicle, starting from stakeholders analysis, moving forward with functional and logical assessments, and concluding with implications on performance studies. Then, when the aircraft platform is established, the focus moves on main subsystems, while repeating a similar approach on a lower level. The overall method allows coverage and tracing of main requirements all along the process. Conclusions on the application of such a method are reported in Section 3, where main results are summarized and strong points as well as potential weaknesses of the approach are discussed together with the suggestions on main future areas to work on.

1.3 Most relevant Model-Based design methodologies showing evidence of state-of-art approaches

Making a review of design processes supported by the Model-Based approach and, in general, by the typical Systems Engineering thinking is not easy since a lot of topics have been already tackled in the past decades, especially within the aerospace domain, universally recognized as the birthplace of Systems Engineering during World War II or shortly after. It is thus necessary to limit the state-of-art review to the most suitable fields, also considering the boundaries of the present work. Starting from the basic principles, it has to be stated that the concept of system defined in [10] already provides a lot of details that can be considered as foundations for the whole systems theory [11], subsequently tailored and modified to match the needs of specific engineering domain such as the one to which this paper belongs to. Aerospace engineering practice comprehends several guidelines and works aimed at characterising systems design, with [12] and [13] among the most extensive ones, including also proper handbooks and standard views on the problems [14]. The core point behind the publications of such a wide set of works is that there is not a golden rule which is valid neither for the whole set of disciplines for which a Systems Engineering approach can be adopted, nor for the subdisciplines of a single engineering domain. In fact, the needs of the different stakeholders involved within the initial design activities, representing the first step of the whole Systems Engineering process [12], can be very different depending on the considered context, and the methodology supporting the design process shall be effectively tuned and modified to cope with specific issues. Tailoring of Systems Engineering process is the key for a good adaptation of the desired approach, as also stated by [13] and [15]. It is also true, on the other hand, that a general standard format for the Systems Engineering process shall be defined, in order to start from a common baseline and, for this reason, different works in literature report typical processes and associated items definitions that can be valid also in the aerospace domains, such as [16-20]. All of them, agree that the definition of the problem, of the needs of main stakeholders and the formulation of top level requirements represent the first bricks for the entire process, followed by a structured definition of what the system shall do, in terms of main functionalities, and by the selection of a proper elements breakdown, responsible for the derived functionalities, characterized also in terms of numerical parameters through performance analysis. The whole conceptual design shall then be connected through a proper traceability policy, specifically focusing on a seamless requirements derivation within the recursive approach, which is the nature of Systems Engineering [13]. After a careful analysis, the author agrees that the main concepts suggested by [12] are very much in line with the definitions provided in Section 2 (and subsequent ones) in terms of main Systems Engineering objects. The need for a new, tailored method for high-speed aircraft, as described in this work, comes from the fact that literature often offers a nice theoretical picture on Systems Engineering practice, rarely going into the details of how to practically implement the main steps, especially in a Model-Based approach. Here is where confusion arises, since theoretical definitions often clash with practical needs, many times dealing also with limitations of tools and software [21]. Typical mistakes consist in modifying the actual methodology to adapt to the tools, usually also because of budget and time constraints which do not allow for on course modifications, while the fair approach should be the other way around. This is also the reason why, together with main standards mentioned before, architectural framework [15], especially within military domains, have been developed to provide comprehensive guidance and an effective commitment, granting the consequent successful development of tailored products. The adoption of specific languages for systems modelling is also a crucial aspect, especially, as it is easy to understand, within the Model-Based approach. One of the most known language with this respect is the System Modelling Language (SysML) [22], for which interesting approaches concerning its practical use can be found in literature [23], [24] as also specified in Section 2. This a perfect example of general purpose language that can be theoretically used for a wide set of engineering domain dealing with systems design, that however can be subjected to tuning in order to adapt to the desired scenario. Also the process itself can be tailored, as specified in Section 2, using standard formats [25] as formalization mean, to properly characterize the flow and to ensure its reusability. The need of characterizing this process, especially in early design stages as Model-Based Systems Engineering (MBSE) approach, comes from the typical project management issues associated to the desire of knowing in advance as much as possible about the system of interest, ensuring more flexibility and freedom concerning the design space, as well as shifting the committed costs towards the end of the design phase (so not to constrain too much the configuration in terms of expenses for future modifications) [12]. However, as well stated by [26], the lack of perceived value of MBSE, especially in early design phases, often opens to criticism, with particular focus on the effectiveness of the application of such kind of methodologies. Several reviews about opportunities and current status of the methodologies are also available [27], [28]. Indeed, the adoption of a well-structured methodology, supported by a formalized process conceived to be reusable and tailored to a specific domain, adopting standard languages and tools, is the key to ensure a seamless flow through the product lifecycle. The definition of methodology, tools, language and data management policies, often referred to as four pillars approach [21], is surely a good practice to tackle the problem. Several methodologies exist in literature in this respect, as [24], [29-32], where this kind of approach proven to be effective in different contexts, belonging to a similar engineering area of interest. Considering all the aforementioned aspects, the author would like to point out however, that some weaknesses can be found within the methodologies available in literature. Most of them, are always affected by a excess of performance-oriented tasks, especially for specific engineering domains, while the first part of the loop, dealing with stakeholders needs identification, definition of high-level requirements and functional breakdown, is often misjudged and neglected. The focus on architecture and functionalities, especially for high-speed vehicles, for which a holistic view is required because of the strong coupling among different disciplines, increasing with vehicle complexity, shall be instead the core of the first part of the Systems Engineering process. Definition of interfaces in a practical manner, ensuring traceability and requirements derivation throughout the whole process is also fundamental, especially when adopting the so-called blank sheet approach, for which influence of previous studies shall not be overestimated (since the risk is to constrain too much the design). Also, looking at the big picture, the opportunity of connecting the system design scenario, with a larger roadmap generation and development plan [33] can be seen as a crucial extension of the Systems Engineering process. In fact, the project itself is just a piece within a larger management view, serving as technology development platform within a wider roadmap strategy, into which the same stakeholders can have a high responsibility. In this way, using the same formalisms and traceability features of the Model-Based environment, it is possible to really link the project with the external strategic streams. For these reasons, the approach proposed in this work, far from being a rigid golden rule and process to high-speed vehicles design (actually proposing an incremental step towards a proper complete solution, as the title suggests), would like to try suggesting a practical implementation mean to face the design problem for the considered domain, starting from the standards and practices already defined in literature, as described in this section, while overcoming the identified limitations. Section 2 will detail the steps of the suggested process, including insights on the used language and process formalization approach, with an eye on both aircraft and on-board system levels.

2. Design methodology and main process

2.1 Reference workflow and terminology

2.1.1 Process baseline

In order to present the reference process supporting the proposed design methodology, it is worth establishing a framework for the formalization of the assets involved, both in terms of elements definition (content) and of language (format). The methodology reported hereafter aims at defining a tailored approach to high-speed transportation systems design using, as reference, the workflow suggested by the European Cooperation for Space Standardization (ECSS) [34] especially for the early design phases, namely Phase 0 and Phase A, dealing respectively with Mission Analysis and Needs identification, as well as with Feasibility analysis. The choice of the paradigm suggested by ECSS is justified by the nature of the case study analysed in this work, which makes benefit from decades of European research in high-speed flight, standing on the boundary of aeronautics and space domains, as well as by the effective and pragmatic way of interpreting the design approach to complex systems. In fact, the overall ECSS approach refers to the so-called multiple-levels lifecycle, as a typical Systems Engineering practice where the analysis is repeated, recursively, at different levels of detail following system decomposition. Phase 0, described in this section as high-level conceptual design, is thus performed once, while a progressively increasing detail is devoted to products belonging to subsystems and components levels. The processes described in the next sections are thus following the aforementioned method content, while representing the main tasks and activity flows adopting the formalisms of the Systems Process Engineering Meta-Model (SPEM) [25], a common meta-model used as an industry standard for modelling processes within software and Systems Engineering practices. On the other hand, functional and logical analyses performed in the frame of Phase 0 and Phase A processes are described using the Systems Modelling Language (SysML) [22], a typical MBSE formalism for systems design being based on the representation of behaviour and architecture features of the System-of-Interest (SoI) through a set of viewpoints or diagrams, populated through a combination of model objects and related links, aiming at ensuring seamless requirements tracing and development. After the conceptual design process, at vehicle level, an example of tailored Phase A, reported as subsystems preliminary design, is described with reference on first iterations dealing with the characterization of peculiar multi-functional plants (Section 2.2). For the sake of clarity, conceptual design process is focused on the STRATOFLY Super-System (or System of Systems) level, the segment level and the system level, where the latter identifies the layer at which the identification of the vehicle product as a whole can be performed. Subsystems design process starts instead from the subsystem level itself, continuing towards lower levels. Within this high-level conceptual design process (tailored Phase 0 of ECSS) [34], the mission statement is derived and mission objectives, constraints, as well as requirements are identified together with stakeholders. Moreover, the main functional architecture of the aircraft, is sketched and a conceptual interface analysis is performed. Additionally, traditional activities related to performance determination are exploited, with particular focus on aircraft matching and on other feasibility studies (Figure 1).

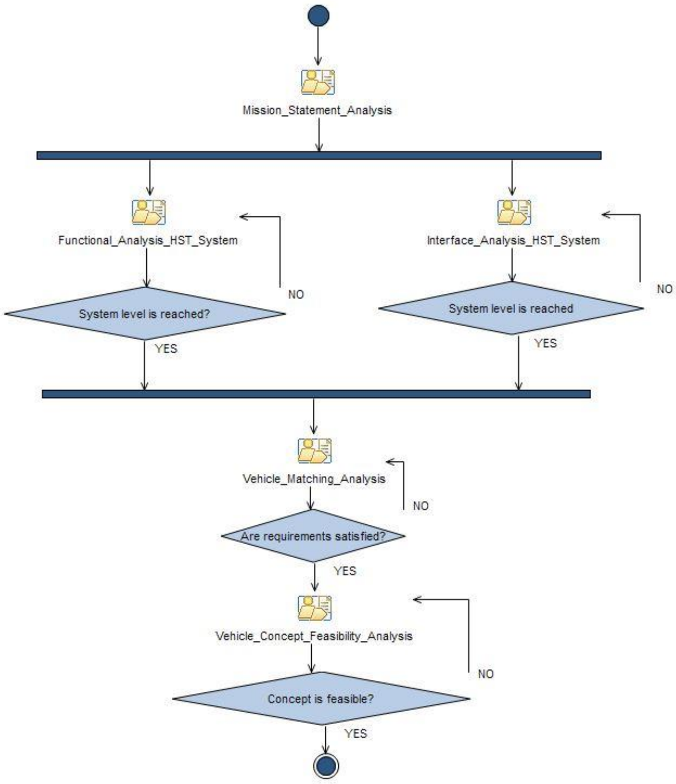

Figure 1. Reference process for conceptual design activity

The overall workflow starts from the mission statement analysis, where stakeholders are identified, together with their needs, and a so-called mission statement is derived as short description of the purpose of the object to be designed. From the mission statement, primary mission objectives are derived, whilst secondary objectives are mainly detected looking at additional stakeholders needs. Furthermore, the derivation of the primary objectives paves the way towards the definition of the first set of mission requirements, whilst secondary objectives are crucial to determine programmatic requirements. This activity helps defining the mission concept as well as the Top Level Function (TLF) of the High-speed Transportation System (HST), to be determined as first step of the subsequent activity. The functional analysis aims at defining the functional breakdown of the vehicle, generating functional requirements and identifying possible products on which functions can be allocated. This is a recursive process starting from the TLF and moving forward up to the required level of detail.

2.1.2 Mission statement analysis

A prerequisite for the formulation of the mission statement (Figure 2) is the identification of stakeholders, together with the elicitation of their needs [13].

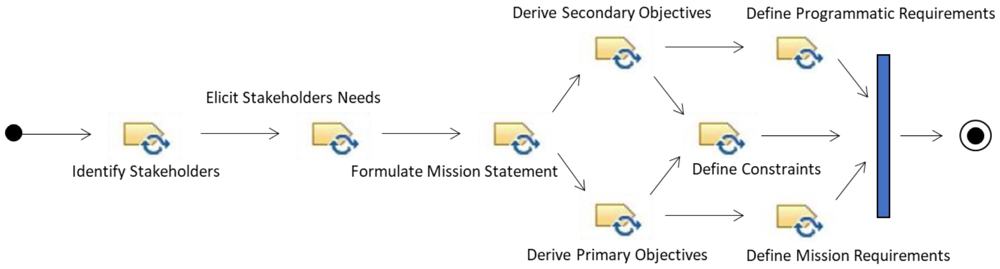

Figure 2. Mission statement analysis workflow

The identification task is necessary as preparatory duty not only to capture the crucial entities expressing interests towards the system, but also to propose a classification that can be helpful to better characterize the needs in the subsequent task. Stakeholders can be usually classified as sponsors, customers, end users and operators respectively [35]. As far as the STRATOFLY case study is concerned, the main sponsor is the European Commission (EC) itself, funding the research on the topic, while end users are identified among the project consortium and the scientific community, which will benefit from the work performed within the different engineering fields involved. Final customers will be the actual passengers of such an aircraft, while operators shall be searched among the companies usually dealing with commercial aviation, that can be considered as part of the External Expert Advisory Board (EEAB) of the project. Elicitation of the needs of these stakeholders, through proper interviews, leads to the definition of StakeHolders Objectives (SHO) as reported in Table 1.

Table 1. List of Stakeholders Objectives (SHO)

Objective ID	Objective description	Objective owner
SHO1	To extend the European industrial leadership	EC
SHO2	To extend knowledge related to propulsion, configuration and innovative subsystems for HST vehicles	EC, STRATOFLY Consortium, Scientific Community, EEAB
SHO3	To raise technologies characterized by low TRL up to TRL 6	EC
SHO4	To reduce flight time	Passengers
SHO5	To fly safely	Passengers
SHO6	To fly comfortably	Passengers
SHO7	To fly cost-effectively	Passengers
SHO8	To fly responsibly	Passengers
SHO9	To promote research in the field of HST systems	STRATOFLY Consortium
SHO10	To reduce lifecycle cost	EEAB
SHO11	To ease maintainability and operation procedures	EEAB

Looking at the context of the project, the main research topic and the stakeholders objectives, it is possible to formulate the mission statement as follows:

To shorten the flight time of one order of magnitude (with respect to the state of the art of civil aviation) carrying at least 300 civil passengers along long haul and antipodal routes, flying at stratospheric altitudes within a future Air Traffic Management (ATM) scenario, reducing the impact on existing on ground infrastructure, in compliance with environmental compatibility and safety issues, assessing the overall economic feasibility of the solution.

Primary objectives can be derived directly from the mission statement. They have been formalized as main SysML use cases within the Use Case Diagram (UCD) shown in Figure 3, where the relationships among them are also highlighted. Secondary objectives are not reported for conciseness.

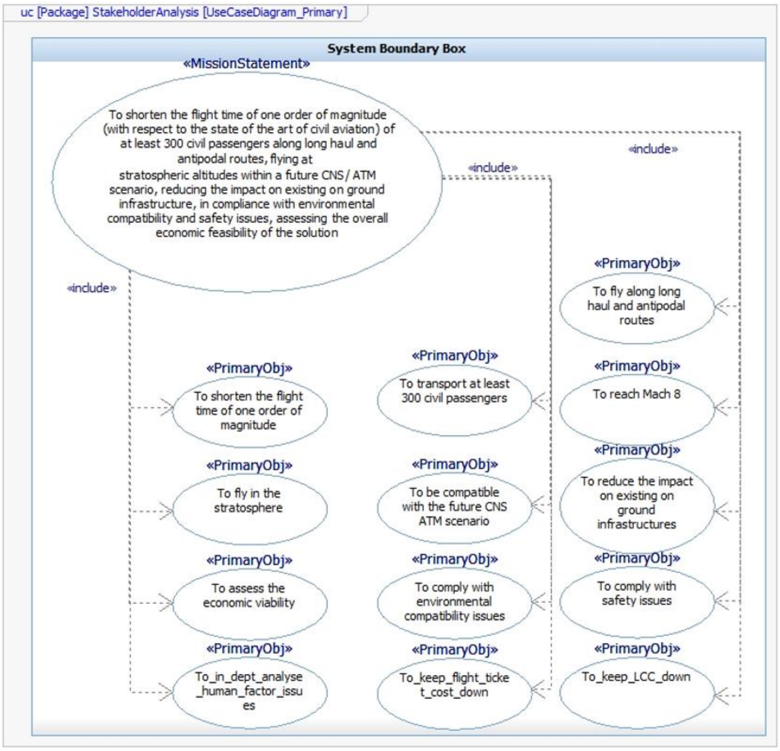

Figure 3. Use Case Diagram with primary mission objectives

Primary objectives are, in turn, the main source for mission requirements. Within the MBSE environment used for the modelling activity of this case study, proper dependencies are used to connect use cases with the related requirements, in order to start the tracing and coverage process that will lead to the final allocation of functional requirements to logical elements of the aircraft design. As example, some mission requirements are reported in Table 2.

Table 2. STRATOFLY Mission Requirements (set)

Derived from	ID	Mission Requirements
PO1	MR_1000	The flight time of civil passenger flights over long haul and antipodal routes shall be shortened of at least one order of magnitude with respect to the current state-of-the-art for civil aviation.
PO2	MR_2000	The transportation system shall be able to transfer at least 300 civil passengers.
PO3	MR_3000	The transportation system shall be able to flight along long haul and antipodal routes.
…	…	…
PO5	MR_5000	The transportation system shall be able to reach at least Mach 8.
…	…	…

Taking advantage of these requirements, the Top Level Function (TLF) can be defined, allowing the instantiation of the high-level functional analysis reported in Section 2.1.3.

2.1.3 Functional analysis (high-level)

The functional analysis (Figure 4) is one of the most important phases of the conceptual design process, since it aims at defining the main capabilities of the system, in order to characterize the logical architecture. It includes the formalization of the functional breakdown, starting from the Top-Level Function (TLF), the identification of main logical products responsible for the related capabilities, as well as the characterization of the products breakdown, up to the desired level. Moreover, a connection between the functional architecture and its usage within a preliminary Concept of Operations (ConOps) can be instantiated, by sketching at logical level the reference mission, in terms of phases and related timing, with the aim of identifying the main elements involved and the states of the system. This is also a preparatory step towards the definition of performance requirements for those mission related characteristics that will affect the feasibility analysis discussed in Section 2.1.5.

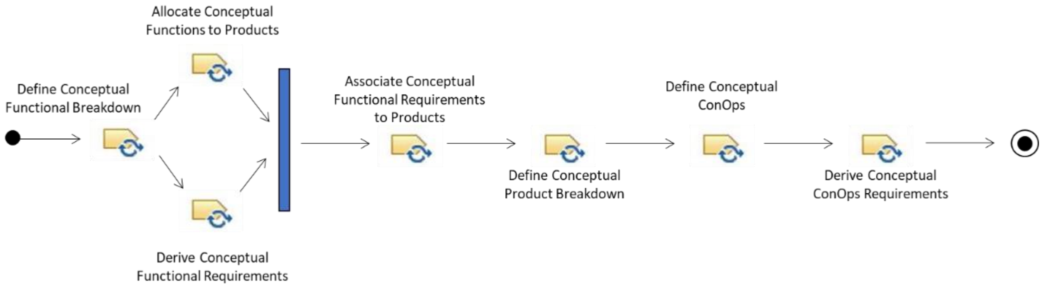

Figure 4. Functional analysis workflow (high-level)

As first step, a functional tree can be defined using the Block Definition Diagram (BDD) formalism of the SysML (Figure 5). The viewpoint adopted in this section aims at limiting the analysis up to the system level, here referred as the level at which the vehicle can be identified as main element of the flight segment.

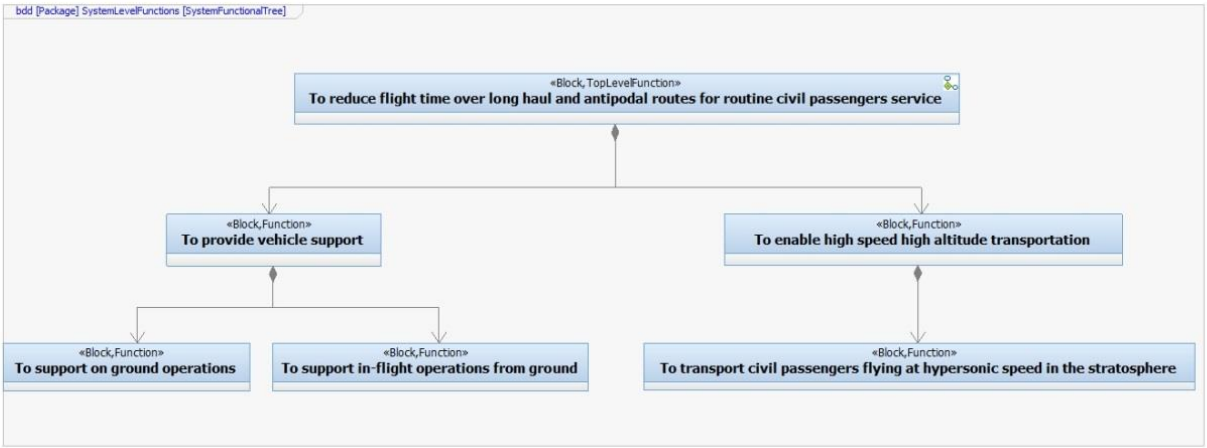

Figure 5. Functional tree (BDD) up to system level

Related functional requirements can be formulated (Table 3), keeping the same hierarchy level specified within the diagram, and corresponding product tree, always implemented as a BDD, can be synthetized as reported in Figure 6, where a clear allocation of functions is showed.

Table 3. Functional requirements up to system level

ID	High-level Functional Requirements
FR@SoSL_1000	The mission shall allow reducing flight time over long haul and antipodal routes for routine civil passengers service.
FR@SegL_1000	The Ground Segment shall provide vehicle support.
FR@SegL_2000	The Flight Segment shall enable high speed high altitude transportation.
FR@SysL_1000	The airport infrastructures and personnel shall support on-ground operations.
FR@SysL_2000	The ground stations shall support in-flight operations from ground.
FR@SysL_3000	The vehicle shall transport civil passengers flying at hypersonic speed in the stratosphere.

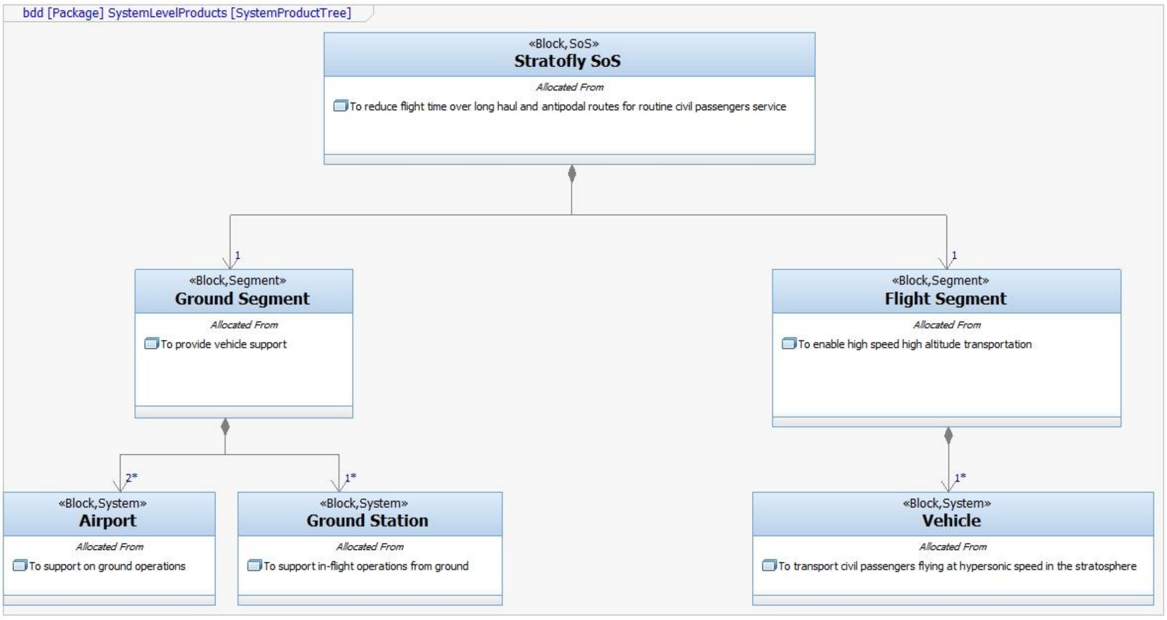

Figure 6. Product tree (BDD) up to system level

This very simple product breakdown can however lead already to a first ConOps, which is essential to establish the main mission layout and elements, subsequently assessed from the numerical performance point of view, within the next steps. From a broad point of view, the operations stage is part of the lifecycle of the System of Interest (SoI) and thus can be formalized in SysML as an additional Use Case Diagram (UCD), populated with the stakeholders already seen in the previous stages (Section 2.1.2) and with new use cases now representing the different lifecycle phases (Figure 7).

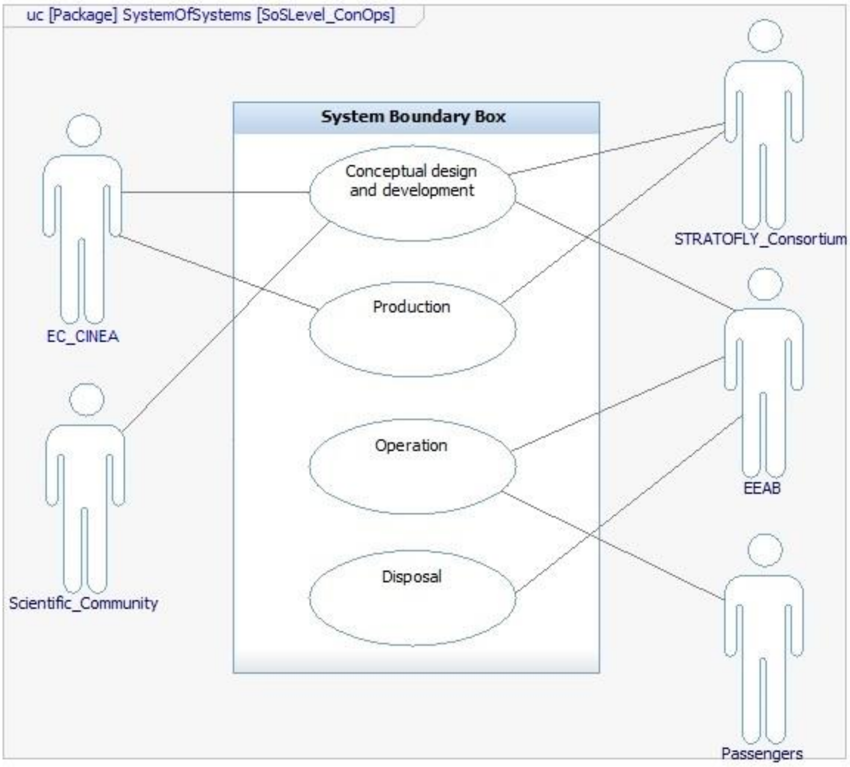

Figure 7. High-level lifecycle representation through UCD

Basic use cases can also be analysed more in depth, leading to the definition of more detailed UCD as reported in Figure 8, where the operations are characterized in terms of ground and flight phases.

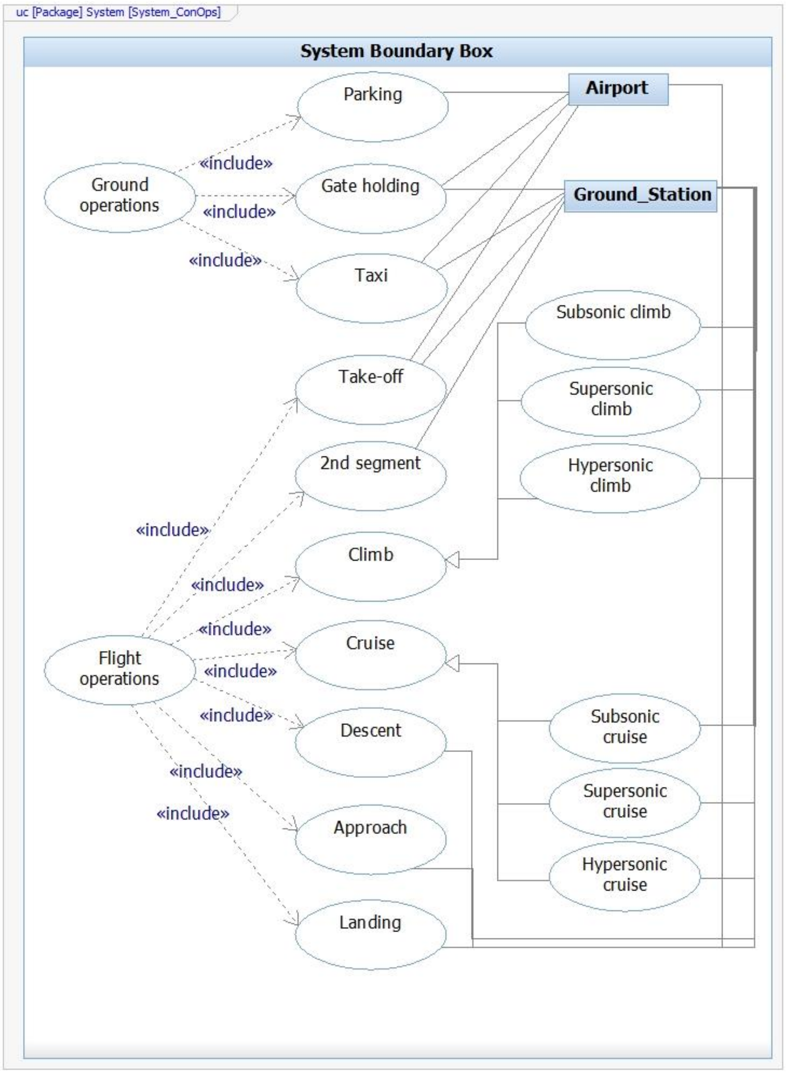

Figure 8. Use cases decomposition for the operations lifecycle stage

In this case, the focus is on the vehicle product, that shall be able to operate within the different use cases, exploiting the required functionalities and interfacing with other systems belonging to the ground segment, such as airports and ground stations. In order to guide the definition of low level functionalities, described in Section 2.2 and to establish a first set of vehicle states, defining its behaviour, it is possible to characterize the use cases through other SysML behaviour diagram, such as Sequence Diagrams (SD) and State Machine Diagram (SMD), as indicated in Figure 9 and Figure 10, where the flight operations are shown. Particularly, the SD can be useful to sketch the preliminary sequence of events and messages exchanged between the vehicle and other systems, with an overview on main items triggering specific activities related to aforementioned use cases, i.e. mission phases in this particular scenario. A reference timing for the nominal mission can also be introduced, sketching the reference profile to be assessed later on. The SD, from the top to the bottom of the chart prepares also the definition of proper mode of operations for the vehicle, since the sequence of activities performed within a specific use case can then be grouped into states and implemented within a SMD, describing the transitions among different situations. All the elements are completely dependent among each other, since the operations use cases are traced on the functions previously defined, with a connection to the related requirements and to the products responsible to meet them, so it is possible to create a whole referenced package within the Model-Based functional analysis.

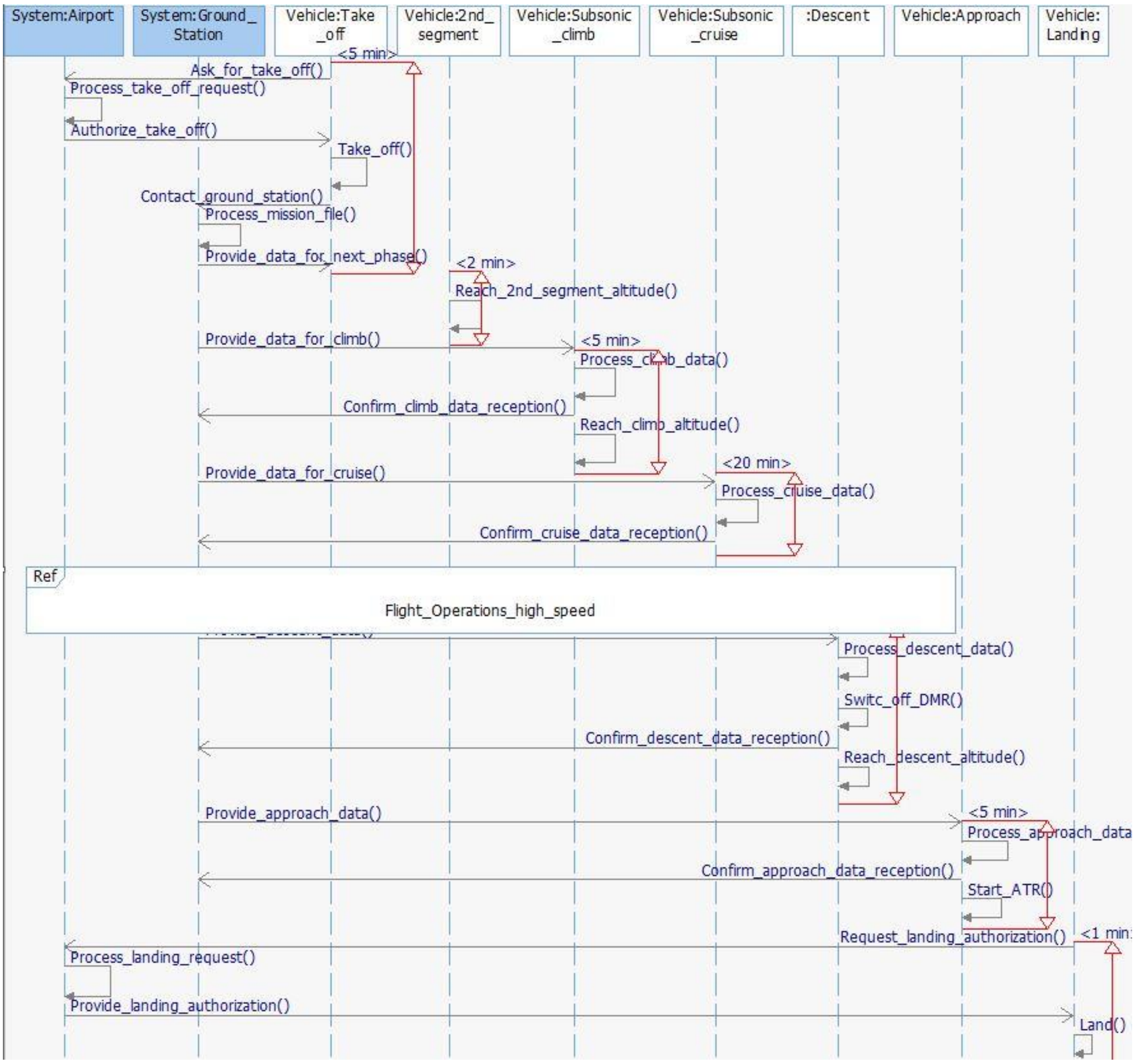

Figure 9. Flight operations sequences and timeline (nominal scenario)

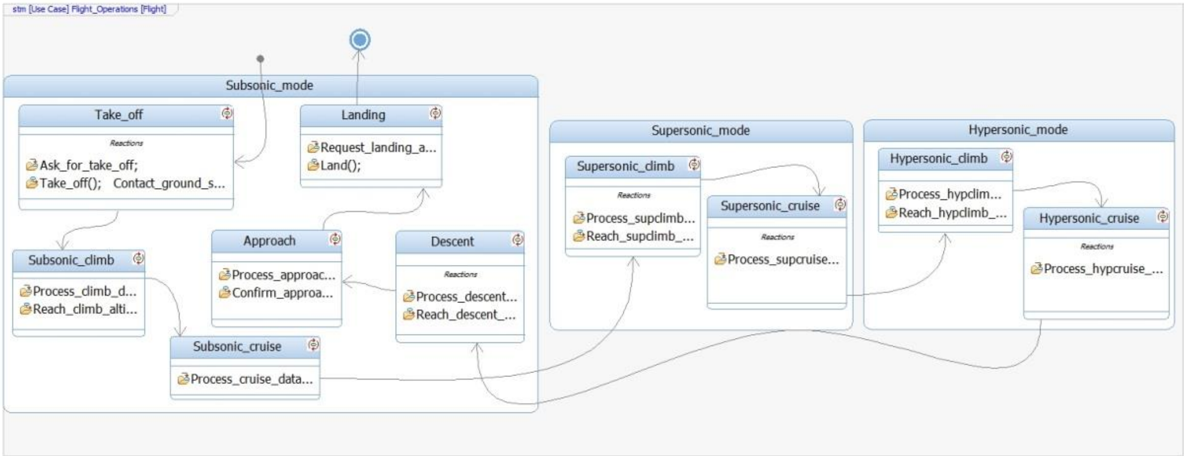

Figure 10. SMD focusing on flight regime states transition

Dedicated requirements (some of which are shown in Table 4 for the system level) can also be formulated and allocated on the logical architecture of the system. Moreover, a first set of interfaces is also introduced within the detailed UCD among systems and segment being part of the STRATOFLY SoI, thus a proper interfaces analysis can start as subsequent step.

Table 4. System level ConOps requirements for STRATOFLY case study

Derived from	ID	Mission concept requirements @ System Level
Use cases analysis (UCD)	OP_SysL1000	The Ground Operations of STRATOFLY vehicle shall include the following phases: - Parking - Gate holding - Taxi
…	…	…
Timing analysis (SD)	OP_SysL14000	The vehicle shall be able to perform taxi-out phase in 15 minutes
Use cases analysis (UCD)	OP_SysL15000	The Flight Operations of STRATOFLY vehicle shall include the following phases: - Take-off - Subsonic Climb - Subsonic Cruise - Supersonic Climb - Supersonic Cruise - Hypersonic Climb - Hypersonic Cruise - Descent - Approach - Landing
…	…	…
Timing analysis (SD)	OP_SysL24000	The vehicle shall complete the take-off phase in 5 minutes
…	…	…
Timing analysis (SD)	OP_SysL27000	The vehicle shall be able to operate in subsonic regime at a cruise altitude of about 12000 m
Timing analysis (SD)	OP_SysL28000	The vehicle shall be able to operate in subsonic regime at Mach 0.8
Timing analysis (SD)	OP_SysL31000	The vehicle shall be able to operate in supersonic regime at a cruise altitude of about 24000 m
Timing analysis (SD)	OP_SysL32000	The vehicle shall be able to operate in supersonic regime at Mach 4
…	…	…
Timing analysis (SD)	OP_SysL37000	The vehicle shall be able to operate in hypersonic regime at a cruise altitude of about 33000 m

2.1.4 Interfaces analysis (high-level)

The definition of the product breakdown shown in Section 2.1.3 through the Block Definition Diagram (BDD) is not only a formalization of a possible tree, but it includes also specific SysML relationships that can be very useful to sketch the interfaces network among the different elements, through the interfaces analysis process (Figure 11).

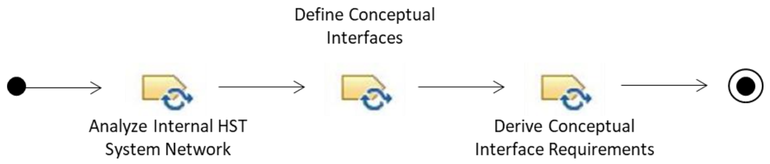

Figure 11. Interfaces analysis workflow (high-level)

In fact, the dependencies used to sketch the diagram allow defining the so-called block-part hierarchical relationships that translates low-level blocks into parts of high-level classes. The situation is clarified in Figure 12, where an Internal Block Diagram (IBD) for the STRATOFLY Super-System is shown. As depicted in Figure 6, where the BDD representing the product breakdown is reported, ground segment and flight segment are part of the STRATOFLY Super-System (or SoS), which is constraining the boundary of this diagram. Inside of it, the two parts representing the segments are shown, with related interconnections and interfaces. These interfaces specify the type of the data or object which flows between them, as well as the flow direction. In this case, three kinds of interfaces are instantiated, and, notably, a bi-directional data interface (green), a one directional electrical interface (yellow) and a bi-directional fluidic (propellant) interface (blue), between ground and flight segment.

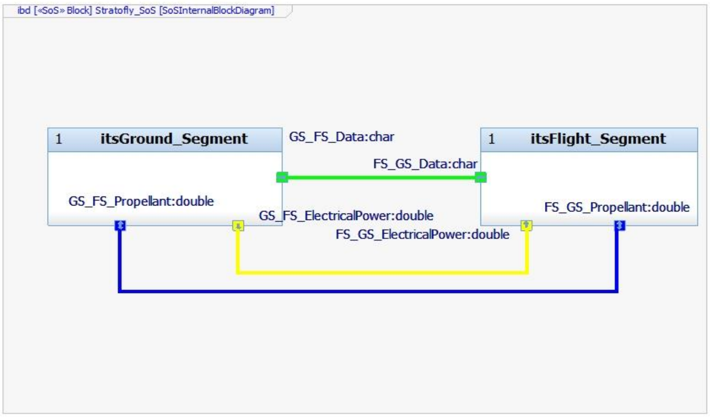

Figure 12. Interfaces specified within the IBD showing STRATOFLY SoS boundaries

The analysis can be deepened, as already discussed, looking into the segments to reach system level. As example, Figure 13 shows the IBD sketching flight segment boundaries, where the vehicle is placed as unique system. In this case, interfaces are present also at the boundary of the diagram itself, in order to reproduce the flows coming from the higher-level IBD (Figure 12), also considering that the limits of the diagram are here representative of the specific segment considered.

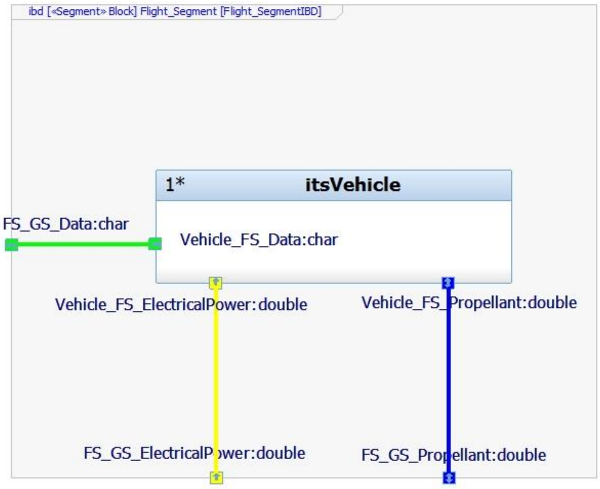

Figure 13. Interfaces specified within the IBD showing flight segment boundaries

Of course, requirements can be derived from this analysis, as shown in Table 5.

Table 5. Interface requirements at system level for STRATOFLY case study

ID	Interface Requirements @ System Level
IR@SysL_1000	The Airport shall be able to provide electrical power to the STRATOFLY vehicle.
IR@SysL_2000	The Airport shall be able to provide propellant to the STRATOFLY vehicle.
IR@SysL_3000	The Airport shall be able to retrieve the propellant from the STRATOFLY vehicle.
IR@SysL_4000	The Ground Station shall be able to send data to the STRATOFLY vehicle.
IR@SysL_5000	The Ground Station shall be able to receive data from the STRATOFLY vehicle.
IR@SysL_6000	The STRATOFLY vehicle shall be able to send data to the Ground Station.
IR@SysL_7000	The STRATOFLY vehicle shall be able to discharge the propellant to the Airport.
IR@SysL_8000	The STRATOFLY vehicle shall be able to receive data from the Ground Station.
IR@SysL_9000	The STRATOFLY vehicle shall be able to receive electrical power from the Airport.
IR@SysL_10000	The STRATOFLY vehicle shall be able to receive propellant from the Airport.

Functional and interface analyses are quite simple at high-level, but an increasing complexity, due to the high amount of links among the different elements is expected when dealing with low-level design process, as described in Section 2.2. However, at this design stages, the elements coming from the overall logical analysis just performed are enough to start analysing the engineering scenario from a performance point of view, as specified within Section 2.1.5. Specifically looking at vehicle product (which is the main subject of the subsequent numerical analysis), it is possible to appreciate the overall network of dependencies instantiated within the Model-Based environment. In fact, from a purely functional point of view, the vehicle is associated to a system level function, deriving in turn from a Top-Level Function (TLF) embedding the main features of the mission statements, formulated according to primary objectives elicited from the stakeholders. On the other hand, the product is responsible to operate within a preliminary sketched Concept of Operations (ConOps), being characterized by a set of states, active within specific time frames and sequences. As just seen, it has also dedicated interfaces with other elements, being part of the flight segment, and potentially being constituted by subsystems and additional parts, as analysed in Section 2.2.

2.1.5 Vehicle performance and feasibility analyses

The vehicle performance and feasibility analysis aims at identifying a suitable design point for the aircraft in terms of basic performance such as thrust, lifting surface, reference masses and available volume starting from the functional design anticipated in the previous sections. The selection of suitable key performance indicators depends also on the preliminary Concept of Operations (ConOps) formalized in Section 2.1.3. The approach proposed in this work is aimed at characterizing the vehicle (STRATOFLY MR3) on the basis of the different flight regimes constituting the reference mission, by firstly defining the Thrust-over-Weight (T/W) as function of the Wing Loading (W/S - ratio between aircraft mass and lifting surface) in different phases and, secondly, by providing a careful assessment of the available volume on board, to host the payload, the subsystems and, most importantly, the propellant. The first process is known as vehicle performance or matching analysis (Figure 14), while the second one is known as volume feasibility analysis (Figure 16).

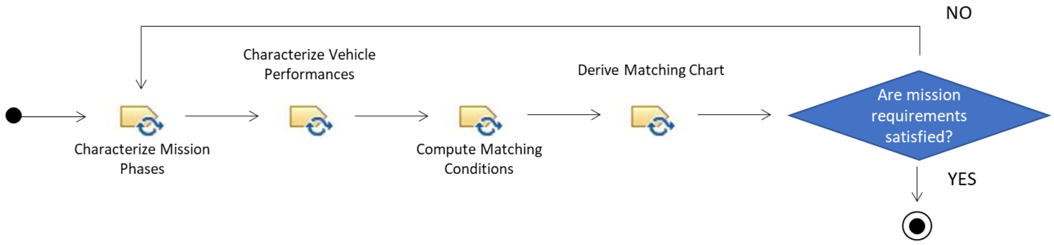

Figure 14. Basic vehicle matching workflow

Particularly the matching process adopted for the specific case, known as Multiple Matching Chart (MMC) approach [37], considers the main operational requirements specified in Section 2.1.3, together with the configuration requirements formulated within the STRATOFLY project and concerning the re-use of the experience matured in LAPCAT II [8-9], in order to set minimum performance requirements to guarantee the feasibility of the concept. The overall matching process, originally defined within [38], supported by [39] and subsequently subjected to updates so to be applicable to different kinds of aircraft configurations [40], as well as specialized to meet the peculiar analyses related to high-speed vehicles [41-42] is based on the graphical representation which relates T/W ratio to the W/S of the aircraft on a 2D chart. This chart allows the identification of a feasible design space and the definition of a design point describing the optimal vehicle configuration in terms of maximum thrust, Maximum Take-Off Mass (MTOM) and wing surface, meeting all the high-level requirements. In the Matching Chart, the different curves are mathematical equations that express requirements for each mission phase in terms of T/W as function of the W/S. Practically speaking, the diagram identifies a spectrum of feasible solutions, in terms of required thrust, to counteracts the drag generated during the flight, with a direct correlation to the lift generation capability of the aircraft. The characterization of mission phases is the first step, taking advantages from the phases definition within ConOps and using proper models to derive T/W ratio requirements as function of W/S for each part of the mission (physical characterization of the phases). Subsequently, the vehicle concept is characterized from the point of view of its high-level configuration (MTOM, wing area and general dimensions) and performance (especially for what concerns aerodynamic efficiency and propulsion plant). Within this task, a deep iterative approach is adopted to evaluate vehicle configuration, starting from assumptions and statistics, and to propose a sustainable concept from the point of view of the consistency between MTOM and wing surface, in the whole set of operating regimes. As starting point, the main requirements and hypotheses affecting the matching of the vehicle are summarized in Table 7.

Table 6. Main specifications for STRATOFLY MR3 vehicle

Parameter	Value	Unit of Measure	Specified by
MTOM	400000	kg	Hypothesis from LAPCAT II
Reference Mass @ Top of Climb (ToC) subsonic	375000	kg	Hypothesis from LAPCAT II
Reference Mass @ Top of Climb (ToC) supersonic	350000	kg	Hypothesis from LAPCAT II
N° of passengers	300	-	MR2000
Subsonic Cruise Mach	0.8	-	OP_SysL28000
Supersonic Cruise Mach	4	-	OP_SysL32000
Hypersonic Cruise Mach	8	-	MR5000
Subsonic Cruise Altitude	12000	m	OP_SysL27000
Supersonic Cruise Altitude	24000	m	OP_SysL31000
Service Ceiling	33000	m	OP_SysL37000
Range	18700	km	Per_HL4000 (see performance req.)
Engines thrust @ sea level (total)	3000	kN	Hypothesis from LAPCAT II
Engines thrust @ ToC subsonic (total)	2800	kN	Hypothesis from LAPCAT II
Engines thrust @ ToC supersonic	500	kN	Hypothesis from LAPCAT II
Engines thrust @ hypersonic cruise level	1033	kN	Hypothesis from LAPCAT II

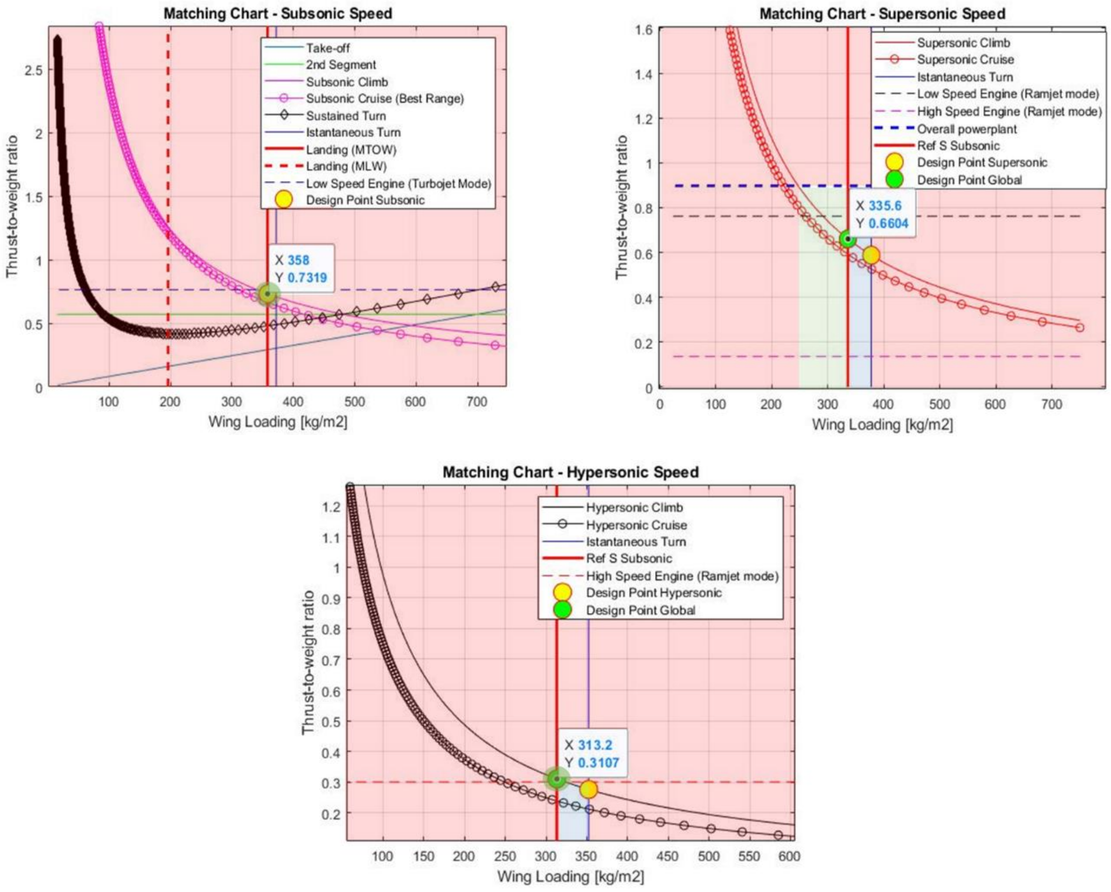

Figure 15. STRATOFLY MR3 vehicle matching in different flight regimes

The derived matching for subsonic, supersonic and hypersonic regimes are reported in Figure 15. High-speed vehicles design space is usually very thin, mainly because of the high demanding performance and of the need of travelling through different flight regimes. In Figure 5, different colour shades are used to highlight the feasible/unfeasible areas, while selected design points are defined as explained hereafter. These results make also benefit from the analyses concerning aerodynamic and propulsive databases of the aircraft to identify suitable equilibrium conditions on which matching requirements are built. For the specific case study, aerodynamics and propulsive data are provided in [43] and in [44] respectively. The different design points are representative of the best solutions looking at a single regime (yellow dots) as well as to global mission (green dots). Even if the high-speed regimes may require a lower wing surface, also considering the reduced mass that the aircraft will have in these conditions, the low-speed phases can be critical from the point of view of lift generation (hypersonic aircraft have usually low aerodynamic performance at subsonic speeds), thus an extension of lifting surface may be required if compared to the hypothesized value looking at the specific regime. Then, the aircraft shall be constrained to the extended value also for the entire mission, globally requiring a higher T/W ratio to perform high-speed phases. This is the reason why subsonic design points are coincident, while global design point is more critical, looking at the charts, for supersonic and hypersonic regimes, if compared to the local ones. Notably, the matching chart for the subsonic regime identifies a very small design space, basically coincident with the design point. In fact, feasible solutions may only be located at W/S values lower than the landing requirement at maximum mass and at T/W higher than the subsonic climb requirement. Since the two requirements are graphically intersecting in the point where also the available T/W line (dotted blue line) intersects the landing W/S requirement at maximum mass, there is just a single possible solution. Supersonic matching chart allows for a wider flexibility, since the presence of both powerplants enables different solutions. In fact, it is possible to identify a global feasibility area (green) where the configuration is valid being consistent with the W/S requirement coming from subsonic regime and the T/W requirement produced by supersonic climb (T/W available with both powerplants is higher than the required one in the green area, for a set of W/S points). Also, it is possible to spot a blue area where, for the same reasons, the concept is feasible but only considering the local W/S requirement, defined for manoeuvres at high speed (not a global solution). Selected (global) design point is the one which guarantees the minimum wing surface. Hypersonic matching chart is instead similar to the subsonic one, with very thin design space, almost coincident with global design point, even if a small area of validity for local W/S requirement seems possible (as for the previous chart). Together with performance assessment in terms of matching, a careful feasibility analysis concerning the compliancy of vehicle configuration, in terms of major dimensions, with mission requirements (such as required fuel volume, range etc…) shall be performed. Feasibility analysis (Figure 16) thus combines results coming from matching analysis, in terms of reference surface, Wing Loading and Thrust-to-Weight ratio, to determine the available volume on board, making benefit also of some semi-empirical relations [41] to estimate the volume allocation on the different elements of its breakdown.

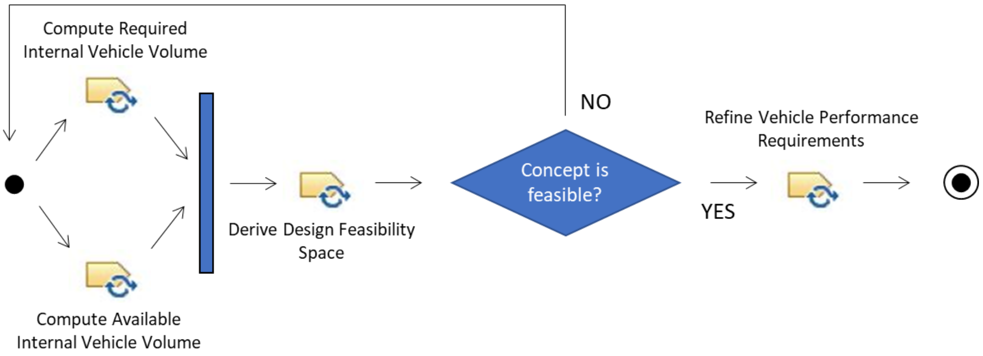

Figure 16. Basic vehicle feasibility analysis workflow

Since the capability of flying over long-haul routes, reducing cruise time, is the crucial advantage of this kind of vehicle category, range requirement is a priority within conceptual design study, to assure competitiveness of the product in operation [45]. The focus on the available volume is thus quite important, also because this is theoretically associated to the maximum achievable aerodynamic efficiency, according to specific configuration parameters [46]. On the other hand, required volume depends on the carried payload, the propellant mass required to cover the desired range, as well as on the overall airframe configuration, including subsystems. The evaluation of design space, oriented to volume requirements determination, can thus be found by following the trends suggested in literature for volume assessment, while available volume is a strict consequence of configuration parameters, such has the ratio of theoretical internal volume over planform area (τ). Figure 17 reports the results per flight regime, as well as the global design point.

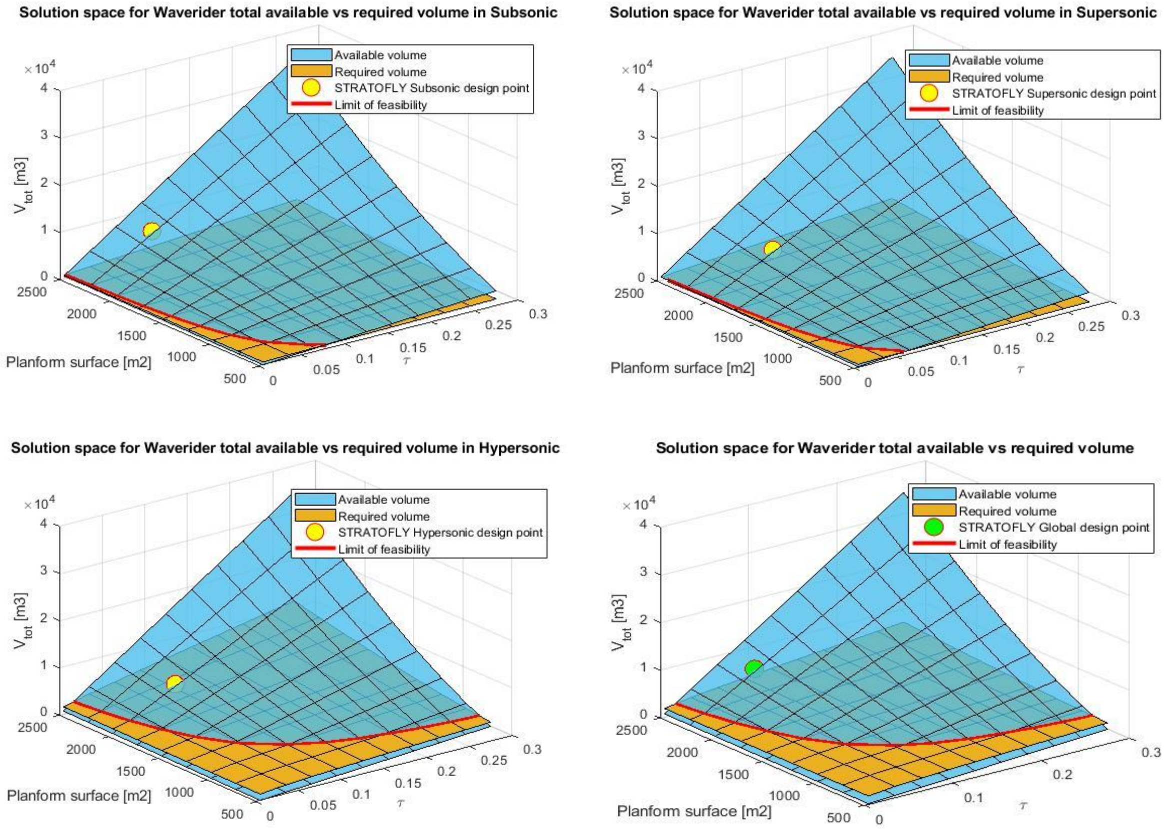

Figure 17. Volume feasibility assessment for the STRATOFLY MR3 vehicle

As for the matching chart, local design points consider the volume required to perform a very specific mission leg, belonging to the aforementioned regime, while global design point includes all the volume necessary to complete the mission (being very sensible to overall propellant mass required). In this case, even if the range requirement is quite high, the vehicle configuration offers enough volume to host the different elements, guaranteeing the feasibility of the concept.

Global mission and aircraft layouts, basing also on the heritage of LAPCAT II legacy [8-9], can then be validated (Figure 18) and final requirements concerning performance and configuration can be established and covered (Table 8 and Table 9).

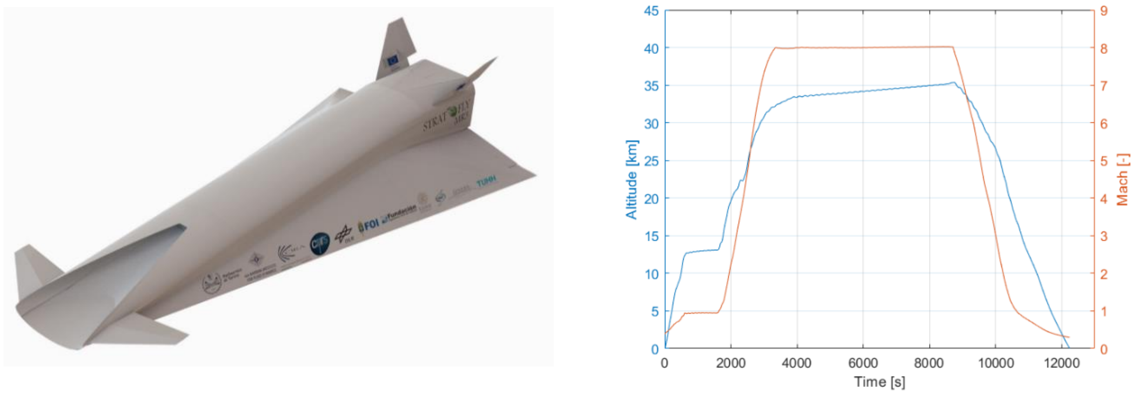

Figure 18. Vehicle and mission layouts as result of the overall conceptual design process [43]

Table 7. High-level performance requirements for STRATOFLY MR3 vehicle

Derived From	ID	High-Level Performance requirements
MR1000	Per_HL1000	The flight time of civil passengers flights over long haul and antipodal routes shall not exceed 4 hours
MR2000	Per_HL2000	The transportation system shall be able to transfer at least 300 civil passengers for a total mass of 33000 kg including 80 + 30 kg per passenger
MR3000	Per_HL4000	The transportation system shall be able to flight along long haul and antipodal routes with a range of at least 18700 km
MR3000	Per_HL12000	The vehicle shall be characterized by an aerodynamic efficiency of about 6.5 in hypersonic cruise
MR5000	Per_HL5000	The vehicle shall reach Mach 8 in hypersonic cruise
MR6000	Per_HL6000	The transportation system shall have a ceiling altitude of at least 33000 m
MR8000	Per_HL7000	The vehicle shall be able to perform take-off and landing from prepared runways having a total length of no more than 4 km
…	…	…
MR10000	Per_HL10000	The vehicle shall fly at subsonic speed within an area of 400 km around the departure and arrival airports
…	…	…

Table 8. Configuration requirements for STRATOFLY MR3 vehicle according to matching and feasibility analyses

Derived from	ID	Configuration Requirements @ System Level
Feasibility Analysis	CR_SysL4000	The STRATOFLY vehicle shall be characterized by a cabin volume of at least 1400 m^3
Matching Analysis	CR_SysL8000	The STRATOFLY vehicle shall be characterized by a wing loading of about 358 $\frac{kg}{m^2}$
Matching Analysis	CR_SysL9000	The STRATOFLY vehicle shall be characterized by a wing surface of about 1117 m^2
Feasibility Analysis	CR_SysL10000	The STRATOFLY vehicle shall be characterized by a τ parameter of at least 0.08
Feasibility Analysis	CR_SysL11000	The STRATOFLY vehicle shall be able to host an internal volume of at least 8600 m^3
Feasibility Analysis	CR_SysL12000	The STRATOFLY vehicle shall be able to host an internal volume for propellant of at least 2550 m^3 in case a propellant density of 70.8 kg/m3 is considered, or at least 2000 m^3 in case propellant density is 90 kg/m3.

The aircraft platform derived in this section is used as reference to deepen the analysis of on-board subsystems in Section 2.2, where the focus is on the one showing the most advanced multi-functional architecture of the whole set, being a peculiar energy management plant.

2.2 Subsystems preliminary design process

2.2.1 Overview

Preliminary subsystems design process is devoted to the characterization of functional, performance and physical aspects of on-board plants, starting from the requirements and constraints derived within conceptual design, at vehicle level. The analysis is performed from subsystem level up to equipment and components, so to investigate the low-level products breakdown. The reference process is shown in Figure 19 where main tasks are highlighted, notably including functional and interface analyses at lower level (N+1/2 indicates in fact the layer of the analysis according to [34]), as well as performance and physical characterization of the different subsystems.

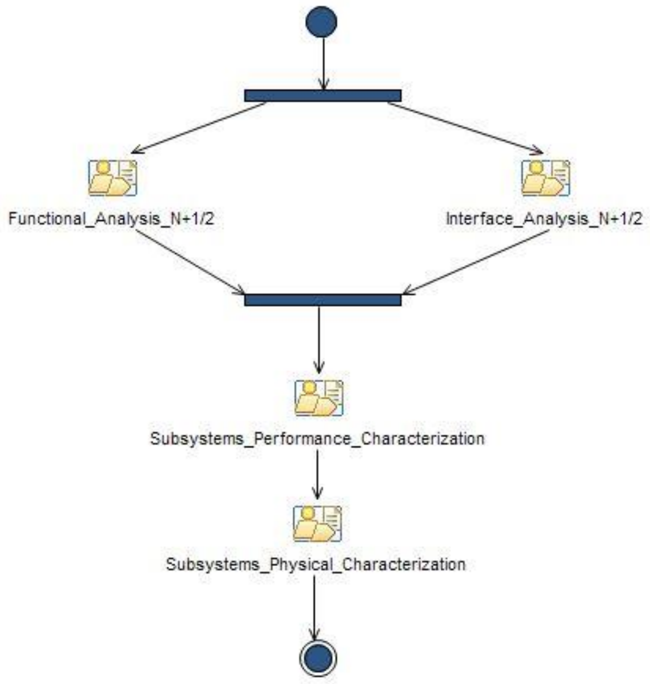

Figure 19. Reference process for preliminary subsystems design

While functional and interface analyses are performed similarly to higher level studies, simply changing the hierarchical level of the focus, performance and physical characterization of the on-board plants strictly depends on the type of subsystem considered, the engineering practices established to face the characterization process itself and to other aspects involved within the specific scientific domain. It is thus not possible to provide a unique view over subsystems design tasks, since they are usually tailored depending on the efforts needed for the sizing. As example, a multi-functional on-board subsystem is taken as reference here to show the interrelations among the different tasks and the effectiveness of the Model-Based approach, which aims at connecting the logical design process with the numerical assessments. The plant under study is referenced as Thermal and Energy Management Subsystem (TEMS) [47], a highly integrated example of embedded on-board architecture, described in Section 2.2.3 together with its own interfaces.

2.2.2 Functional analysis (low-level)

The hand-off between the conceptual vehicle design and the subsystems design processes shall occur first at functional level, since high-level functions shall then be decomposed at lower level, in order to meet the required hierarchy (Figure 20).

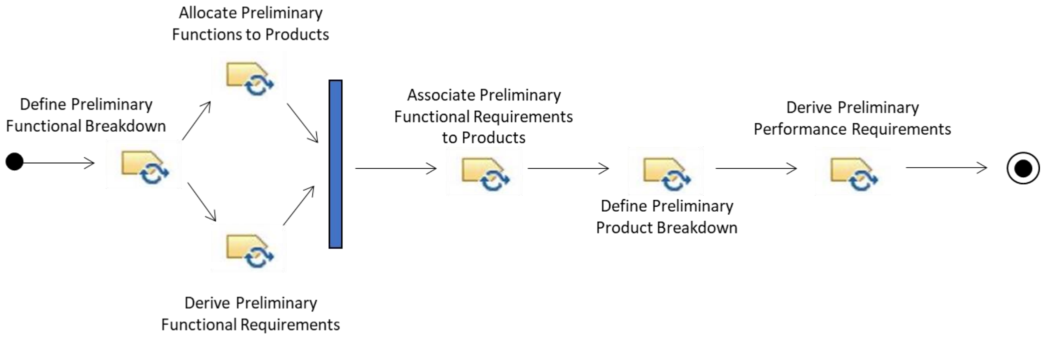

Figure 20. Subsystems functional analysis workflow (low-level)

In this case, the main function associated to the STRATOFLY MR3 vehicle, defined in Section 2.1.3, is here decomposed (Figure 21) in order to generate additional requirements and, subsequently, to identify suitable subsystems responsible to satisfy them.

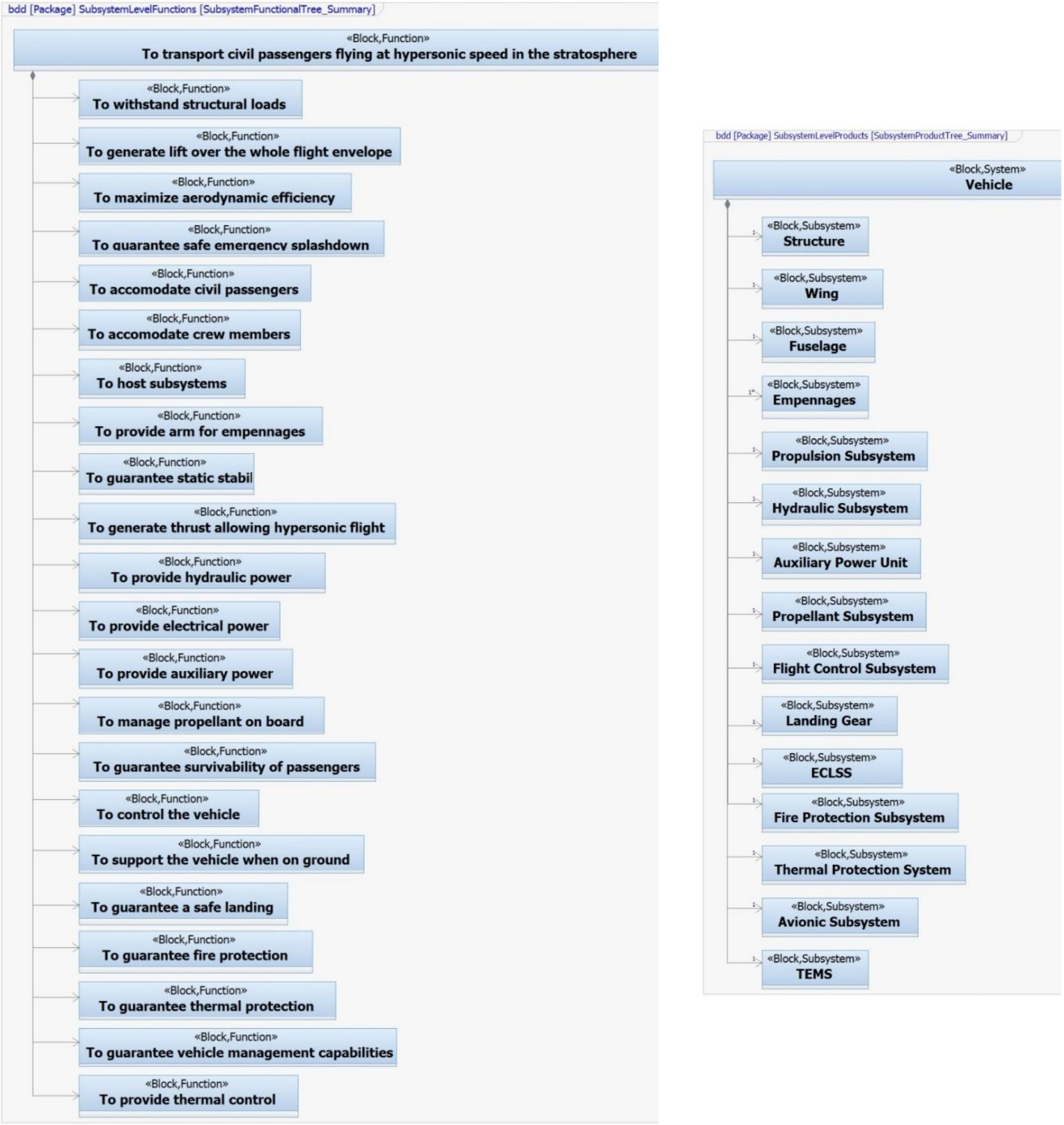

Figure 21. Functional and product trees (BDD) at subsystem level

Functions are allocated to products and proper requirements are updated accordingly, as shown in Table 10 for a limited set, with focus on the TEMS and on the main subsystems interfaced with it and dealing with cryogenic fluids, as discussed in Section 2.2.3.

Table 9. Example of functional requirements at subsystem level

ID	Functional Requirements @ Subsystem Level
FR@SubSysL_10000	The propulsion subsystem shall generate thrust allowing hypersonic flight.
FR@SubSysL_12000	The Thermal and Energy Management Subsystem (TEMS) shall provide electrical power.
FR@SubSysL_14000	The propellant subsystem shall manage propellant on board.
FR@SubSysL_15000	The Environmental Control and Life Support Subsystem (ECLSS) shall guarantee survivability of passengers.
FR@SubSysL_20000	The Thermal Protection Subsystem (TPS) shall guarantee thermal protection.
FR@SubSysL_22000	The Thermal and Energy Management Subsystem (TEMS) shall provide thermal control.

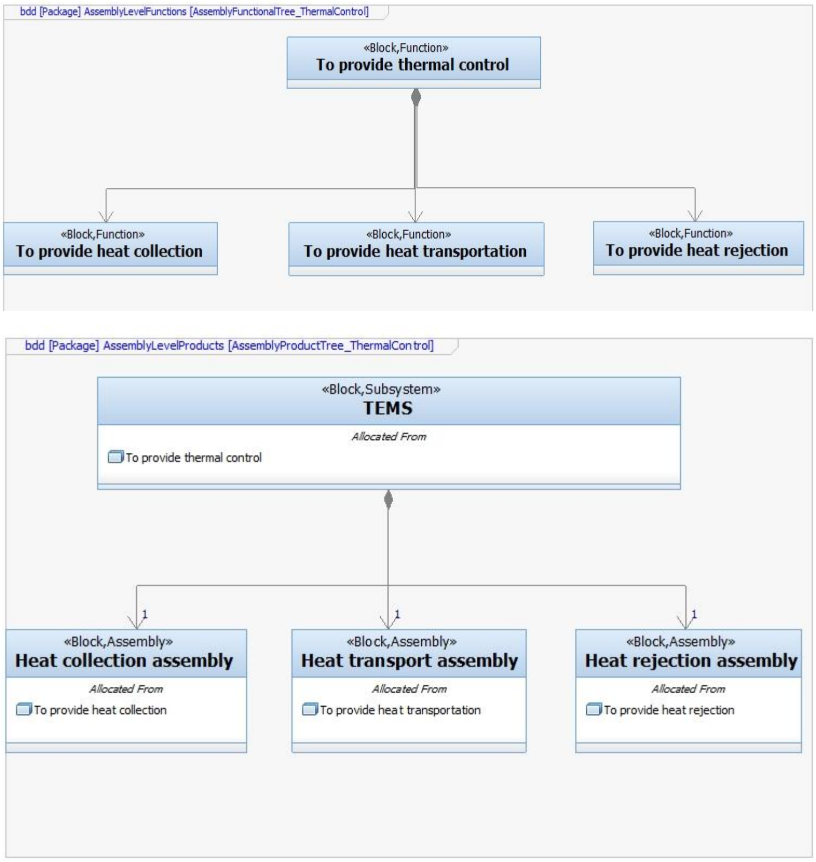

Figure 22. Functional and product breakdown at assembly level for TEMS

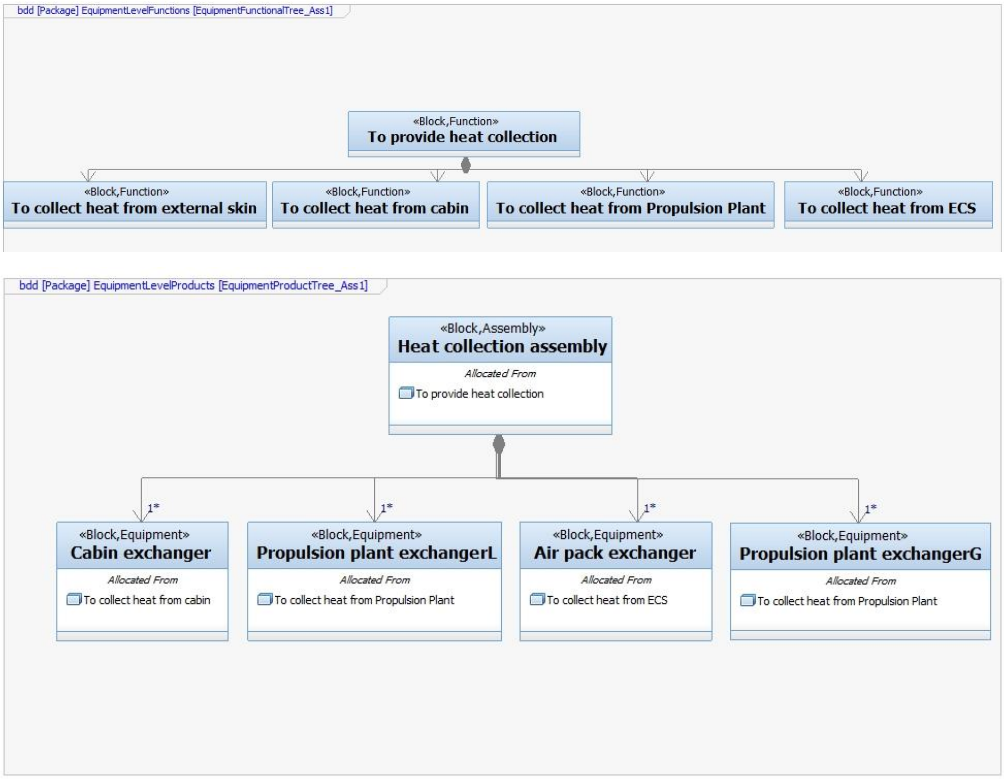

Figure 23. Functional and product breakdowns at equipment level for TEMS (heat collection assembly only)

Analysis can be repeated in a recursive way, at lower levels, deriving for example assembly and equipment-related functionalities, as well as associated products architecture (shown for the thermal control functionality branch in Figure 22 and 23). Once the main functionalities characterizing the overall subsystems are identified, and allocated on reference elements, it is very much interesting to have a look at the main interface among them (Section 2.2.3), to sketch the subsystem layout and working cycle that would be, in turn, investigated numerically within performance and physical assessments (Section 2.2.4).

2.2.3 Interfaces analysis (low-level)

The concept of the Thermal and Energy Management Subsystem (TEMS), defined in [47] and re-used within the STRATOFLY MR3 vehicle concept, is based on the exploitation of both liquid and gaseous hydrogen propellant for the cooling of the aircraft and on-board subsystems critical parts, as well as for the contribution of secondary power generation. This is a very common architecture within high-speed vehicles concepts, since the connection of on-board subsystems with the powerplant allows exploring efficient and multi-purpose thermodynamic cycles [48-49]. Notably, since the liquid hydrogen stored within the tanks is easily subjected to boil-off phenomena, especially in hypersonic flight environment, it is possible to make benefit of this vapor to cool down main users, upon compression within dedicated turbomachinery. The fluid then collects the heat from the different loads, which can be rejected within the combustion chamber of the propulsion plants through a proper mixing with the liquid fraction. The liquid hydrogen, in turn, can be used within a regenerative cycle to specifically cool down the propulsion plant itself, being then expanded within a dedicated turbine, reducing its own temperature and driving the boil-off compressor previously cited. In this way, the enthalpy required to drive the turbine can be provided directly through the regenerative cycle, without the need of instantiating a dedicated secondary combustion. Moreover, the excess of power produced by the turbine, can be directed to proper generators attached to the driving shaft through some gearboxes, to contribute to the electrical power generation capabilities of the plane. This is a highly integrated cycle, envisaging a lot of interfaces among different plants. The interfaces analysis (Figure 24) is thus crucial to identify the relevant requirements and the architecture itself of the TEMS, preparing also some interesting tasks described within Section 2.2.4.

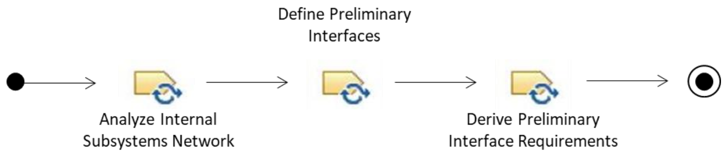

Figure 24. Subsystems interfaces analysis workflow (low-level)

Starting from the overall TEMS layout, the Internal Block Diagram (IBD) showing the different interfaces among the three assemblies shown in Figure 22 can be represented as in Figure 25. In this case, the collection assembly collects the heat from different sources outside the TEMS (through the overall subsystems network on-board the MR3 vehicle, not shown here) and transfers the heat to the transport assembly or directly through the rejection assembly (red lines). Liquid propellant (blue line) coming from the fuel subsystem is provided to the collection assembly and both the gaseous and the liquid fractions are used for different purposes while concluding their journey through the rejection assembly and outside the TEMS (to reach the propulsion plant). Within the rejection assembly, the liquid hydrogen turbine provides mechanical power (purple line) to the utilities outside the TEMS. As example of lower level IBD, the heat collection assembly is explored in Figure 27, where details about the connection of main equipment shown in Figure 23 are reported. In this case, as described before, it is interesting to see how the heat collection from the propulsion plant (through a proper liquid hydrogen exchanger) is performed only on the propellant line, while other utilities make benefit of the boil-off lines. The instantiation of such kind of interfaces is very helpful to generate consistent requirements (not reported here for brevity) and to start sketching the architecture of the plant, at least at logical level, to prepare further numerical investigations about the performance during the reference mission. Also, it allows to preliminary evaluate possible non-nominal scenarios in terms of loss of functionalities and related connection during very specific conditions, with the opportunity of anticipating peculiar tasks of the safety assessment typically used within the aeronautical domain [50-53].

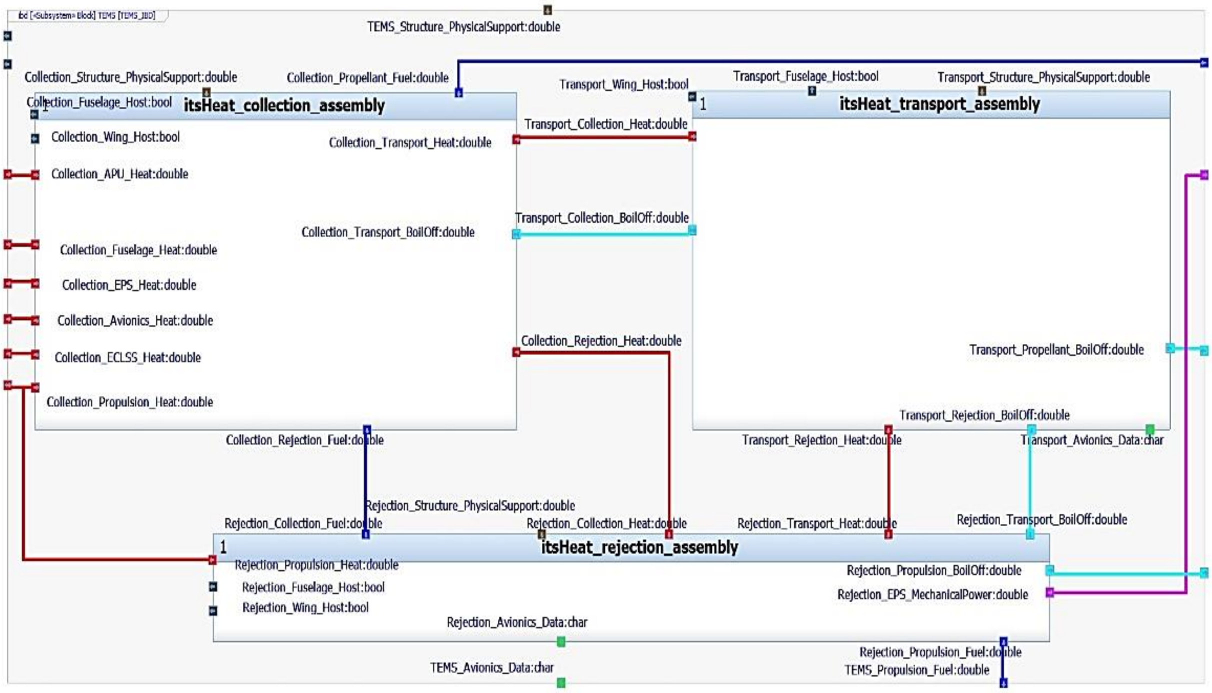

Figure 25. Interfaces definition at assembly level for TEMS

2.2.4 Performance and physical characterization of subsystems

As already stated in Section 2.2.1, numerical analysis of on-board subsystems, typically dealing with performance evaluation and physical characteristics determination, is a quite heterogeneous process strictly depending on the nature of the plant and on the best practices involved. This paper does not aim at investigating in detail the numerical assessment faced within the TEMS design, since the topic would require a whole different discussion. However, this section is aimed at highlighting the strong points associated to the correlation of such kinds of analyses with the Model-Based process just shown, with an eye on interoperability and application lifecycle features usually faced during this phase of the design. First of all, it is important to distinguish between performance and physical characterizations. The first process (Figure 26) is conceived to derive subsystem performance requirements by analysing the related operational environment.

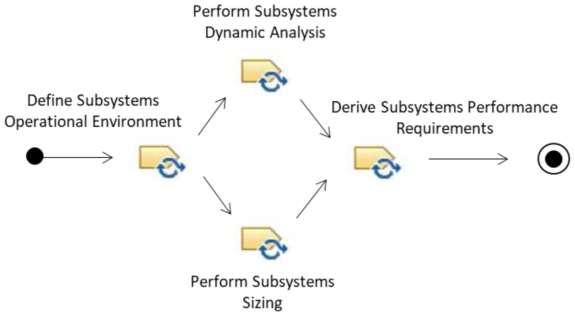

Figure 26. Subsystems performance analysis workflow

This allows deriving the required performance for the subsystem of interest, through the sizing process, and to ultimately analyse the dynamic behaviour of the plant and its components. The overall workflow requires the knowledge of the operating environment, the mathematical characterization of constituting components of the plant and of the interfaces among them, in order to implement a well-defined simulation. Usually, a static sizing process is also performed as preparatory step, in order to identify relevant performance in steady (critical) conditions.

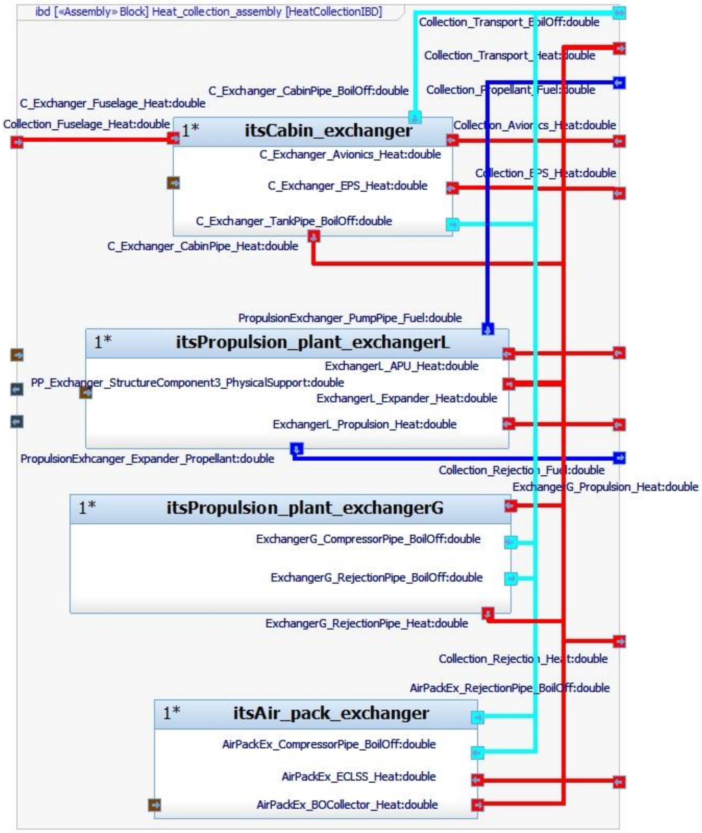

Figure 27. Interfaces definition at equipment level for heat collection assembly of TEMS

As the word suggests, the effort is concentrating on the determination of performance and operating variables of the system, whilst constructional and physical parameters are less important (often, the use of specific or dimensionless variables is even adopted). The instantiation of a dynamic simulation is particularly interesting, since this assumes the knowledge of a proper model architecture to be implemented within the desired simulation environment. The power of the interface analysis, supported with the whole set of tasks previously shown is that the model objects and nodes defined within the logical environment can be effectively translated directly within the final simulation environment by means of proper interoperability standards, or dedicated connectors, which are typically provided to support seamless integration of the Model-Based toolchains. As demonstrated in [54], the model structure defined within the interface analysis at different levels, can be used as a framework container to host numerical relationships benefitting from the connections and the relationships previously instantiated. This lowers a lot the time required to set up the model architecture within the simulation environment, leaving more time to the designer to concentrate on the real mathematical modelling of the elements involved. Different interoperability strategies can be pursued to reach this goal, and even heterogeneous simulation campaigns [55], using different dynamic model sources within a single environment, can be considered as further step towards an effective portability of models, also among different specialists. Connection with a various set of external environments can also be instantiated, with particular focus on CAD and multi-body models, if applicable [56]. On the other hand, physical characterization process (Figure 28) makes use of the relevant performance, especially in design conditions, to identify suitable and applicable relationships aimed at describing the so-called subsystem breakdowns, usually consisting of mass and volume budgets for the different elements, as well as of estimation of components dimensions. Even if this approach is theoretically different from performance analysis, physical analysis makes benefit of the data obtained during sizing and even dynamic analysis for the selected subsystem, since the understanding of operating parameters and behaviour of the plant is a crucial step to move towards physical characterization. The rating of the sub-systems elements is in fact fundamental to tune the relationships and to obtain a reliable estimation of physical characteristics. One of the main differences with the performance characterization process can be the use of statistical-oriented models to define components breakdown, since estimation relationships for physical features may include, together with design drivers associated to operating variables, also constructional issues and engineering rules of thumb.

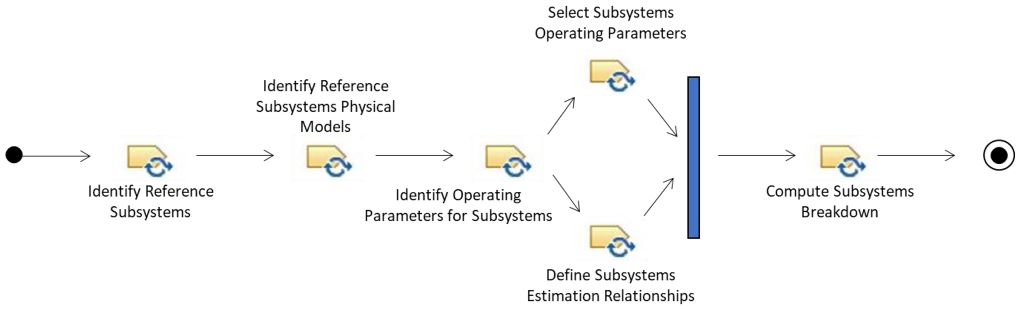

Figure 28. Subsystems physical analysis workflow

Example of approaches on the topic are common in literature [57-58], but unexpectedly, the efforts required to reach model convergence can be higher if compared to performance characterization campaigns, since their range of applicability can be restricted to very specific case studies, while universal validity may not be guaranteed. This is also the reason why, especially in aeronautics, physical characterization processes have been studied for a long time, suggesting best practices and relationships already some decades ago [59-60]. At the same time, the importance of such tasks is undeniable, since the knowledge of subsystems breakdown, derived, in turn, as combination of individual components breakdown, is a milestone for the verification of installation requirements and may contribute to a lower-level feasibility analysis, performed similarly to the one suggested in Section 2.1.5.

3. Conclusions and future works

Application of Systems Engineering approaches, particularly with the exploitation of Model-Based tools and processes, has proven to be an effective solution to deal with complexity management and requirements development within different engineering fields. High-speed aviation is expected to develop again as mid-term hot topic for aeronautics, since new concepts for the evolution of both commercial transportation and re-usable access to space are going to be studied in the next decades. Concepts associated to effectiveness and competitiveness of such products are going to be inevitably re-defined, while their success in operation can be highly affected by the capability of the design methodologies to manage complexity in early stages of the lifecycle. This paper showed how the exploitation of proper Model-Based Systems Engineering practices is crucial to support design efforts in the field of high-speed transportation, while focusing on the STRATOFLY MR3 hypersonic cruiser case study, belonging to the European research heritage on the topic. Main design processes and workflows have been specified for conceptual and preliminary phases of aircraft and subsystems characterization, from functional to performance and physical aspects definition. A special focus was dedicated to the opportunity of connecting in a seamless way the different tasks, properly formalized within standardized languages and frameworks, highlighting the effective requirements trace and coverage capability of the approach. Moreover, interoperability features between the logical architecture definition of the System of Interest and the traditional engineering practices associated to performance characterization and physical assessment have been discussed. Activities such as aircraft matching and feasibility analyses together with subsystem level performance identification tasks have been integrated with functional and logical definition processes within a thorough approach for complex vehicle design. The work is aimed at proposing possible methods to face in a more standardized way the entire assessment procedures, trying to suggest promising way forward on the topic. For this reason, it cannot be seen as a unique solution to tackle the design challenges that are expected to emerge in the future engineering scenarios, but, on the contrary, it shall be seen as a clear evidence on how the work on methodologies and processes establishment and formalization cannot be forgotten while increasing technology readiness of enabling fields of engineering. This means that it will no longer be possible in the future to focus on specific scientific areas without considering the holistic framework where they will be integrated, suggesting that competitiveness in operation will be guaranteed only if an integrated design approach is applied in early product lifecycle phases. Main future works shall then be focused on the instantiation of these techniques concerning systems development and requirements management according to the latest digitalization trends and technological improvements concerning Model-Based engineering, to ensure the effective implementation of engineering practices to be used as standards within the aviation of the future.

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