TRANSLATING THE CONCEPT OF SUSTAINABILITY FOR THE DETERMINATION OF REQUIREMENTS FOR THE DESIGN OF FUTURE AIRCRAFT

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Abstract

Achieving sustainability is becoming increasingly essential in the aviation sector and such goal has been addressed in many studies and research projects throughout the recent years. The majority of those initiatives focuses on new technological solutions. Also, the development of such new sustainable systems (e.g. aircraft) mainly targets only environmental sustainability: the reduction of greenhouse gases, pollutant and noise emissions. However, focusing only on technological aspects neglects the systemic character of sustainability; on the other hand, the sustainability goals targeted are often quite vague and incomplete. The aim of this paper is to propose a structured approach for the determination of clear, correct and unambiguous requirements covering the entire concept of sustainability in the air transport system, and then using them to drive the design of sustainable future aircraft.

Keywords: Sustainability, Systems Engineering, Requirements, Aircraft Design

1. Introduction

The aviation sector has embarked on a journey towards eliminating (as much as possible) the impact of its activities on the climate and on the planet. Several strategies and roadmaps investigating a variety of different solutions to achieve sustainable targets are being published and implemented by various players all across the aviation sector. Regardless of the specificities of each strategy, it is clear that the transition to a sustainable aviation is a challenge which involves the entire Air Transport System (ATS) and beyond. In Europe, this systemic challenge is framed in the ACARE's Fly the Green Deal (FTGD) vision [1]. This vision describes a "sustainable aviation in 2050", and provides short-, medium-, and long-term goals which support achieving such vision. Given the number and type of stakeholders involved in ACARE, such vision can be considered representative of the expectations of the entire European aviation R&D sector, while also providing a snapshot of the sentiments of the worldwide aviation sector.

With this background, ACARE's vision can be seen as a blueprint to describe and derive how the air transport system, and constituents thereof, shall be conceived and designed to belong to a sustainable future. In order to tackle the development of any system effectively, including a sustainable ATS and all its constituents, it is essential to unequivocally understand the needs of all involved stakeholders. In this case, ACARE represents aviation stakeholders and the FTGD's goals identify their needs; from those needs, clear, unambiguous, verifiable, complete and correct requirements shall be derived. Having requirements which fit this description is essential for a successful development and implementation of any system. If requirements are not fitting this description, this can hinder the development of the new system. According to a report published by the Standish Group [2], almost 45% of projects' or programs' failures are due to lack of stakeholders' involvement, lack of correct understanding of their needs, and to limitations related to the definition of system requirements, which might be incomplete or might change over time. Therefore, a structured approach guiding the complete and clear collection of stakeholders' needs and their transformation into system requirements is recommended by multiple organizations. The International Standard ISO/IEC/IEEE 29148 [3] provides standard guidelines addressing requirements engineering processes. This is also endorsed by the

International Council on Systems Engineering (INCOSE), which established a Requirements Working Group that in 2017 published a guide addressing recommendations and rules for writing good requirements [4].

Following this, a structured approach based on Systems Engineering, such as the one suggested by INCOSE, shall allow to determine requirements for the design of a sustainable ATS, and all the systems (e.g. aircraft) that are part of it, from the needs of expressed by the stakeholder ACARE in the FTGD's vision. To the authors' knowledge, well written requirements which can drive the development of sustainable aeronautical systems and generated through a structured approach are not (yet or publicly) available, making this the aim and original contribution of this work.

Next to identifying needs and defining requirements, the Systems Engineering approach promoted by INCOSE recommends to establish processes to validate stakeholders' needs and verify the derived requirements, already at the initial stages of the design process. The verification of requirements of a technological system (such as an aircraft) requires means of compliance (MoC) (for example tests, measurements, etc.), which are already well integrated in the current aeronautical design and certification processes. On the other hand, the validation of needs poses a more interesting challenge, especially regarding the specificities of sustainability needs. As the topic of sustainability covers more than technological aspects or other measurable aspects (e.g. economic considerations, emissions of greenhouse gases, level of noise), and it drifts into social values which hardly can be quantified as engineering quantities, new ways of validating whether the conceived ATS (and parts thereof) satisfies the goals embodied by the vision of FTGD are necessary. The proposal made by the authors is to model and use operational scenarios.

By identifying and validating needs and deriving requirements in a structured manner, three long-term objectives can be achieved:

1) the extracted needs and requirements from FTGD can be used for designing ATS which is sustainable by design, with sustainability as its main driver;

2) by explicating the requirements from FTGD in structured way, it can be determined whether the verification of those requirements is sufficient to achieve a sustainable aviation;

3) provide a harmonised approach that can be applied to other (on-going and planned) initiatives, enabling the derivation of needs and requirements in a standardised format, and mapping the contribution of each initiative to the overall targets of a sustainable aviation.

In order to contribute towards the stated objectives, the current work is organized as follows. The state of art of requirement engineering in relation with sustainability within the aviation sector is given in section 2. The structured approach implemented in this work to translate sustainability goals gathered from the FTGD's vision into requirements is described in section 3. Section 4 introduces a case study, as example of the system of interest to be designed according to the sustainability requirements extracted from FTGD and identified in this work. The derived aircraft-level needs and requirements are presented in sections 4.3 and 4.4, respectively. Section 5 discusses the obtained requirements built by following the proposed structured approach, while section 6 concludes the paper by presenting further activities necessary to continue the present research work towards the long-term objectives.

2. Sustainability, Systems Engineering and requirement engineering

Sustainability has become an essential aspect for every industry, as the transition to a more sustainable society, underpinned by the energy transition, is impacting every human activity. The very nature of sustainability requires a holistic and systemic perspective in order to capture its complexity. From this it can be argued that Systems Engineering and Model-Based Systems Engineering (MBSE) approaches are particularly suited to model sustainability; as such, they have been leveraged to account for sustainability aspects in various industries/systems.

Examples of the application of Systems Engineering or MBSE in connection to sustainability within the aviation sector are limited. When Systems Engineering and/or MBSE and sustainability are mentioned together, the sustainability character is linked to the technological solutions investigated. The particular technology considered is already assumed to enable aviation to become sustainable, while the role of Systems Engineering and MBSE is to accelerate the development and implementation of such

technology, not to ensure its sustainable character. Examples of this are presented in [5] and [6]; in those studies, sustainability appears not as a requirement, but more as an additional parameter, considered a-posteriori, after the traditional stakeholder requirements are identified. In [5], MBSE is used to include a qualitative sustainability awareness assessment earlier in the design stage, but not as part of the system requirements; by performing this assessment on the already identified solutions, more sustainable system and business alternatives are identified. This approach appears more in the direction of a risk assessment and not as requirements definition; also, the qualitative aspect may limit the implementation of such approach in engineering, a context in which design decisions highly rely on quantification. In [6], MBSE is used to create a link between the aircraft manufacturing system and the environmental system; information from the manufacturing system are linked to an LCA (as a sustainability assessment) enabling a clear identification and collection of all the output from the manufacturing system which are necessary for an environmental assessment.
Though those limited examples provide a solid foundation for linking sustainability to aviation by using a Systems Engineering approach, there are limitations. First of all, those aviation-related examples follow a traditional flow by first approaching the technical stakeholder requirements, and only as a second step including sustainability aspects. This traditional approach means that the design space is already framed based on the technical requirements; the optimal solution is identified in such design space and sustainability is added a-posteriori, mainly as a verification or as an evaluation of such design. In addition to this, the current state of art primarily connects the concept of sustainability with environmental aspects (emissions, waste, etc.), almost neglecting economic and social aspects which are equally important in a full definition of sustainability.

This work proposes to go beyond the current practices, by using Systems Engineering and MBSE approaches (requirements engineering, in particular) to translate sustainability objectives, targets and goals into requirements; those sustainability requirements can be combined with other, traditional, requirements (e.g. a specific functionality or minimizing production cost), creating a more comprehensive set of requirements. Such approach has been followed in [7], where the UN Sustainable Development Goals (SDGs) [8] are used as starting point to derive sustainability requirements for business development in multi-national companies. This work wants to follow a similar approach for the aviation industry, as it can allow to introduce sustainability requirements at the same time as the technology-driven requirements. In this way, the resulting designs shall fulfil all requirements at once.

3. Translation of sustainable aviation goals into requirements for a sustainable ATS

The present section describes how to transform sustainability goals, as those collected in the FTGD's vision, into requirements for the ATS. The structured approach proposed in the paper is taken from [9], which includes also guidelines prescribed by the International Standard ISO/IEC/IEEE 29148 [3] and by INCOSE [4].

This approach starts with the identification of the system of interest, its stakeholders, and the collection of their needs. As introduced earlier, the system of interest addressed here is the ATS. The stakeholders are individuals or groups of people who might have an interest on the system of interest during its entire life cycle (definition adapted from [10]); examples of system stakeholders are OEMs, passengers, airlines, society, and governmental bodies. As stated previously, the FTGD's vision is used in this work as the source of stakeholders' needs. All the goals listed in the annexes of FTGD are considered to represent needs collected from the various stakeholders, collectively represented by ACARE as unique stakeholder.

As first step, the stakeholder's goals are investigated. When goals are characterized by unclarity and ambiguity, since they do not follow any rule or structure, they are identified as *stakeholder (unvalidated) needs*. To solve the unclarity, it is important to involve the stakeholder(s) and the designer(s) together, in order to ensure that the designer correctly understands what the stakeholder wants from the system (e.g. the ATS in the present paper) (adapted from [11]). This activity is named *validation* [12], and various approaches (e.g. the Quality Function Development [13]) are available in literature to support stakeholder(s) and designer(s) in reaching a common agreement on what the future system of interest should do and how. The needs resulting from the validation are *validated needs*. In this paper, an approach based on the modelling of operational scenarios is proposed. The standard ISO/IEC 29148 defines an operational scenario as a "*description of an imagined sequence of events that includes the* *interaction of the product or service with its environment and users*" [3], where the *product* can be the system under design. Additionally, "[a] scenario describes a system from a user's perspective" [14], showing "*how the proposed system should operate and interact with its users and its external interfaces under a given set of circumstances*" [3]. The scenarios-based method is chosen due to the large agreement in literature that operational scenarios improve the communication between designers and stakeholders (adapted from [15]).The method proposed in the present research is derived and extended from the works done by Liu *et al.* [15] and Gui *et al*. [16]. It aims at identifying the functions that the system should perform based on the interactions between the system and its users (or other systems) given a certain goal. Based on these required functions, additional stakeholder needs can be identified. Therefore, a scenario can be built in order to describe: 1) *when* and *where* the system is operated in order to achieve a specific goal; 2) what are the *pre-conditions* (i.e. states that the system is in at the beginning of each scenario) and the *post-conditions* (i.e. states that the system is in at the conclusion of the scenario); 3) *which users or other systems* interact with the system of interest and *how*. Since this description should enhance the communication between designers and stakeholders, a model-based approach can be adopted; therefore, a scenario model can be created by using a selected modelling language. In this work, the System Modelling Language (SysML) [17] is used, and SysML Sequence Diagrams are created to model operational scenarios.

Afterwards, the validated needs are translated into requirements; requirements are subject to predefined rules and structures in order to be correct, complete, unambiguous and verifiable [4]. Depending on what a requirement states, each requirement can be classified as a specific type of requirements (Figure 1). Requirements can be of "functional" type, when they define what functions have to be performed by the system of interest [11]. "Performance" requirements, instead, define at what level the system has to perform the requested functions [11]. The third and last type of requirement considered in this paper, is the "design (constraint)" requirement, which imposes boundaries to the system, hence limiting the available design space [18].
Depending on the type, the requirements are to follow a predetermined structure, called *pattern*. Requirement patterns are a necessary condition to generate complete requirements. As represented in Figure 1, these patterns prescribe both mandatory and optional elements (the latter included in square brackets) to be included into the requirement text. Additionally, the approach presented in this work creates the text of the requirements by following grammatical and syntactical rules, which are collected in [4].

Functional requirements:

Pattern: The SYSTEM shall [exhibit] FUNCTION [while in CONDITION]

Example: "The aircraft shall provide propulsive power [during the entire mission]"

Performance requirements:

Pattern: The SYSTEM shall FUNCTION with PERFORMANCE [and TIMING upon EVENT TRIGGER] while in CONDITION

Example: "The aircraft shall fly at min Mach 0.8 during cruise"

Design (constraint) requirements:

Pattern: The SYSTEM shall [exhibit] DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION]

Example: "The aircraft shall have technologies with maturity TRL 9"

Figure 1 – Requirement patterns depending on requirement types (adapted from [9])

Finally, each requirement is characterized by a series of attributes, which are additional elements used to support the management of the requirements. A long list of attributes is recommended by INCOSE [4]. In the present work, the following attributes are considered: identification number (ID), parent source (the origin of a requirement), MoC (means used to verify that the designed system is compliant with a specific requirement) and the requirement version.

The approach here described is increasingly applied in various design projects within the aviation sector. The original contribution of the current work is to apply such approach to link a strategic, long-term, sustainable vision to guide the design of the systems belonging to such vision. The next section presents a case study, to exemplify how the approach can be applied.

4. A case study: the sustainable European Future Long-Range Aircraft

The structured approach developed in section 3 is followed here to generate requirements needed for the development of a new, clean-sheet, long-range aircraft. First of all, the rationale for the chosen use case is presented. Then, a preliminary evaluation of FTGD's goals in relation with the selected use case is presented in section 4.2. For the determination of needs, the scenario-method presented in section 3 is applied in section 4.3. From all the identified needs, requirements for the sustainable European Future Long-Range Aircraft (FLRA) are derived and listed in section 4.4.

4.1 Rationale for the selected case study

The approach developed and presented in the section 3 can be applied to the entirety of the ATS. In order to validate such approach in an efficient and effective manner, a part of the entire ATS is selected for this work. Given the area of interest of the authors, the aircraft is chosen as system of interest. This reduces the scope considered, but, given the existing variety of aircraft types and missions, developing generic aircraft needs and requirements is still unmanageable in one study. So, the system of interest is narrowed down further.

As part of the transition to a sustainable aviation in Europe, considerable focus is given towards developing solutions for regional aircraft and for short- and medium-range aircraft, as embodied in the Clean Aviation Joint Undertaking activities [19]. Nonetheless, the majority of emissions is produced by long-range flights [20], for which there appears to be limited R&D activity on-going or upcoming at medium TRL. To fill in this gap and to align with other low TRL activities, the case selected for this current work focuses on the FLRA:

- designed and manufactured in Europe (according to the "Made in Europe" principles and objectives [21]),
- considered for flights within the EU and for flights departing the EU (in line with FTGD),
- with entry into service (EIS) by 2035, in order to meet sustainability targets in 2050.

Such new, clean-sheet, long-range aircraft is to be designed and produced, then operated, and lastly retired, in ways which fit sustainability strategies and approaches (specifically for the aviation sector, but not only), as presented in the vision of FTGD and in line with current and upcoming European and international regulations.

The design of an aircraft has already proven to be a complex process; as past projects, such as the EU-H2020 AGILE [22] and AGILE 4.0 [23] projects, have shown, requirements address multiple stages of the system life cycle, from production, through operation, to maintenance. Such requirements may also come from so-called *enabling systems* (e.g. the manufacturing system). Therefore, already without including sustainability, requirements are manifold and often conflicting. All the above-mentioned sustainability goals and regulations will also result in requirements for the aircraft, throughout its entire life cycle. In order to design the best solutions, the entirety of the requirements must be considered already in the conceptual design stage. The next sections present how MBSE techniques can be applied to support the determination of requirements from stakeholder needs (ACARE's in this case).

4.2 Selection of the FTGD goals

As mentioned earlier, ACARE's vision can be used as blueprint to describe and derive how the ATS, and constituents thereof, shall be designed to belong to a sustainable future, at least from a European perspective. In order to tackle effectively the development of a sustainable ATS and all its constituents, it is essential to unequivocally understand the needs of all involved stakeholders (here represented by ACARE,), and from those needs to derive clear, unambiguous, verifiable, complete and correct requirements. FTGD mentions ([1] page 10) that the goals included in the annexes of the document are detailed and quantitative; this statement can be interpreted as such goals already are requirements for the development of a sustainable ATS. In reality, a review of those goals reveals that the goals are of different quality, with varying level of clarity, and whose quantification is not always indicated, univocal or even possible. In this light, the goals of FTGD can be seen more as an overall representation of the needs of ACARE rather than requirements. Based on this, it is necessary to follow the approach described in section 3, translating the stakeholder needs in validated needs and then in requirements.

In order to derive requirements for the ATS or the FLRA, the goals from the annexes of FTGD are analysed. All goals from Annex A and B are included in the analysis. From Annex C only goals from "Digital transformation" and "Safety, security and resilience" are considered; from "Development, Demonstration and Deployment" only few goals are considered, as the authors deem the majority of the goals in this section to lie primarily beyond the ATS (or the aircraft of interest). Goals from "Education, training and research" are not included in the analysis, as the authors consider all those goals as not applicable to the ATS (or to the aircraft of interest). Annexes D and E do not indicate goals; therefore, no contributions from those annexes are included in the analysis.

From the analysis of the retained goals, it appears that the different goals can be grouped in two categories:

1) goals considered beyond the boundaries of the ATS (and consequently, beyond the boundaries of the aircraft system -FLRA- selected);
2) goals within the boundaries of the ATS (and FLRA) that can be translated in needs towards the ATS (or the FLRA).

The sustainability goals falling into the first category are primarily coming from Annex C. This is an expected outcome, given that in FTGD Annex C includes actors and actions which have been identified as enabling the "Aviation Pillars" (Annexes A and B). Also, some goals from Annex B fall in this category, for example those regarding the energy transition. Examples of goals falling in this first category are:

- By 2030, non-CO_2 climate effects are fully understood, managed, monitored and reduction targets are set inline with the latest scientific understanding and available mitigation solutions (Annex A, page 47).
- In research computing capacity is no longer a limiting issue. Real time simulations including CFD- and FEM-analyses are possible to a level such that both design and off-design performance are being predicted accurately (Annex C, page 55).

Goals belonging to the first category are not transformed into needs, or further into requirements, in the current work. However, the approach proposed in this current work can be applied to those goals and transform them into requirements. Though they are beyond the scope of the current work, it is important that those requirements are generated as they could include additional ATS (or aircraft) requirements. Without those requirements, the ATS (or aircraft) may not fulfil all the sustainability needs, thus fail to be the desired solution.

4.3 From FTGD goals, through scenarios, to ATS and aircraft needs

All goals within the boundaries of the system of interest (i.e. those belonging to the second category identified in section 4.2) can be included in one or more operational scenarios to derive validated needs. These goals are primarily coming from Annexes A and B, and in a smaller proportion from Annex C. As mentioned above, this reflects the structure of FTGD, with Annexes A and B focusing on "Aviation Pillars" actors and actions, while the other annexes covering enablers. Examples of goals falling in the second category are:

- By 2050, net-zero CO_2 emissions has [sic] been achieved for all intra-EU flights and those departing the EU (Annex A, page 47).
- Demonstrate passenger-centric aircraft, including easy access, cabin comfort and baggage handling (Annex C, page 56).

Not all the goals of FTGD's annexes are retained; some goals can be considered as superseded by or linked to goals. For example, a goal targeting 2035 is superseded by the corresponding subsequent 2050 goal. Also, as the current work does not address any specific technology that might contribute to make a new aircraft sustainable, goals which already included a solution have not been considered for the translation into requirements. This choice is deliberate, since the authors suggest an approach that is agnostic, unbiased by any specific solution, hence keeping the space of potential solutions as large as possible. If a generalisation of the goal is possible (based on the content of FTGD), the goal is retained in its generalised text. For example, the following goal is considered:

- By 2035, all aircraft have 100% capability and over 10% make significant regular use (around 50% of the time) of SAF in Europe (Annex B, page 51).

This goal indicates the wish to use SAF (Sustainable Aviation Fuel) as energy source for all aircraft. SAF is a specific solution. FTGD reports the following text at page 23: "These vehicles are powered by a range of fully sustainable fuels and energy sources. [1]" Based on this, the goal mentioned above is combined with other goals also referring to specific sustainable energy sources (hydrogen, etc.) and retained in the following form:

The [air] vehicles are powered by a range of fully sustainable fuels and energy sources (Table 1 B12).

The goals extracted from FTGD are applicable to the entire ATS; in this context and for the purpose of this current work, those goals shall be levelled as needs for the FLRA. To explain this step, the following ACARE's goal is selected from Annex A of the FTGD's vision as example:

- By 2050, net-zero CO_2 emissions has been achieved for all intra-EU flights and those departing the EU (Annex A, page 47).

This goal is generic, not identifying any specific part of the ATS, while hinting towards the aircraft. To ensure that a requirement for the FLRA is derived from this goal, this goal has first to be transformed into a stakeholder need specifically related to the aircraft. This step, from ATS goals to stakeholder (unverified) needs, has to be performed for all goals. The operational scenario-method described in section 3, built to transform stakeholder needs in validated needs, can also support the transition of ATS goals towards the aircraft level. In the specific case of the FTGD, the quality and level of granularity of the goals is such that the authors consider not necessary to apply the scenario-method to all goals. For example, the goal mentioned earlier:

By 2050, net-zero CO_2 emissions have been achieved for all intra-EU flights and those departing the EU.

appears sufficiently clear as a stakeholder need at ATS level. So, given that the system of interest is the FLRA, the following validated need is derived by the authors:

By 2050, the aircraft will not emit net-CO_2 emissions (ID need: N1)

For other goals (for example, the already mentioned B12 in Table 1), the level of clarity and granularity is such that the authors consider the use of scenario essential to determine first stakeholder needs, and then validated needs. In this paper, the scenario-method is detailed for one example, but, as already mentioned, the same process can be applied to all goals, when necessary. The example chosen is composed by the following FTGD's goals:

- 90% of travellers within Europe are able to complete their journey in less than four hours (Annex A, page 48);
- 90% of freight within Europe is able to complete the journey, seamlessly, in less than four hours (Annex A, page 48).

Those goals can be summarised by the stakeholder need of:

90% of travellers and freight within Europe are able to complete their journey, seamlessly, in less than four hours.

This stakeholder need is open to many assumptions, for example regarding the moments which the duration of four hours is determined upon. To clarify the need, an operational scenario is built. The scenario represents the journey of one passenger and its luggage within Europe, in a mixed mobility system of which the FLRA covers one segment of the journey. Despite the boundary of a journey within Europe, the FLRA is still included as an option, as in the future it could well be that what is now considered long-range air vehicle (as used only for long distance trips due to mainly economic reasons in terms of load factor) may become an option for intra-EU flight (e.g. in case of a hub-to-hub network model, combined with local air mobility, or in case of less frequent flights requiring larger passenger capacity).
The scenario in which completing the journey within four hours is considered possible, identifies the so-called *nominal* scenario; in the *off-nominal* scenarios, the journey cannot be completed within the four hours target because of *disturbances* on the system of interest (e.g. some aircraft failure might hamper the punctuality of the scheduled flight). By representing each step of the passenger's journey and the actions involved in both nominal and off-nominal scenarios, it is possible to identify the impact and influence that a wide range of activities may have on the air leg of the journey. A visual

representation of the scenario in SysML is presented in Figure 2.

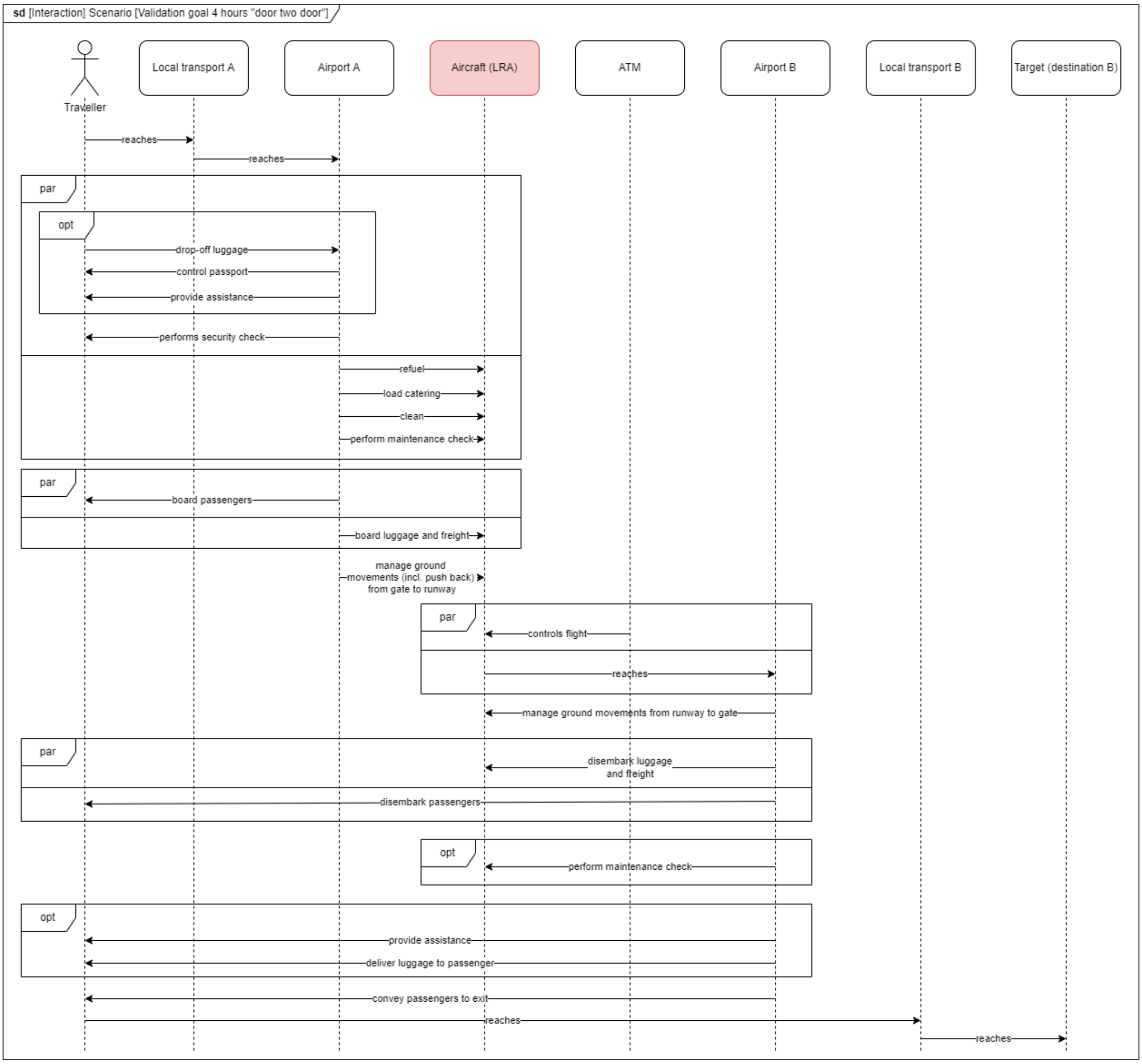

Figure 2 – SysML Sequence Diagram modeling the ooperational scenario for the goal relative to the journey within four hours

By modelling the role of the various actors (e.g. traveller) and agents (e.g. airport) in the scenario, it is possible to identify what characteristics and requirements each agent and actor involved must have to achieve the designated target. The off-nominal scenarios enable the identification of risks towards achieving the designated goal.

The visualisation of the operational scenario chosen presents a traveller departing from a generic point, which is assumed determining the start of the four hours journey. The traveller has to reach the airport by local transport and then proceed through tasks such as the drop-off of the baggage, the security check and the emigration procedure, as applicable according to the destination; also, the traveller may require assistance at the airport. While the traveller undergoes those steps, the aircraft needs to be prepared for the flight. The aircraft needs to be refuelled, maintenance checks performed, and the cabin cleaned and the catering brought onboard. While the traveller boards the aircraft, the luggage (and eventual freight) needs to be loaded on the aircraft. Once ready, the aircraft needs to taxi to its departure runway. In flight the aircraft performs the assigned flight route. Upon landing, the aircraft needs to reach is assigned gate and then passengers, baggage and freight are to be offloaded. The traveller collects the luggage and performs eventual security or immigration tasks, before reaching the local transport for the last leg of the journey to the destination.

The scenario-method used allows to clearly list and make visible the activities and tasks of all agents

and actors involved. Based on such overview, ideas that may ensure a four hours journey can be proposed; for example, multitasking, parallelization, increase speed of execution, or avoid activities. Some of those ideas involve ATM or airport operations, but some involve the aircraft. Those may require the air vehicle to be designed towards, for example, ensuring more efficient boarding and disembarkation processes. Those ideas can be formalised as validated needs.
For the example considered and based only on the expertise of the authors, some of the aircraft validated needs that can be identified from the considered operational scenario are:

- *The aircraft has to be ready (prepared) on time before departure;*
    - *The aircraft has to avoid delays due to failures;*
    - *The aircraft has to allow quick and organized boarding/deboarding of passengers, luggage and freight;*
    - *The aircraft has to allow refuelling/recharging within a specified amount of time;*
- *The aircraft has to support faster and/or longer pushback/assisted taxiing operations;*
- *The aircraft has to have navigation equipment to follow the shortest/fastest route to destination*.

This list is not comprehensive of all the needs which can be generated by the operational scenario for the selected stakeholder need; it is meant only to explicate the methodology used. The list clearly highlights how multiple validated needs can be derived from each goal and from each stakeholder need. This also supports the statement made earlier in this paper that both the goals that were not retained as beyond the boundaries of the system of interest, and the goals which were not brought in the scenario-method right now, could generate more needs. The authors suggest to perform a comprehensive extraction of the needs as future work.
Table 1 collects the goals extracted from FTGD and the derived validated needs for the FLRA. The goals which are tackled by the scenario-method are indicated by * in Table 1.

4.4 From needs to aircraft requirements

In this section, the validated needs indicated in Table 1 are translated into requirements following the approach derived from INCOSE and furtherly developed in AGILE 4.0 project, and presented in section 3. One example is presented in this paper, but all requirements derived from the validated needs are reported, too.
Following on the example mentioned in section 4.3, the validated need presented generates two performance requirements, stating that the system (i.e. the aircraft) shall perform the function of emitting CO_2 emissions with a performance (i.e. maximum 0 kg), respectively in two conditions, i.e. on ground (first requirement with ID: ReqAC_p10) and in flight (second requirement with ID: ReqAC_p20). The two derived requirements are written below. It should be noted that the time constraint specified in the need N1 (i.e. by 2050) is omitted in the two requirements, since the designed aircraft has an EIS of 2035, and therefore will be operated before 2050, satisfying the time constraint of the need.

ReqAC_p10: *The aircraft shall emit CO_2 net emissions of maximum 0 kg while on ground*

ReqAC_p20: *The aircraft shall emit CO_2 net emissions of maximum 0 kg while in flight*

Table 2 lists all requirements derived from the validated needs of Table 1. The text of the requirements is written by following the patterns previously described and following all the grammatical and syntactical rules recommended in [4]. Finally, the requirements are completed by a series of attributes supporting their management: the ID, the type, the MoC used to verify the requirements, and the parent (need).

Table 1 – Goals derived from the FTGD that can be translated in needs towards the FLRA

ID Goal	Text from FTGD	Need for the aircraft of interest	ID Need
A4	By 2050, net-zero CO_2 emissions has been achieved for all intra-EU flights and those departing the EU	By 2050, the aircraft will not emit net-CO_2 emissions	N1
A5	By 2050 new technologies and operational procedures in service result in a 90% reduction in NOx emissions from all intra-EU flights and those departing the EU relative to the year 2000	By 2050, the aircraft will emit 10% of the NOx emissions compared to the 2000 baseline	N2
A6	By 2050 new technologies and operational procedures in service result in a 90% reduction in non-volatile particulate matter (nvPM) emissions from all intra-EU flights and those departing the EU relative to the year 2000	By 2050, the aircraft will emit 10% of the nvPM emissions compared to the 2000 baseline	N3
A7	By 2050 new technologies and operational procedures in service result in a 90% reduction in warming contrail cirrus relative to the 2000 baseline	By 2050, the aircraft operations will cause only 10% of contrails compared to the 2000 baseline	N4
A8	By 2050 new technologies, fuels and operational procedures reduce the climate impact of CO_2 and non-CO_2 effects of all intra-EU flights and those departing the EU by 90% relative to the year 2000.	The aircraft in operation/flight needs to have 90% reduction on the climate impact of CO_2 and non-CO_2 effects compared to the year 2000	N5
A12	By 2030, all airports have carried out an assessment of the best trade-off between noise exposure and emissions reductions in order to implement the most efficient Noise Abatement Departure Procedure(s)	The aircraft will be able to fulfil the current Noise Abatement Departure procedures	N6
A14	A policy framework is established and applied, comprising metrics and calculation techniques for predicting, measuring and setting standards for the health, social, environmental, climate and other impacts of air transport, such as noise and local air quality, and enforcing compliance	The aircraft will be able to record and provide all the data necessary for measuring the impact of its operations	N7
A16* - A17*	90% of travellers and freight within Europe are able to complete their journey in less than four hours[1]	The aircraft has to be ready on time before departure	N8
		The aircraft has to avoid delays due to failure	N9
		The aircraft has to allow quick and organized boarding/deboarding of passengers, luggage and freight	N10
		The aircraft has to allow refuelling/recharging within a specified amount of time	N11
		The aircraft has to support faster and/or longer pushback/assisted taxiing operations	N12
		The aircraft has to have navigation equipment to follow the fastest route to destination	N13
A18*	Air transport is an integrated component of the overall mobility system that is resilient to and automatically reconfigurable against disruptive events so that the traveller or cargo has a 95% probability of completing the journey on-time	The aircraft will operate its schedule in coordination with other means of transport	N14
		The aircraft will use traffic management system common with other means of transport	N15
A19	By 2050 technologies, operational improvements and noise abatement procedures reduce the perceived noise emission of flying aircraft by 65% per operation relative to the 2000 baseline	The aircraft needs to reduce the perceived noise emission when flying by 65% per operation/flight relative to the 2000 baseline.	N16
A21	Operational noise abatement procedures are applied so that for Continues Descent Operations (CDO), relative to 2019 baseline, there is a 90% of reduction in average time in level flight by 2050 in Europe	The aircraft needs to be able to sustain continuous descent operations	N17
A24	By 2035 Zero Emission air vehicles are starting to be deployed across Europe	The aircraft will have an EIS 2035	N18
A26	By 2050, compared to 2022 there is a 30% increase in cost competitiveness of “Made in Europe” aviation technology, products and services throughout the supply chain achieved by streamlining systems engineering, design, manufacturing and upgrade, enhancing technology and people capabilities, and improving process efficiency	The aircraft needs to be 30% more cost competitive compared to the 2022 true cost	N19
A27	By 2050, there is a 50% reduction in the cost of certification, enabled by enhanced digital capabilities and new standards	The certification cost of the aircraft will be reduced of 50%	N20
B12*	The [air] vehicles are powered by a range of fully sustainable fuels and energy sources[1]	The aircraft will operate with any available sustainable energy source	N21
B16	By 2050, overall European fleet fuel efficiency will have improved by between 30% and 50% compared to 2018 levels	The aircraft will have at least 30% energy efficiency compared to 2018 levels	N22
B17	By 2050, air vehicles, their propulsion systems and the energy sources they utilise will be designed using circularity principles, facilitated by ecodesign, with transparency and traceability from production, operation to end-of-life	The aircraft will be designed using circularity principles	N23
		The aircraft will be designed according to ecodesign principles	N24
B22	By 2030 operational fuel efficiency has improved by at least 5% compared to 2018 due to optimized flight trajectories and flight operations. This includes the benefit of minimised aircraft movements on-ground and reduced engine/electric taxi	The aircraft needs to be able to operate in-flight with energy efficient operations	N25
		The aircraft needs to operate on ground with limited to no noise	N26
B24	All flights are planned with the ability to re-plan dynamically en-route, to climate optimized routes eliminating adverse environmental and minimizing social impact, such as emissions and noise	The aircraft will be able to change route in real-time	N27
B25	All air vehicles have access to ground infrastructure optimised for their operation, multimodality and passenger experience. Coherent ground infrastructure has been developed including airports, vertiports and heliports with the relevant servicing and connecting facilities to other modes (incl. baggage handling and integrated security)	The aircraft will fit the ground infrastructures of the airport	N28
B31	By 2050, airports and other aviation infrastructure operate with zero emissions	The aircraft will fit airports and other aviation infrastructure operating with zero emissions	N29
C2	There are no successful cyber-attacks on aircraft and critical aviation infrastructure	The aircraft needs to resist to cyber-attacks	N30
C3	European aviation is using the new EU digital backbone and design standards, enabling researchers, the supply chain and the OEMs to validate via digital twins the end-to-end viability and impact of European Aircraft	The aircraft needs to have a digital twin/thread/product passport.	N31
C12*	Demonstrate passenger-centric aircraft, including easy access, cabin comfort and baggage handling	The aircraft will allow passenger to board, sit and move around with ease, in respect of age and different physical abilities	N32
		The aircraft will have sufficient in-cabin baggage storage for all the passengers	N33
C24	Levels of safety have increased by a factor of five compared to 2020	The aircraft needs to be 5 times safer than in 2020	N34

[1] This text has been rephrased from [1]

Table 2 – List of requirements of the sustainable FLRA.

ID	Requirement	Type	Means of Compliance	Parent
ReqAC_f10	The aircraft shall record impact data	Functional	by design	N7
ReqAC_f20	The aircraft shall provide impact data	Functional	by design	N7
ReqAC_f30	The aircraft shall operate with energy efficient operations while in flight	Functional	by design	N25
ReqAC_f40	The aircraft shall resist to cyber-attacks	Functional	by design	N30
ReqAC_f50	The aircraft shall allow rerouting dynamically	Functional	by design	N14
ReqAC_f60	The aircraft shall operate in zero-emission airports	Functional	by design	N29
ReqAC_f70	The aircraft shall fulfil current Noise Abatement Departure procedures	Functional	by design	N6
ReqAC_f80	The aircraft shall sustain continuous descent operations	Functional	by design	N17
ReqAC_p10	The aircraft shall emit CO_2 net emissions of maximum 0 kg while on ground	Performance	by simulation/analysis	N1, N5, N12
ReqAC_p20	The aircraft shall emit CO_2 net emissions of maximum 0 kg while in flight	Performance	by simulation/analysis	N1, N5
ReqAC_p30	The aircraft shall emit NOx emissions of max TBD kg while in any condition	Performance	by simulation/analysis	N2, N5, N12
ReqAC_p40	The aircraft shall emit nvPM emissions of max TBD kg while in any condition	Performance	by simulation/analysis	N3, N5, N12
ReqAC_p50	The aircraft shall emit contrail emissions of max TBD kg while in flight	Performance	by simulation/analysis	N4, N5
ReqAC_p60	The aircraft shall emit perceived noise of max TBD dB while in flight	Performance	by simulation/analysis	N16
ReqAC_p65	The aircraft shall emit perceived noise of max TBD dB while on ground	Performance	by simulation/analysis	N12, N16, N26
ReqAC_p70	The aircraft shall consume energy per 1 kg of payload per 1 km of range of max TBD J/kg/km while in flight	Performance	by simulation/analysis	N22
ReqAC_p80	The aircraft shall change route within max TBD seconds while in flight	Performance	by simulation/analysis	N27
ReqAC_p90	The aircraft shall refuel/recharge in max TBD minutes on ground	Performance	by simulation/analysis	N11
ReqAC_p100	The aircraft shall perform pushback in max TBD minutes on ground	Performance	by simulation/analysis	N12
ReqAC_d10	The aircraft shall have an EIS of maximum 2035	Design (constraint)	by design	N18
ReqAC_d20	The aircraft shall have a true cost of max TBD $	Design (constraint)	by simulation/analysis	N19
ReqAC_d30	The aircraft shall have a certification cost of max TBD $	Design (constraint)	by simulation/analysis	N20
ReqAC_d40	The aircraft shall exhibit circular characteristics	Design (constraint)	by design	N23
ReqAC_d50	The aircraft shall exhibit ecodesign characteristics	Design (constraint)	by design	N24
ReqAC_d60	The aircraft shall make use of fully sustainable energy sources	Design (constraint)	by design	N21
ReqAC_d70	The aircraft shall have a wingspan of max TDB m	Design (constraint)	by simulation/analysis	N28
ReqAC_d80	The aircraft shall have a digital twin	Design (constraint)	by design	N31
ReqAC_d90	The aircraft shall have a number of catastrophic failures rate of max TBD per flight hour	Design (constraint)	by simulation/analysis	N34
ReqAC_d100	The aircraft shall have a turn around time of max TBD minutes	Design (constraint)	by simulation/analysis	N8, N10
ReqAC_d110	The aircraft shall have a failures rate of max TBD failures per flight hour	Design (constraint)	by simulation/analysis	N9
ReqAC_d120	The aircraft shall have equipment to fly the fastest route	Design (constraint)	by design	N13
ReqAC_d130	The aircraft shall have traffic management equipment common to other means of transport	Design (constraint)	by design	N15
ReqAC_d140	The aircraft shall have an aisle width of min TBD m	Design (constraint)	by design	N32
ReqAC_d150	The aircraft shall have a baggage storage in cabin with volume of min TBD m3	Design (constraint)	by design	N33

5. Discussion

Past projects (e.g. AGILE 4.0) demonstrate how listing requirements following a structured approach improves the aircraft design process. The requirements generated in those projects and those used currently focus on technical or on quantifiable aspects (such as Mach number or the number of passengers); they are generally identified as top-level aircraft requirements (TLAR), and they are hereafter indicated as “traditional” requirements. Traditional requirements cover operation, production and, to a lesser extent, other life cycle phases of an aircraft. Some of the traditional requirements are already stemming from sustainability considerations and targets, as, for example, the requirement to utilise electric propulsion systems. Currently, the approach to incorporate requirements generated from sustainability considerations is to add them to the traditional requirements, while giving those latter still higher relevance. This translates in imposing additional constraints on an already constraint design space. By deriving requirements from the objective of sustainability itself, the design space remains open to really innovative solutions, solutions that could meet more sustainability requirements, including those stemming from social aspects, which tend to be downplayed at the moment.

When looking at the requirements derived, it is possible to notice that at times traditional requirements and sustainability requirements are the same (e.g. the aircraft shall operate with energy efficient operations while in flight). In other cases, sustainability requirements complement traditional requirements, by expanding the list of requirements to fulfil (e.g. the aircraft shall be designed according to circularity principles). It can be foreseen that in some cases traditional and sustainability requirements may appear difficult to fulfil simultaneously (e.g. the aircraft shall have an EIS of maximum 2035). In the first two cases, the new set of requirements, resulting from the combination of the sustainability and traditional requirements, can be used in the following design activities. The third case indicates the challenges which the R&D community (and the aviation sector) need to resolve for a transition to an ATS as sustainable as possible.

Fundamental for sustainability is its systemic and holistic character. This means that an aircraft cannot be defined as sustainable unless the system it operates within and all its enabling systems (e.g. manufacturing) are also sustainable. This implies that the sustainability objective cannot possibly be fulfilled by the aircraft alone. It has been mentioned how, among the goals of FTGD, some refer to enabling systems. As identified in AGILE4.0, needs and requirements of enabling systems can have an influence on the system of interest [24]; for this reason, those needs and requirements need to be accounted for in the system of interest. The determination of those needs and requirements relies on the knowledge of experts of the enabling systems; therefore, it is not possible to derive such needs and requirements in this work. Some examples of enabling system goals are presented in Table 1, together with examples of needs for the aircraft of interest (e.g. Table1, C3). When no need could be identified based on the knowledge of the authors, the goals have not been included in Table 1, highlighting a limitation of the proposed approach: the completeness of the goals.

Though the list of the goals from FTGD is already extensive, it is far from complete. Many other aspects that can have an impact on the aircraft design are missing, such as dependency on import of critical materials. As already mentioned, some missing needs could be identified from those derived from the goals targeting aspects beyond the FLRA; others from needs of enabling systems mentioned above. Finally, more needs could have been derived by implementing the scenario approach from the very beginning, when collecting the stakeholder (ACARE and its members) goals and expectations. It is clear that some goals presented in the FTGD annexes hint towards embodying needs (and requirements) which are currently not explicated. Unfortunately, the level of unclarity of some goals is such that a translation of the goals into needs and, afterwards, into requirements simply based on the expertise of the authors is not possible. By implementing the structured process and the scenario-method described in section 3, and by involving a broader group of experts, more comprehensive sustainability requirements can be determined.

Last, a major criticism to the aviation sector is that the current and planned effort for the transition to a sustainable aviation are not sufficient. By writing requirements in this structured approach, it is possible to align the requirements with the highest-level objective and verify whether the goals are complete and sufficient towards such objective. For example, ACARE's high level objective is to achieve a climate neutral aviation by 2050. When the requirements on emissions are listed, it can be seen that the corresponding ACARE's needs (and requirements) are not sufficient towards a climate neutral aviation, as addressing 100% of CO_2 emissions but only 90% of other types of emissions, and not including all emissions known to have impacts on the climate. To address this discrepancy, the proposed approach can be applied starting from the highest-level objective of FTGD at ATS level, and then cascaded down to needs and requirements for each system of the ATS and further, within each subsystem, down to the lowest level of granularity necessary to be considered towards the highest level FTGD's goals.

6. Conclusions and next steps

The current work presents an approach to derive requirements addressing sustainability from the FTGD' visions that can be included in future aircraft design activities. In particular, those requirements aim to represent the functionalities and constraints that the FLRA must fulfil in order to be considered sustainable and to operate within a sustainable air transport system.

As the structured approach is based on Systems Engineering, it can be applied to the overall ATS and to each system of the ATS. Originating from this work, next steps can be:

- Initiate the design of the FLRA system according to the derived high-level requirements, by generating more detailed, lower level requirements, including proposing MoC for the verification of the requirements;

- Follow the same structured approach, starting from FTGD's goals and arriving to requirements, for the design of other sustainable aircraft types;
- Propose roadmaps and strategies based on identified gaps in FTGD's goals in order to towards fulfilling those gaps and achieving the FTGD's goals;
- Derive needs and requirements for a sustainable ATS from sources other than FTGD by using the same proposed structured approach.

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8. Copyright Statement

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