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# System of Systems Architectural Design of On-Demand Electric Aviation Based on Mission Analysis

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**Abstract**— System of systems engineering (SoS) approaches are required for the architectural design of complex systems. In this paper, we propose an approach for the architectural design of SoS based on the mission profile modeling and analysis. The mission profile is decomposed to operations and the operations are mathematically modeled. This approach is applied to a case study of on-demand electric aviation system, for the evaluation of the different alternatives at the SoS mission level. Results show that using mathematical modeling and Multidisciplinary Design Analysis (MDA) facilitate the exploration of the different alternatives of SoS architectures. This helps SoS architects in making strategic decisions for the choice of best solutions in conceptual level.

**Keywords**—*SoS architecture; MDA; On-Demand Electric Aviation*

## I. INTRODUCTION

Several works are currently on going to study the possibility of wide use of on-demand aviation. For instance, Uber defines on-demand aviation as a network of small aircrafts that would make it possible for users to summon flying transport whenever they want to easily get around within and between cities. The feasibility study of such a project requires system of systems engineering approaches to optimize the network of various interacting legacy and new aircraft concepts brought together to satisfy multiple objectives of the on-demand aviation.

In this paper, we present an approach for the design of SoS architectures allowing the integrated analysis of the SoS mission profile with the operational capabilities at the system level. After presenting the evaluation process, a case study of on-demand electric aircrafts is considered to illustrate the efficiency of the method.

The rest of the paper is organized as following: a state of the art is considered in the next section. Then, the proposed approach and the case study are presented in section three. Finally, the paper ends with a conclusion and some perspectives.

## II. State of art

Systems of systems (SoS) are defined as large-scale concurrent and distributed systems that are comprised of complex systems [1]. System of Systems Engineering (SoSE) engages a complex and holistic problem space, including organizational, managerial, policy, human/social, and political dimensions that exist in conditions of emergence, ambiguity,

and uncertainty [2]. Compared to classical systems engineering (SE), SoSE focuses on the autonomy of the systems making the SoS and their interoperability to accomplish the SoS missions more efficiently. The component systems of an SoS can operate independently to produce products or services satisfying their customer objectives. The SoS may connect systems through interoperability arrangements that do not require tight coupling or strong integrations [3]. This, in turn, leads to the attribute that an SoS maintains its inherent operational character even as system components join or disengage from the SoS.

One of the critical decisions in SoSE is the SoS architectural design, which process starts with analysis of needs, proceeds with solution synthesis, and completes with evaluation of the solution to meet the stated needs [4].

The evaluation of SoS architectures is a real challenge for SoS architect. Indeed, the complexity lies in the development of models allowing not all the evaluation of autonomous complex systems, but also the evaluation of the missions performed by a set of interoperating complex systems.

The literature shows that several techniques have been developed in recent years for the design and evaluation of system architectures. For instance, authors in [6] suggested a SysML-based approach for complex systems architectural design. In addition, authors in [7] proposed to use multi-agent methodology for the multi-level modeling of complex systems.

In SoS engineering, a mission is an important information that can guide the entire SoS development process. The literature provides some proposals that focus on SoS mission. For example, a language for SoS mission description has been developed in [8] to organize the mission-related information in a set of complementary models.

Multidisciplinary Design Analysis (MDA) is a field of research that studies the application of numerical techniques to the design of engineering systems involving multiple disciplines or components. MDA software tools usually integrate several optimization algorithms for the multidisciplinary design optimization. Thus, this engineering field is also known as MDO or MDAO [9].

Despite its wide use in various fields of engineering [10, 11], MDA is little used for SoS architectural design. Through the mission profile analysis of On-Demand Electric Aviation (ODEA), we illustrate in this paper the contribution of using MDA in the SoS architectural design.

### III. CASES STUDY OF MISSION PROFILE ANALYSIS FOR ON-DEMAND ELECTRIC AVIATION

Every day, millions of hours are wasted on the road worldwide by citizens in cities to travel between home and work. On-demand aviation, has the potential to radically improve urban mobility, giving people back time lost in their daily commutes. Some companies, such as Uber [5], are now studying the idea to develop networks of small, electric aircrafts to enable rapid and reliable transportation between suburbs and cities and, ultimately, within cities. The electric propulsion systems are less noisy, compared to helicopters, and they have very reduced operational emissions. Safety can also be improved by the technology of autonomy to significantly reduce operator error [5].

The development of an infrastructure to support an urban on-demand electric aviation will likely have a significant cost advantages over heavy-infrastructure approaches such as roads, rails, bridges and tunnels. Multiple takeoff and landing pads, as well as charging infrastructure, could be developed on tops of parking garages, existing helipads, and even unused land surrounding highway interchanges.

The development of the network of small electric aircrafts with the corresponding infrastructure requires SoSE approaches to integrate systems into a systems of systems that ultimately contribute to the evolution of the overall SoS architecture. Indeed, the choice of the exact configurations for the electric aircraft can be impacted by the choice of the infrastructure architecture, and vice-versa. Therefore, any viable configuration for the electric small aircrafts should be duly considered.

The development phase process of SoS architecture is adopted from [3] as following:

1. **SoS goals:** to define the SoS business objectives that drive the SoS mission.
2. **SoS services:** to define the operational capabilities required to achieve the SoS goals.
3. **System services:** to define the operational capabilities needed to achieve the SoS services.
4. **System behavior:** to define the functional capabilities needed to achieve the system services.
5. **Subsystem behavior:** to define the functional capabilities needed to achieve the system behavior.

The paper scope does not allow to detail all the SoS features. However, to illustrate this process with the case of the on-demand aviation system we will be limited to only some features as following:

1. **SoS goals:** provide a fast, economical, ecological, intelligent, reliable and safe transportation system.
2. **SoS services:** the operational capabilities to achieve the SoS goals concern the services required by interoperating the SoS components: the vehicles, the infrastructure and operations system, the rider experience and the economics.
3. **System services:** every SoS component system is considered as dependent interoperable system. For

instance, the vehicle services are defined with the operational capabilities to respect safety requirements, noise, emissions and vehicle performances. The infrastructure and operations system services are concerned about the way heliports and helistops locations will be chosen. They are also concerned about how and where the aircrafts will be charged.

4. **System behavior:** The functional capabilities needed to achieve the system services depend on the system components of the SoS. For the vehicles for example, the functional capabilities represent the operations to be carried out by the vehicles: take-off, cruise, hover, landing, etc.
5. **Subsystem behavior:** Taking as an example the vehicle subsystems behavior, the functional capabilities required to achieve the system behavior are related to the energy source (battery) capability, the rotors capabilities, the wings capabilities, etc.

The verification process for SoS architectures is based on the definition of measures of merits (MOMs) [3]:

1. SoS goals: Measure of policy effectiveness (MOPEs), to measure how well are the policy objectives that drive the SoS level mission being met.
2. SoS services: Measures of Service Effectiveness (MOSEs), to measure how well does the SoS level performs the SoS mission.
3. System services: Measure of Service Effectiveness (MOEs), to measure how well the system performs the system mission.
4. System behavior: Measures of Performances (MOPs), to measure the attributes or properties of system behavior.

As a measure of service effectiveness (MOSEs) we can consider metrics like travel range, maximum required power during travel and total required energy.

The Measure of Service Effectiveness (MOEs) for vehicles depends on the electric aircraft concept to be used. Indeed, several configurations could be studied. Therefore, the network of electric aircrafts could be composed either of a unique class of aircrafts or of a mixture of the following three known classes:

- The ROTORCRAFT class: which concerns the multirotor aircrafts such as drones and helicopters.
- The VTOL class: or Vertical Takeoff and Landing configuration which is a short-winged architecture with rotors for vertical takeoff and landing.
- The USTOL class: or Ultra Short Takeoff and Landing, which is a winged aircraft that uses the advantage of Propulsion Airframe Interaction (PAI) concept to leverage the distributed electric propulsion to take-off and landing in a very short distance.

Mathematical modeling is used to define evaluation models for the mission profiles of the three classes of electric aircrafts (Rotor, Votl and Ustol). Interoperating these models using MDA technique allows us to analyze several mission profiles combing different aircraft classes.

The mission profile of an aircraft can be defined with the following operations: take-off, cruise, hover, reserve flight and landing, as indicated in Fig.1.

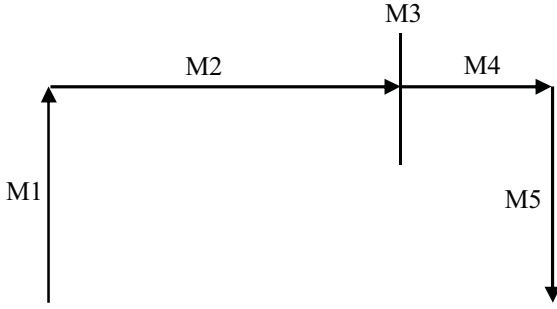


Fig. 1. Electric aircraft mission profile

Table 1 summarizes the operations that could be performed by the three classes of aircrafts.

TABLE I. LIST OF AIRCRAFT OPERATIONS

Operations	Aircraft classes		
	Rotorcraft	Vtol	Ustol
M1	Vertical take-off	Vertical take-off	Short distance take-off
M2	Cruise	Cruise	Cruise
M3	Hover	Hover	Not considered
M4	Reserve	Reserve	Reserve
M5	Vertical landing	Vertical Landing	Short distance landing

As indicated in Table 1, the hover operation is not taken into consideration for the *Ustol* configuration.

For the mathematical modeling of mission profiles, a set of mission common parameters and values is required to the evaluation of the different aircraft configurations. These common parameters and values are given in Table II.

TABLE II. LIST OF MISSION COMMON PARAMETERS AND VALUES

Mission common parameters	Value	unit	Description
	$H_c$	300	$m$
$\rho_a$	1.225	$kg/m^3$	Air density
$g$	9.81	$m/s^2$	Acceleration of gravity
$V_c$	240	$km/h$	Cruise velocity
$\eta$	0.85	-	Global propulsion efficiency
$FOM$	0.7	-	Factor of Merit
$\rho_b$	150	$Wh/kg$	Battery density
$M_{lp}$	100	$kg$	Mass of one passenger with baggage
$N_p$	1 to 4	-	Number of passengers per vehicle

The evaluation of every operation of the mission profile requires also to define a set of local parameters related to each operation. The operations parameters are given in Table 3.

TABLE III. LIST OF OPERATIONS PARAMETERS

Operations Parameters	unit	Description
	$t_i$	$s$
$d_i$	$m$	Distance of the operation
$v_i$	$m/s$	Mean velocity during the operation
$F_i$	$N$	Thrust/Drag required for the operation
$E_i$	$kJ$	Required energy
$P_i$	$kW$	Required power
$\rho_{bi}$	$Wh/kg$	Required energy density
$M_{bi}$	$kg$	Battery mass required for the operation

The set of equations relating these parameters is given by the following four equations:

$$v_i = \frac{d_i}{t_i} \quad (1)$$

$$E_i = P_i \cdot t_i \quad (2)$$

$$M_{bi} = \frac{E_i}{\rho_b} \quad (3)$$

$$\rho_{bi} = \frac{E_i}{M_t} \quad (4)$$

The aerodynamic behavior of the three configurations depends on four parameters as defined in the Table 4.

TABLE IV. LIST OF AERODYNAMIC PARAMETERS

Vehicle Class	Lift to drag ratio in take-off and landing $C_m$	Lift to drag ratio in cruise $C_c$	Disk Loading DL ( $kg/m^2$ )	Thrust to Drag Ratio $R_{tw}$ (T/Mt.g)
Rotor	4.25	4.25	22	1.15
Vtol	7.5	10	73.2	1.15
Ustol	17.5	15		0.34

The required energy density for every operation is calculated using the following five equations:

$$\rho_{b1} = \frac{g \cdot d_1 + \frac{v_1^2}{2} + \left(\frac{g}{C_m}\right) \cdot d_1}{\eta} \quad (5)$$

$$\rho_{b2} = \frac{1}{2} \cdot v_2^2 + \left(\frac{g}{C_c}\right) \cdot d_2 \quad (6)$$

$$\rho_{b3} = g \cdot \left(\frac{DL}{2 \cdot Rho_a}\right)^{0.5} \cdot t_3 \cdot FOM \quad (7)$$

$$\rho_{b4} = \frac{v_4^2}{2} + \left(\frac{g}{C_c}\right) \cdot d_4 \quad (8)$$

$$\rho_{b5} = \frac{\frac{v_5^2}{2} + \left(\frac{g}{C_m}\right) \cdot d_5}{nu} \quad (9)$$

Combing equations (4) and (5), the battery mass required for every operation is given by:

$$M_{bi} = \frac{\rho_{bi}}{\rho_b} \cdot M_t \quad (10)$$

The total battery mass is calculated with:

$$M_b = \sum_{i=1}^5 M_{bi} \quad (11)$$

The total vehicle mass  $M_t$  is calculated as the sum of the battery mass ( $M_b$ ), the passengers mass ( $M_p$ ) and the empty vehicle mass ( $M_a$ ):

$$M_t = M_p + M_b + M_a \quad (12)$$

The empty vehicle mass  $M_a$  is determined as a fraction of the total mass  $M_t$ .

The maximum power is calculated with:

$$P_{max} = \max(P_i); 1 \leq i \leq 5 \quad (13)$$

The previous equations were easily programmed using Excel software.

Figure 2 shows the results of the range variation effect on the total mass and the maximum power for the Rotor configuration with one passenger.

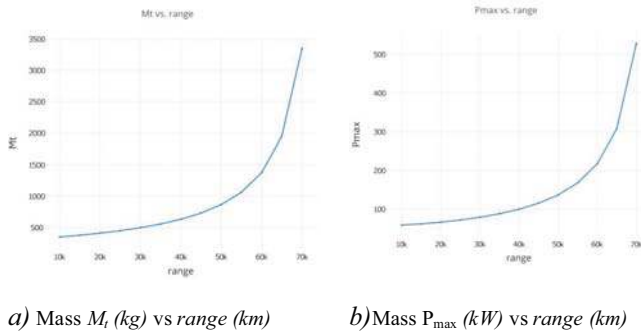
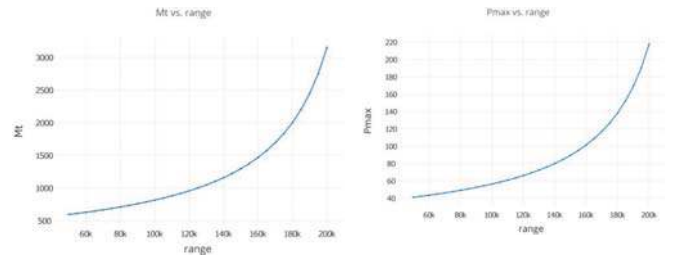


Fig. 2. Rotor configuration: simulation results for one passenger ( $N_p=1$ )

The results show that for a range between 10 and 50 km, the total mass  $M_t$  varies between 400 and 900 kg and the maximum power  $P_{max}$  varies between 50 and 150 kW. However, for ranges greater than 50 km, the variation of  $M_t$  and  $P_{max}$  are higher.

Figure 3 shows the results of the range variation effect on the total mass and the maximum power for the Vtol configuration with two passengers.



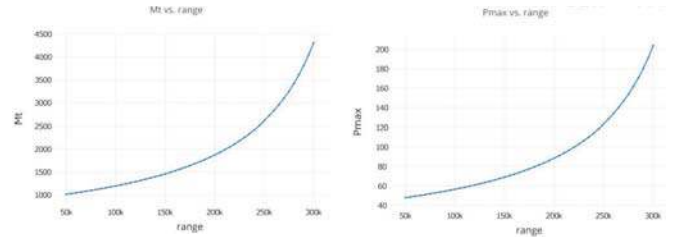
c)  $M_t$  (kg) vs range (km)

d)  $P_{max}$  (kW) vs range (km)

Fig. 3. Vtol configuration: simulation results for two passengers ( $N_p=2$ )

The results show that for a range between 50 and 160 km, the total mass  $M_t$  varies between 600 and 1500 kg and the maximum power  $P_{max}$  varies between 50 and 100 kW. However, for ranges greater than 160 km, the variation of  $M_t$  and  $P_{max}$  are higher.

Figure 4 shows the results of the range variation effect on the total mass and the maximum power for the Ustol configuration with four passengers.



e)  $M_t$  (kg) vs range (km)

f)  $P_{max}$  (kW) vs range (km)

Fig. 4. Ustol configuration: simulation results for four passengers ( $N_p=4$ )

The results show that for a range between 50 and 250 km, the total mass  $M_t$  varies between 1000 and 2500 kg and the maximum power  $P_{max}$  varies between 50 and 120 kW. However, for ranges greater than 250 km, the variation of  $M_t$  and  $P_{max}$  are higher.

For the SoS level evaluation, the developed Excel components for every aircraft class were implemented in an MDA software tool, ModelCenter® of Phoenix Integration, in order to be able to analyze all the possible interactions between the vehicles at the SoS level.

For illustration, we consider the case-study of the travelling scenario using ROTOR concept with USTOL concept.

Figure 5 shows the implementation of the SoS evaluation level using the MDA software tool.

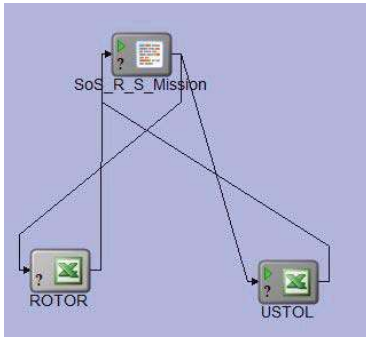


Fig. 5. MDA implementation for the evaluation of the travelling missions at SoS level

The SoS mission is evaluated using the interaction between ROTOR and USTOL components to calculate the total energy used in kWh.

Figure 6 shows the results of variation of the total energy as a function of the ranges performed with the two configurations Rotor (one passenger) and Ustol (four passengers).

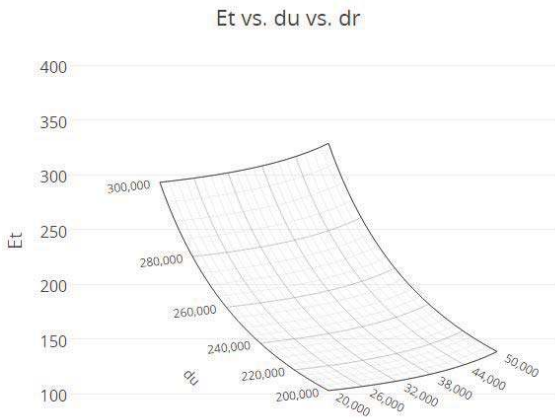


Fig. 6. Variation of the total energy in kWh of a mission performed by interoperating two aircraft configurations (Rotor and Ustol).

Results show that by varying the range between 20 and 50 km for the Rotor aircraft and between 200 and 300 km for the Ustol configuration, the total consumed energy varies between 100 and 300 kWh.

Whit this case study we demonstrated that by considering three mission profiles of three electric aircraft classes (Rotor, Vtol and Ustol), SoS architect can analyze several other mission profiles by interoperating two or more aircraft classes. This interoperation was facilitated by using MDA technology. MDA can also integrate other analysis codes from other disciplines such as safety, reliability and manufacturability. This helps the SoS architect to make a better exploration of the design space at the conceptual level and then make the best decisions.

#### IV. CONCLUSION

On-demand electric aviation is a typical case-study requiring SoSE approaches for architectural design analysis. In this paper, we presented an approach for the SoS architectural design based on the SoS mission profile analysis. Results of the case study of the on-demand electric aviation showed that mathematical modeling of the mission profile for several candidate concepts and their integration using MDA technique allows exploring more complex SoS mission profiles, combing more than one aircraft concept. This allows SoS architect to explore alternatives that could give better results compared to missions performed by single aircraft concepts. In conclusion, this approach allows the SoS architect to make the best decisions at the conceptual level of the SoS development process.

As a future work, we suggest to use MDA/MDO techniques for the multi-mission optimization to identify the optimal SoS architects.

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