ABSTRACT

Development of a complex product usually initiates with requirements and architecture design. Usually, for a complex product such as in the aerospace industry, the number of requirements is numerous and as one of the methodologies is Model-Based System Engineering (MBSE) that copes these challenges according to stakeholders needs. Models in MBSE have a different physics nature and specifically for the aerospace industry it can be approximations which are based on the statistical data or 1D models based on the physical equations. Despite MBSE approach solves a wide range of the issues on the high level of product development and helps to choose appropriate architecture, the technical requirements are usually not taken into account on that stage. An approach to deal with specified challenges is Optimization-Driven Product Development (ODPD) and the aim of this work is to demonstrate the leveraging of ODPD to the small Unmanned Aerial Vehicles (UAV) case study.

Keywords: optimization-driven product development, MBSE, small UAV

1 INTRODUCTION

Architecture or system design of a complex product especially for the aerospace industry usually starts with initial requirements to the system (Giachetti et al. 2018). Analysis of various architectures of a product leads to choosing an appropriate one that meets all the initial requirements. One of the powerful approaches which helps to analyze and check requirements is Model Based System Engineering (MBSE) (Bocciarelli et al. 2019; Moller et al. 2016). According to the (INCOSE 2007) MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. The core of this approach is a model which serve to the analysis of the whole range of product architectures on an early stage of product development and also the verification of the requirements based on the simulation (Aiello et al. 2017). For different industries, the structure, type of models and the software tools where models created are very diverse. The high-level models can be approximations which are based on the statistical data or 1D models based on the physical equations. MBSE approach is realized in specific tool or software based on the SysML language (Arantes et al. 2018; Tang et al. 2018; Navas et al. 2018). A lot
of frameworks built on SysML are being developed in order to connect high-level requirements and numerical technical requirements with the functionality of a real product by means of the numerical models and the main challenge is the development of a universal tool, suitable for different industries and for the different types of product. The main goal of these frameworks is to provide the technical feasibility analysis on the stage of product architecture development (Cicconi et al. 2018) or provide an dependability analysis (Tundis et al. 2017). An approach which allows to solve the specified challenges is Optimization Driven Product Development (ODPD) (Merkel and Schumacher 2003). This approach implies to use models on all stages of product development in the optimization loop for principal requirements to meet all customers needs by means of optimization. The special platforms and software are used to support the ODPD approach and the main point is to create an optimization workflow with numerical models describing the functionality and real physics of a product with the various composition of models from the system, functional and discipline levels. A developer obtains several benefits from the use of the specified platform: re-using design knowledge (Verhagen et al. 2012), supporting the decision-making process (Papageorgiou and Ölvander 2018) and decreased time to market of a product. These platforms, such as pSeven (PSeven 2019), Optimus (Optimus 2019), Heeds (HEEDS 2019) and others are used as an integration platform for different multidisciplinary numerical models and for solving the problems from different industries. They provide the whole range of optimization methods, data analytics and means for decision making support. By using these platforms the researcher or engineer is only concentrated on the value-added activities and there is no need to perform any coding or scripting to integrate the results or computational core to the developed in-house framework.

In the literature, there is numerous number of papers, devoted to the using optimization in a whole range of research field, starting from the applying optimization to the only one discipline problem (Alexandrov et al. 2000; Chen and Lu 2018), considering multidisciplinary optimization with different optimization techniques (Papageorgiou et al. 2018; Venter and Sobieszczanski-Sobieski 2004; Giachetti, Holness and McGuire 2018), using meta-models as a tool for decrease computational complicity of the task (Zadeh, Sayadi and Kosari 2019), and finishing with developing frameworks for performing optimization (Papageorgiou et al. 2018). Despite the numerous papers devoted to the application of the optimization based on the numerical models, there is no approach where the optimization with numerical models on all levels was a digital thread of product development. Thus the aim of this research work is to demonstrate the leveraging of ODPD approach on the small Unmanned Aerial Vehicles (UAV) case study by means of applying optimization on the system level, functional level and by using existing optimization framework to generate a digital thread through all stages of product development.

2 METHODOLOGY

Optimization-Driven Product Development methodology is mainly promoted and proposed by vendors which offer the optimization software to solve the whole range of engineering problems. Different vendors propose an easy solution for multidiscipline optimization without deep knowledge of optimization algorithms while various scholars use both the commercial and open source software tools (Papageorgiou et al. 2018). In the current research, the Optimus, LMS Amesim (LMS 2019), Cameo MagicDraw (Magic Inc. 2019), Matlab (MATLAB 2019), NX CAD (NX 2019), STAR-CCM+ (STAR 2019) software were used for implementation of proposed approach. The idea behind the leveraging specified software is to implement proposed approach in the easiest way without any additional scripting and coding.

The whole development process for UAV is already well studied and known (Cai, Dias and Seneviratne 2014; Jodeh et al. 2006). The proposed approach starts from the mission objective and high-level requirements. Then the high-level model is created based on the statistics and the analytical approximation. In the considered case study the high-level model was developed in Cameo MagicDraw with integrated Matlab-based scripts. (Cameo MagicDraw is the software tool to support MBSE methodology and which allows taking into account all requirements for the product, Matlab is multi-paradigm numerical computing environment where the all high-level model as equation based can be developed). The first application of
the optimization techniques applies directly to the high-level model. The connection between initial requirements and the Matlab high-level model in Cameo is presented in Figure 1.

![Figure 1: High-level model of a small UAV with initial requirements prepared in Cameo and based on equations, realized in Matlab.](image)

Optimization applied to the high-level model is performed to find the range of permissible input parameters to meet the initial requirements and then to find preliminary values of input parameters that meet mission objectives. After the stage of the high-level optimization, the preparation of a functional model with refinement optimization is performed. The functional model serves to simulate the functionality of the complex systems based on the 1D physical equations. The software LMS Amesim or similar is used for functional modeling. Optimization applied to the functional model refines initial requirements to the technical requirements and gives the technical feasibility of UAV is verified. The functional model looks as presented on figure 2.

![Figure 2: Functional-level model of a small UAV with technical parameters of a UAV components and structure.](image)

Usually in the functional model (the Amesim model in this research), there are lot of technical parameters of a system such as initial velocity, battery capacity, lift and drag coefficients, wings span and area and others. The values of some parameters specifically aerodynamics properties or mass are determined by full computational fluid dynamic (CFD) analysis for example in Star CCM+ or by CAD modeling in Siemens NX. In such a way the 3D numerical models are involved in the functional model. After the functional model is prepared, the precise optimization for specific mission is performed. This optimization may include not only functional but also a detailed level of numerical models. Thus, after finishing the optimization for functional level, the numerical values of full number of technical parameters for the specific mission would be calculated and the development process of the whole structure would be continued with deeper details. The next stage of product development deals with prototyping. On this stage, the verification between numerical models and the produced prototype is performed. The Hardware-in-th-
Loop tests are applied on this stage (Ambroziak et al. 2018; Jodeh et al. 2006). The last step is an operational phase of a UAV when the optimization plays an important role. Based on the data, obtained from sensors the optimization is performed in real-time for verification of all developed numerical model. The whole number of verified numerical models with continuous optimization based on new available data from sensors represents Digital Twin of a product. Digital twin is the virtual representation of a physical systems in the various assets which act like a bridge between physics and digital world (Mayani, Svendsen and Oedegaard 2018). The whole process of applying optimization to the product development can be presented as follows:

Figure 3: Optimization process for product development.

The holistic methodology of applying optimization presented in figure 3 is under the development to this moment and some important results of applying optimization to the system and functional level are presented in this study. In the next section, the realization of the presented methodology is implemented based on the small UAV case study.

3 CASE STUDY

3.1 Mission description

The considered small UAV was developed by group of students who pass through the project oriented courses during 3 terms. The whole educational process was presented earlier in (Nikolaev et al. 2018). Each year the new version of UAV is being developed with different characteristics. The mass of the previous UAV was about 4 kg. The current version of UAV is about 1 kg. The UAV serves to perform specific observation missions and has following initial requirements: 1 - UAV should be launched from a hand; 2 - UAV should be launched from a tube launch system; 3 - UAV should carries camera on board for area observation. These three mission objectives give some numerical estimation for main system-level requirements such as payload mass, power consumption, cruise altitude, climb duration, time of steady flight, maximum flight overload, gravity constant, air density and tube dimensions. The second requirement implies the construction of the UAV that has a deployable wings. Based on the initial requirements and mission statements the mathematical model is developed using Matlab. The basic description of the high-
level Matlab model is presented below. The main goal of the high-level model is to analyze the whole range of product architectures and finally to choose optimal one with refined requirements for a specific mission in order to start the next stage of the development.

3.2 High-level model description

The high-level model of the UAV is constructed based on the key metrics defining the system performance. The first evaluation of the UAV can be calculated based on the mass. Thus, the mass of an aircraft can be defined as the sum of its subsystems. Power consumption is taken into account.

\[ M_{UAV} = M_p + M_s + M_{prop} + M_{cs} + M_{ps}, \quad P_{UAV} = P_p + P_{prop} + P_{cs} \quad (1) \]

where \( M_p \) – payload mass, \( M_s \) – structure mass, \( M_{prop} \) – propulsion system mass, \( M_{cs} \) – control system mass and \( M_{ps} \) – mass of power supply system, \( P_{UAV} \) – overall power consumption of an airplane, \( P_p \) – payload power consumption, \( P_{prop} \) – power consumption of propulsion system, \( P_{cs} \) – power consumption by control system. The initiation of the calculation process starts from the assignment of initial masses and consuming power defined by (1) accordingly, based on which further subsystems parameters will be recalculated.

Payload. Since the UAV aims to the mission of territory surveillance, needed in the cases of forest fires, pipeline monitoring, forest inventory, and so on and there are not any restricted requirements for the payload ground sample resolution, the simple HD camera (GoPro) is chosen for image capturing and data storage. In this case the payload mass and payload consumption are known: \( M_p = 0.071 \text{ kg} \) with overall power consumption \( P_p = 5.1 \text{ W} \).

Structure Subsystem. According to the data of the previous UAV (Nikolaev et al. 2018; Gusev et al. 2018) the structure mass of the UAV consists of 30 % the whole mass, wherein the deployable wings mass is calculated based on the wing geometry. The lift and drag coefficients were evaluated according to the chosen wing profile. In addition, the launch from the tube imposes the limits upon the available dimensions, among which maximum wingspan, fuselage cross-sectional area, aspect ratio and length of the UAV. The limitations of these parameters restrict the available range for drone parameters and allowable UAV architectures.

Control Subsystem. To maintain the flight control the design of the control subsystem is taken into consideration. The mass of the control subsystem is calculated as follows:

\[ M_{cs} = M_{servo} + M_{autopilot} + M_{rec} + M_{gps}, \]

where \( M_{servo} \) – mass of servomotor, \( M_{autopilot} \) – autopilot mass, \( M_{rec} \) – receiver mass, \( M_{gps} \) – GPS mass. Having all the equipment, the control system mass is evaluated as \( 0.16 \text{ kg} \) with an acceptable margin.

Propulsion Subsystem. From the conceptual design it has been chosen the usage of impeller placed inside the fuselage for thrust production. This choice was mainly justified by the first initial requirement. In order to provide the flow stream into an impeller the air-intake, mounted on the fuselage with two inlets for the flow collection were implemented. According to the preliminary estimation, the mass of the propulsion system is evaluated as \( M_{prop} = 0.22 \text{ kg} \), which includes impeller, air-intake, and tube for the output flow. The required thrust \( T \) for cruise flight is calculated based on the condition for the horizontal flight and the climb thrust \( T_c \) is evaluated as in equation

\[ T = \frac{\rho v^2}{2} S (C_d + \frac{C_l^2}{\pi AR e}), \quad T_c = \frac{V_{vert}}{v} M_{UAV} g + T \quad (2) \]

where \( T \) – required thrust, \( \rho \) – air density, \( v \) – velocity, \( S \) – cross-sectional area, \( C_d \) – drag coefficient, \( C_l \) – lift coefficient, \( AR \) – aspect ratio and \( e \) – Oswald efficiency number, \( T_c \) – climb thrust. \( V_{vert} \) – required velocity of climbing, \( g \) – gravitational acceleration. According to the obtained thrust, the consumed power can be calculated using current and voltage characteristics for thrust in impeller documentation.
Power Supply Subsystem and System Integration. For the particular time of flight, the weight of the power supply system can be calculated using the specific energy of the battery. After the identification of each subsystems mass, as it was shown above the masses of each subsystem using equation and power consumption (1) can be calculated. Finally, the initial and recalculated mass are compared, and if they have different values, the calculation process starts again assigning the final mass to the initial mass. The mathematical model based on the equations above has some limitation on the initial parameters according to the mission statement and initial requirements as following: 1. Lift Coefficient [0.2, 0.4]; 2. Aspect Ratio [5, 12]; 3. Wingspan [0.6, 0.9] m; 4. Velocity [5, 40] m/s; 5. Time of flight [5, 40] min.

### 3.3 Range of UAV architectures

The whole range of product architectures and initial requirements can be evaluated based on the equations (1-2). Figure 4 represents the dependency between UAV mass, flight duration and velocity for all existing architectures.

![Figure 4: The whole range of UAV architectures: representation in mass-velocity-time of flight dependency.](image)

Figure 4 shows not only the architectures of a UAV with possible mass, velocities and time of flight, but also represents the feasibility of basic properties of a UAV. This means that each point on a surface with a non-zero mass reflects the specific architecture with mass, velocity and time of flight. Points with zero mass represent that the equations (1-2) do not have the solution and the UAV with these parameters is not exists. The next stage after the graphical representation of the existing architectures is to evaluate precisely the numerical values for input parameters for specific missions. This step is performing by optimization.

### 3.4 High-level model optimization

In this case-study, three specific mission can be formulated based on the initial requirements and limitation for initial parameters. The first one is the minimization of mass that means the minimum cost of a UAV, the second one is the maximization of flight time and the third one is the maximization of flight coverage. The optimization process was set up in Optimus software. Since the Optimus has a whole range of external program connectors including Matlab interface the whole process of solving three optimization problems was finished fast. The results of optimization are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>The lowest mass</th>
<th>The longest flight time</th>
<th>The highest flight coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Coefficient</td>
<td>0.377</td>
<td>0.349</td>
<td>0.210</td>
</tr>
</tbody>
</table>
The starting point for further detailed functional optimization was prepared based on the high-level optimization results. The third mission with maximization of flight coverage was considered for detailed optimization.

### 3.5 Detailed optimization on functional level

#### 3.5.1 Preliminary stages

For functional level modeling, Amesim software was used. Amesim is a convenient tool for functional level modeling, which takes into account CFD results and verified UAV subsystems. Applying different conditions for parameters of the functional model, such as initial speed and altitude, flight mission, crosswind, battery capacity and so forth, one could simulate a 3D flight trajectory. The view of the functional model presented in figure 2 and the model consists of 4 subsystems: 1 - Propulsion subsystem; 2 - Energy supply subsystem; 3 - Tube subsystem; 4 - Flight dynamics subsystem. UAV propulsion subsystem consists of a high-speed impeller joined with a 5-blade propeller. Amesim propulsion model was designed using signal and aeronautic libraries. Propeller CFD parameters were calculated in Star CCM+ and put in the corresponding module. Validated model on a special testing stand has shown an error with the real data less than 10%. Figure 5 represents some results of CFD calculation for impeller and testing results. The lift to drag ratio for the UAV also was evaluated in Star CCM+ software and then was used in Amesim model. The mass of the UAV depending on the capacity of the batteries was evaluated in NX CAD model and then was used as an input parameter for Amesim model. In figure 6 the CFD results of the whole structure (left, middle) and NX CAD model for mass estimation (right) of the UAV are presented. Thus the Amesim functional model of the UAV has verified submodels inside and the precise optimization for specific mission is applied starting from the initial point of optimization on high-level.

![Figure 5: Results of CFD calculations for impeller and real testing.](image-url)
Figure 6: CFD analysis of whole UAV structure and CAD model of the UAV for mass evaluation.

3.5.2 Formulation of the optimization problem on the functional level

The Amesim model allows to take into account the number of technical requirements that determine precisely the operation of the UAV during flight. Among them battery capacity, initial pitch angle, initial velocity, cruise velocity and others. Amesim model allows simulating the whole trajectory of the UAV depending on mentioned technical requirements. Figure 7a shows the trajectory of the UAV on climbing, cruise and landing stages.

Figure 7: a) - Trajectory of the UAV; b) - The UAV climbing simulation in Amesim with different pitch angle and climbing speed.

According to the mission objective and initial requirements that UAV could be launched from a pneumatic tube as well as by hands, the initial conditions are determined by initial speed, initial pitch angle, and initial altitude. Transforming these initial requirements to the specific mission the trajectory can be divided into the three stages: 1 - Climbing to 200 meters altitude; 2 - Observation at a height of 200 meters; 3 – Landing.

The most important stages are climbing and observation and to specify the optimization task the two subtasks were formulated: minimization of power consumption during the climbing; maximization of observation distance.

3.5.3 Minimization of power consumption during the climbing

According to the Amesim simulation for different pitch angles (see figure 7b) the increasing bigger pitch angle leads to the decreasing consumption and also climbing velocity influences on energy consumption. Thus the optimal parameters exist to achieve less energy consumption during climbing. The optimization task was solved in pSeven software. pSeven is a software platform that provides advanced tools for Optimization, Design Exploration and Predictive Modeling, packaged in an easy-to-use graphical user
interface. The results of optimization: the bounds, input parameters and optimal values obtained in optimization are presented in table 2 and some graphical representations are shown in figure 8.

Table 2: Amesim model input and output parameters for climbing energy consumption optimization in pSeven.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Range</th>
<th>Optimal values</th>
<th>Output Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial UAV speed [m/s]</td>
<td>[5; 10]</td>
<td>9.47</td>
<td>State of the charge at the 200 meters altitude</td>
</tr>
<tr>
<td>Climbing speed [m/s]</td>
<td>[10; 30]</td>
<td>17.02</td>
<td>Optimal State of the charge:</td>
</tr>
<tr>
<td>Initial pitch angle [deg]</td>
<td>[3; 20]</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Climbing pitch angle [deg]</td>
<td>[8; 40]</td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>Battery capacity [Ah]</td>
<td>[3.3; 4.5]</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Results of the state of the charge optimization: a) – the whole range of solutions, b) – precise values near-optimal solution.

Optimization results shown in figure 8 and table 2 represents that different solutions inside the considered architecture are also available. Thus the whole range of newly generated solutions may be used to achieve the best performance for particular customers needs.

3.5.4 Maximization of observation distance

Optimization on the cruise stage is applied to maximize the observation distance that depends only on cruise velocity which is equal to initial speed, pitch angle and battery capacity. Table 3 and figure 9 represents the results of optimization with the range of used parameters.

Table 3: Amesim model input and output parameters for cruise distance optimization in pSeven.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Range</th>
<th>Optimal values</th>
<th>Output Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise UAV speed [m/s]</td>
<td>[10; 30]</td>
<td>10.9</td>
<td>Optimal Longitudinal Distance [m]:</td>
</tr>
<tr>
<td>Initial pitch angle [deg]</td>
<td>[1; 10]</td>
<td>6.45</td>
<td>38116</td>
</tr>
<tr>
<td>Battery capacity [Ah]</td>
<td>[3.3; 4.6]</td>
<td>4.60</td>
<td></td>
</tr>
</tbody>
</table>
Figure 9: Results of the observation distance optimization: a) – the whole range of solutions, b) – precise values near-optimal solution.

The whole range of solution presented in figure 10 also shows that it is possible to generate the design of the UAV near the optimal solution. In case of distance the maximum possible limit was calculated. It means for the specific mission an alternative solution can be chosen with parameters that meet customer needs.

4 RESULTS, DISCUSSION, CONCLUSIONS AND FUTURE PLANS

The main results of this research are focused on the methodology of applying optimization as a driven force for product development. The results presented above show that the application of optimization expands the range of feasible solutions for a specific mission. Architecture calculated at high-level optimization stage gives a lot of opportunities on how to implement architecture on the functional level. Technically the results of optimization on high-level are the starting point for the following optimization on the functional level. Results of optimization on the functional level give the initial estimations of values for performing CAD modeling and CAE numerical simulation. Then such a process is applied to the validation and verification of a numerical model and physical prototype.

It turns out the product development and digital twin creation are inextricably linked with the numbers of optimization loops as shown in figure 3. Specifically, these optimization loops represent the acting force of product development which gives the best solutions on early stage before the production stage.

But also it should be noted that the number of optimization loops strictly depends on the product itself. Before the optimization starts the number of high-quality numerical models that describe the product functionality should be developed. The numerical models should be parameterized and have to be easy for changing during the transition to another architecture. All of this gives the requirements to the digital twin creation and only in compliance with these requirements the reliable digital twin of the product can be created.

Moreover, in this paper, only two phases of product development were encompassed. To develop the holistic approach it is required to span all stages of product development including prototyping, testing and operational phase with a real-data acquisition. In future work, all these steps should be implemented.

REFERENCES


**AUTHOR BIOGRAPHIES**

**MIKHAIL GUSEV** is a research scientist in Center for Design, Manufacturing, and Materials, at the Skolkovo Institute of Science and Technology. He received his Ph.D. from Bauman Moscow State Technical University. Her research interests include optimization approach and development methodology of Digital Twin concept for different industries including metallurgy and aerospace. His email address is m.gusev@skoltech.ru.

**SERGEI NIKO LAEV** received his Ph.D. from Bauman Moscow State Technical University, and currently is Research Scientist in Center for Design, Manufacturing, and Materials, at the Skolkovo Institute of Science and Technology. His research interests include structural dynamics, and combined physics-based/data-driven modeling of complex systems. His email address is s.nikolaev@skoltech.ru.

**ANATOLII P APULOV** received a B.S. in Physics from Novosibirsk State University, and currently a second year Master Student at Skolkovo Institute of Science and Technology. His research focuses on implementation of model-based systems engineering for the design of complex systems. He can be reached at anatolii.papulov@skoltech.ru.

**SERGEI BELOV** is a second year master student at Skolkovo Institute of Science and Technology. His research interests are physics-based modeling and data science. His email address is sergei.belov@skoltech.ru.

**DANIIL PADALITSA** received his engineer's degree from Moscow Aviation Institute and currently is engineer in the Cyber-Physical Systems Laboratory at Skolkovo Institute of Science and Technology. His research interests include computational fluid dynamics and advanced design. His email address is d.padalitsa@skoltech.ru.

**IGHOR UZHINSKY** is a full professor in Center for Design, Manufacturing, and Materials, at the Skolkovo Institute of Science and Technology. He received his Ph.D. from Moscow Institute of Physics and Technology. His research interest are development of a complex product based on physics numerical models. His email address is I.Uzhinsky@skoltech.ru.