Leveraging Transdisciplinary Engineering in a Changing and Connected World
P. Koomsap et al. (Eds.)

doi:10.3233/ATDE230598

A Method of Integrating Design Information in the Aircraft Preliminary Design Process

Wojciech SKARKA[a, b,1]
[a] *Silesian University of Technology, Poland*
[b] *SkyTech eLab LLC, Poland*

Abstract. When designing light aircraft, the designer should take into account many different factors from various fields, such as aerodynamics, structural strength, flight mechanics, etc., from the conception stage. To perform advanced analyzes during development and optimisation work, it is usually necessary to quickly generate an aircraft model in the CAD environment. Such a primary geometric form is the input model for further analyses. The paper presents a method of quick generation of the CAD model including the conceptual form of the aircraft. The model is created on the basis of previously identified assumptions and construction rules used in the design of aircraft. The rules are based on integrated information from the fields of aircraft design, aerodynamics, and flight mechanics, as well as good engineering practises and aviation regulations. The structure of the information and the way of its integration into the CAD model were presented. Generative modelling is used to generate the CAD model. The model also includes strength verification algorithms, which are commonly used in conceptual design. The geometric model is based on a hierarchical structure adapted for reuse. The structure of the model is simplified for the purposes of preliminary model generation, but has the potential for further extensive development and refinement. This basic geometry can be used for further development and refinement. The paper also presents the verification of the method on the example of ready-made commercial aircraft and glider structures, starting from classic structures and ending with structures with the best performance used in air sports.

Keywords. Generative model, information integration, aircraft design, design automation, CAD model reusability

Introduction

In the initial phases of aircraft design, it is particularly burdensome and laborious to move from the initial calculation phase to the construction of a geometric model of the structure in the CAD system, as to perform well as preliminary verification of the structure. A large number of potential solutions, a large number of constraints resulting from various types of requirements and the coupling of relationships controlling the rules of engineering calculations greatly hinder the design process. Usually, at this stage, tedious analytical calculations are made, based on which both operational parameters and the corresponding geometrical parameters of the aircraft structure are determined. These

---

[1] Corresponding Author, Mail: wojciech.skarka@polsl.pl.

relations are analyzed, and through tradeoffs and subsequent approximations, preliminary construction concepts are reached. Such a transdisciplinary action, taking into account the phenomena of flight mechanics, aerodynamics, strength of materials, manufacturing technology supported by the assessment of experienced experts, usually allows obtaining a good design, which in the next stages in simulation and optimisation processes can be effectively developed. This complexity means that there is no established procedure for the initial design and construction of aircraft, the optimal solution is achieved through iterative adjustment of parameters. This is an extremely time-consuming process that requires a lot of work. Most of the time is spent calculating the impact of empirically selected parameters on the flight properties of the aircraft. Interpreting the results of the calculation is only a small part of this process. At the same time, the effects with the design assumptions [1]. Automating the process of going through the designer from the stage of a blank sheet to a verified CAD model of an aircraft can be an invaluable help and greatly speed up the construction process. The article presents a method of automating this stage of design. The method is based on procedures commonly used in the design of aircrafts [2, 3] and gliders [4]. Experienced designers use similar procedures widely. The initial concept of an aircraft is often based on a purely geometric design aspect. Despite this, experienced designers are able to intuitively choose the parameters and appearance so that the necessary systems are at the right places without major interference in the shape [5].

The number of issues raised during the design of the aircraft makes this process an iterative process. It includes four main phases: conceptual design, initial design, detailed design, and testing and evaluation. Phase one is the most important of them. It determines the approach to designing a product that meets the requirements of the structure. Determines the scope and time of work, the costs of execution, and the technologies that can be used. During this phase, there is little calculation; the most important element is to choose the ideas to be developed from among the many possibilities considered. In the next phase of the initial design, the concept takes a geometric form and a series of calculations ensures the consistency of the proposed solution. [6]. Sometimes methods based on Knowledge Based Engineering are used to support these processes. "KBE is an engineering solution where the design process and product knowledge is consolidated and implemented in the software, (...) and then used to generate new but similar design solutions for a new set of inputs" [7]. According to Du Yao, the goal of KBE is to orient an inexperienced designer toward the best solutions by reducing the workload on repetitive design tasks. [8, 9]. The transition from the analytical or numerical calculation phase to the geometric representation is a very laborious process. These processes draw on the resources of previous CAD designs and models built for reuse and adapted for this purpose [10]. Sometimes more advanced methods based on Generative Modelling [11] are used, which allows for quick and automatic generation of the geometry of the designed object in the CAD system. Building Generative Models is subordinated and systematised, and this process is preceded by time-consuming identification and acquisition of knowledge in a given project scope [12]. Models and design processes use procedural design methods or more advanced ones based on Model-Based Design [13, 14]. The effort that must be put into building Generative Models usually pays off in a significant shortening of the first phases of the design process. In subsequent detailed design phases, the application of Generative Modelling is usually more difficult. The below described system based on Generative Modeling is intended for use in the preliminary design phase in professional applications for designing aircraft, gliders and unmanned aerial vehicles in the classic fixed-wing layout

1. Method of integrating design information in the aircraft preliminary design process

Automation of the preliminary design process is based on autonomous coexistence and the use of the following resources: Geometry database, Material database, User interface for input data.

These resources are linked through relationships, rules and formulas of the calculation model, which actively using databases and information obtained by the user, makes calculations on this data, calculating the characteristics of the aircraft and geometric data needed to create a CAD geometric model. These elements integrated in the whole define model of calculations and relationships of geometry, aerodynamics, loads and structural verification parameters

The calculated geometric data of the aircraft is retrieved by a parameterized model in the CAD system. Based on these values, the model takes the appropriate form and size as a result of this process. The model is a combination of many elements constituting the basic fragments of the basic division of the airframe structure. Parameterizing the geometric model of the aircraft in CAD system we have to take into account that, the results of these calculations are used in the generated model in the environment designed earlier. The entire dependency is shown in a flowchart showing the main resources that are affected by those resources during the preliminary design phase. Figure 1.

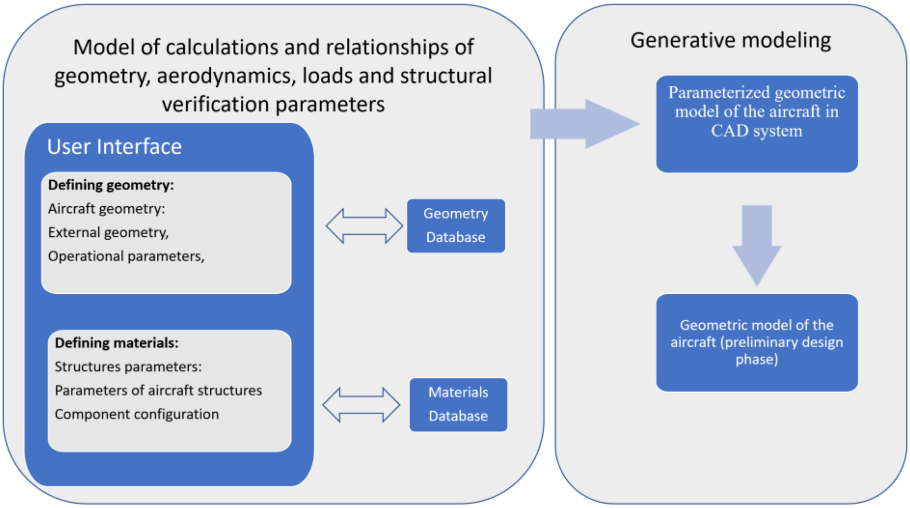


Figure 1. A block diagram showing the process of automating the preliminary design of the aircraft.

1.1. Parameterized geometric model of the aircraft.

The parameterized geometric model is represented by an assembly file in the Siemens NX system, which contains: half of the wing, aileron, flap vertical stabilizer, rudder, half of the horizontal stabilizer, elevator, fuselage.

In addition to these parts, mirror reflections of the wing halves, ailerons, flaps, halves of the horizontal stabilizer and elevator are present in the assembly. All these elements are connected by two types of connections – hinge type and anchor type. Hinge connections are applicable to all control surfaces. For each such connection, an axis of rotation and a point of contact shall be defined. The remaining constraints are based on local coordinate systems. Each of the models is built in such a way that their position is calculated relative to one common coordinate system. The plane ZX of this system is the plane of symmetry of the aircraft, the plane YZ is the vertical plane tangent passing through the point of intersection of the leading edge with the x-axis, and the plane XY is the horizontal plane passing through this point. The coordinate system adopted in the calculation is fundamentally different from the coordinate system adopted in the CAD model. The aircraft model is created by reading the data calculated in the previous steps from MS Excel spreadsheets. The geometry definitions of some elements are based on data and definitions from sheets, and the definitions of some parameters are different from those used in sheets and adapted to efficiently generate geometry. Such an example is the shapes of aerodynamic profiles, which are based on the NACA profile generator [15] and are based on equations defining the profile shape directly in the Siemens NX system. Due to the initial and preliminary nature of CAD models, communication with the calculation model system is one-way. These models are further processed and changed, and binding them permanently to parameters in the sheets would limit the possibilities of their further processing.

1.2. Database.

The database contains a collection of construction and material information. Construction data refer to the separated elements of the airframe assembly, i.e.: wing, wing mechanization, fuselage, vertical and horizontal tail. The database contains the basic structural configurations for the wing and ballast systems, as well as general data necessary for mechanical and aerodynamic calculations. The material part includes basic material data of materials used for aircraft supporting structures such as wood, light alloys and composites of various types.

1.3. Interface

The interface is based on the MS Excel spreadsheet system. The applied division into sheets allows for the separation of individual modules. The use of field colors and active color changes of these fields facilitate both editing and interpretation of strength verification results. The interface of the part of the system responsible for data entry is enriched with visualization materials supporting the designer in the selection and interpretation of data. The intensive use of graphs facilitates the interpretation of both geometric data (Figure 2.) and results, e.g. loads.

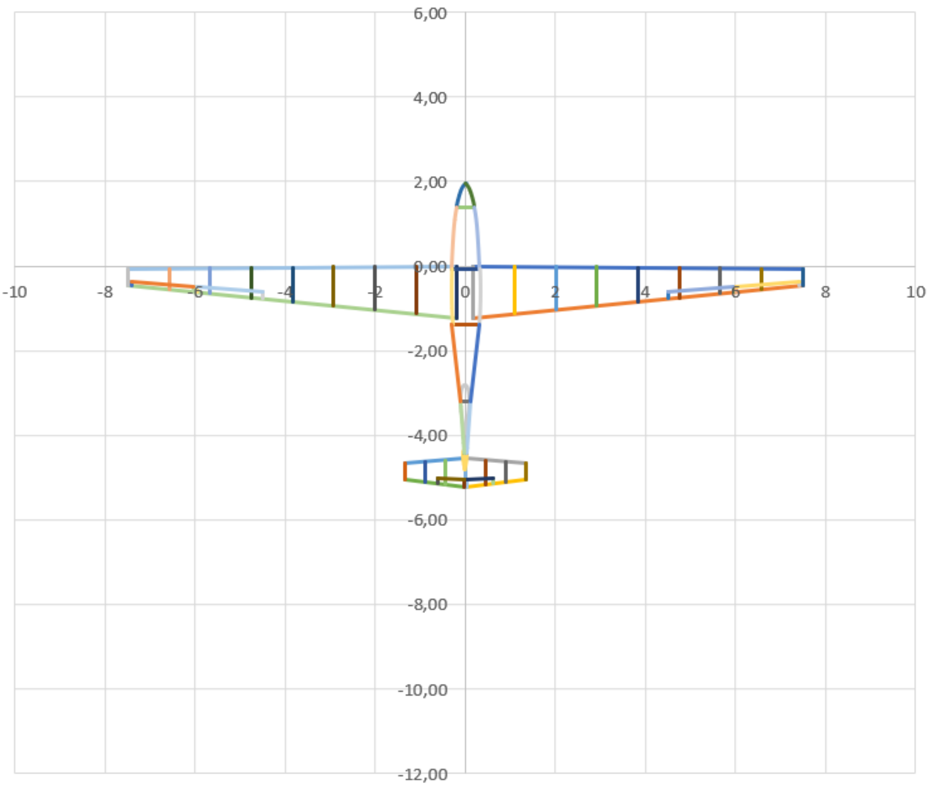


Figure 2. Geometric interpretation of the system's results directly in the MS Excel system.

1.4. Model of calculations and relationships of geometry, aerodynamics, loads and structural verification parameters

The calculation model implemented in the MS Excel system is directly integrated with both the interface and the material database. The division into sheets reflects the separation of these three elements of the system, but the multitude of references and the degree of complexity of these references blurs the differences between these system modules. The calculation model, together with the system interface, represents the flow of the design procedure.

2. The process of building an aircraft model

The geometry of the airframe is determined in the Interface tab. It contains a list of geometrical parameters necessary in a complete description of the structure. In order to facilitate the identification of geometric parameters, schematic drawings with marked parameter identification numbers have been created. Each parameter has a unit that is used in calculations and loading into the model.

Aerodynamic parameters are used only for calculations within the MS Excel spreadsheet. The situation is different in the case of the geometry of the airfoil. The representation of the airfoil shape in the .csv file are coordinates from a few to several dozen points in a two-dimensional form. While Excel calculations are based on the interpolation of the points that define the profile, shapes based on airfoil in Siemens NX are defined by coordinate equations. For this reason, the format of the representation of points in the source file and the model is incompatible. The trade-off between simplicity: transforming the shape described by imported points to adjust geometry, calculating dependent geometries (such as caisson tube radius, surface areas, and spar heights) and preparing equations for import by the Generative Model, and the complexity of formulas and the number of dependencies led to several restrictions on entering point coordinates into the spreadsheet.

After reading data from the xlsx file to create geometry in the model, elements are built by defining characteristic cross-sections – for all elements except the fuselage, the geometry at the beginning and end of the element is considered. The next step is to connect the cross-sections using linear interpolation, and in the case of the hull using guide curves - guidelines. In the case of a wing, a curve is created on a two-dimensional plane using equations that define the airfoil. This two-dimensional representation is positioned appropriately in space using the "y" coordinate in the model. After the appropriate transformation of the generator's equations using the "law curve" tool, a curve is created, the values of which "x" and "z" are described using the transformed equations. For the root of the wing, the value of the coordinate "y" is equal to the distance of the first rib from the axis of the aircraft, while the coordinate "y" for the wing tip is equal to half the wingspan.

The shell of the wing half is formed as a surface extension through curves. Then this surface is thickened inwards by the thickness defined in MS Excel spreadsheets. This is one of the solids visible in the model. Subsequent solids form the volumes of the ribs. They are created at equal distances in the number defined in the spreadsheet. All of them are of equal thickness, and their outer outline is defined by the inner outline of the shell cross-section. The next solid created is the spar. It is formed similarly to the shell – it is a swipe through two curves at the ends of the halves of the wing. The width and thickness of the spar caps as well as the thickness of the web is defined by the user in spreadsheets, while the height of the spar is calculated in MS Excel spreadsheets.

In the case of the strength of user-defined parameters of individual structures, the whole procedure is an iterative method consisting in adjusting each of the values until the indicators regarding the safety factor indicate the correctness of the selection of each of them. All calculations are carried out automatically in the MS Excel sheet tab dedicated to the given wing assembly. This is where all the formulas are located and the necessary links between them and the user interface are set, so that when the user enters a given parameter, it is automatically loaded and the strength of the component is calculated on its basis, taking into account predefined conditions containing aerodynamic parameters and aircraft flight conditions. The spreadsheet workspace is divided into individual sections that contain described values, which contain fixed values, predefined values, calculation quantities, and resulting values from formulas stored in the spreadsheet. The results of the calculations are simplified to present them in the form of a safety factor, which is to represent the multiplicity with which the structure meets the strength at the assumed parameters. The user is informed by displaying its exact value and color marking indicating the correct or inappropriate selection of one of the parameters.

The value of the safety factor is influenced not only by the specific parameters stored, but also by the selected options from the drop-down lists for specific configurations of aircraft assemblies and the materials used for their construction, which directly affect the method of calculations carried out, and thus their results. The user must thus iteratively select such quantities so that finally each indicated safety factor is within the optimal range for further reading into the Siemens NX system.

When the selection of all options and parameters is completed, it is possible to save all operations and read them directly in the NX Siemens dialog box by updating all model references to the cells of the MS Excel spreadsheet containing the mentioned parameter values of all aircraft components.

After you enter the data and verify it in your spreadsheet, you need to complete the tabs accordingly, open the model file, and manually update the CAD model parameters.

3. Verification of system operation

To check the correctness of operation, a number of checks were performed during the implementation of the system, checking the operation of individual modules. In addition, the system is verified after the integration of all system modules. For this purpose, it was decided to completely generate a glider with a size and characteristics similar to the SZD – 56 – 2 Diana 2 and SZD – 32 Foka 5 glider, recognizing that the similarity of the system's result to the real structure, which was still significantly improved in further design steps, will testify to a good level of system result.
The most important results are summarised in Table 1.

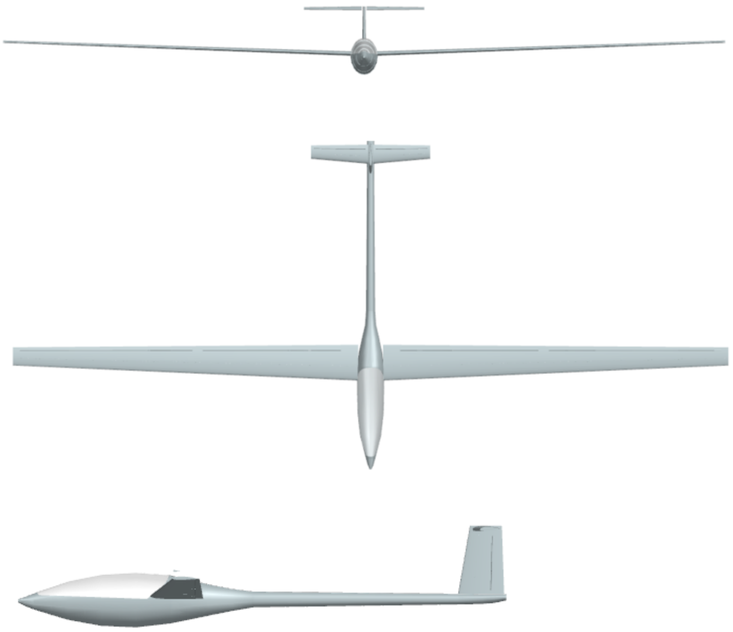
Table 1. Comparison of calculation parameters and actual selected glider designs

Parameter	**Diana 2** **Commercial glider**	**Diana2I** **System results**	**Foka 5** **Commercial glider**	**Foka 5** **System results**
Wing area [m^2]	8,64	8,475	12,2	12,1
Stall speed [m/s]	16,7	26,5	18.9	19,4
Optimum speed	N/A	N/A	23,6	23,6

For verification, two completely different types of glider were chosen. The Diana 2 glider is a very modern glider whose wing has been significantly optimized and the wing airfoil significantly modified as a function of span. greatly improving the parameters of the glider. This glider is one of the world leaders in its class. The stall speed for an optimized glider varies by as much as 1.6 times. This is due to significant simplifications of the wing in the preliminary design system and the use of a homogeneous profile in the generative modeling system. Comparing this result to the previous version of Diana 1, the stall speed ratio is 1.12, which is already a very similar value. Despite such large differences, the result treated as a preliminary project that has yet to be optimized should be considered good.

Another glider used for verification is Foka 5, which was flown in 1966, so it is an old construction, and its wing is based on the NACA profile. The result of the generative modeling system is almost identical to the real construction.

Result of generative model comparative to Diana 2



Diana 2 real design

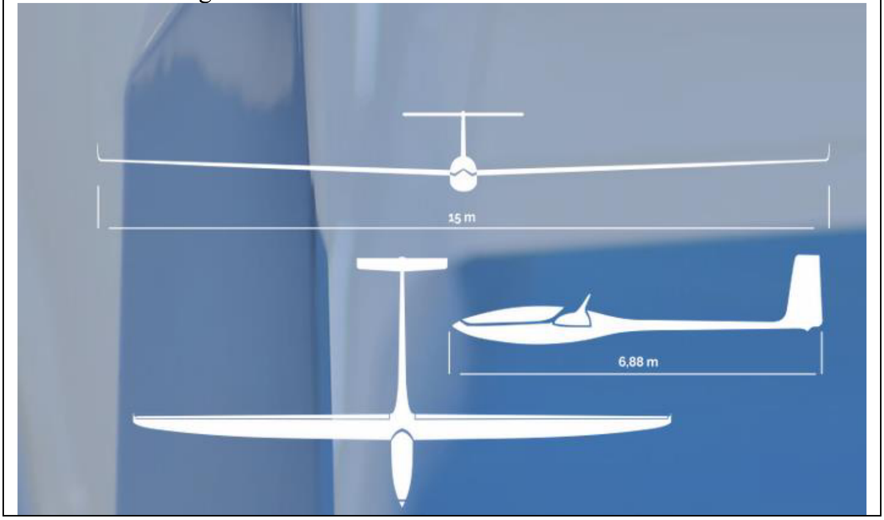


Figure 3. Comparative mapping of the preliminary design for the reference glider for the Diana 2 glider.

The results of both examples testify to the good operation of the glider preliminary design system. Successfully the result in the form of a geometric model can be optimized in subsequent steps using modern numerical methods. In the preliminary stage, no detailed structural or aerodynamic optimization is performed. It is only on the basis of the initial geometry that it is possible to further optimize the newly designed aircraft/gliders

In addition, the strength calculation module was verified by comparing the results of analytical calculations of system operation and verification calculations made using FEM methods. The detailed comparison includes safety factors determined by alternative methods for 20 important points for the most important wing elements, the results vary from approx. 50% to approx. 115%. Such differences are fully justified taking into account the accuracy of the methods used for the analysis.

4. Summary and conclusions

The proposed system of automation of the preliminary design process using the method of integrating data from many disciplines into this process and the use of an generative model integrated with the database in which these data were integrated has been verified on historical and modern real aircrafts examples. The final form of the geometric model in Siemens NX guarantees the possibility of further development and optimization. This is due to the parametric and flexible structure of the model itself, the most important feature of which is high stability in a wide range of variability of geometric parameters. This construction of the model guarantees its easy use in further analyses using CFD and FEM methods. In the next steps, the material and geometric base will be developed, in particular, it is planned to develop the system with propulsion modules, which due to previous applications – gliders – were not included. Another planned direction of development is UAV technology. However, the dynamic situation in the processes and design requirements and the fairly wide range of interpretations left in the UAV regulations stand in the way.

Acknowledgement

This research was partially funded from EEA and Norway Grants 2014–2021 and was partially carried out in the framework of the project No. NOR/POLNOR/LEPolUAV/0066/2019 “Long-endurance UAV for collecting air quality data with high spatial and temporal resolutions”.

References

[1] D. Howe, *Aircraft Conceptual Design Synthesis*, Professional Engineering Publishing Limited, London and Bury St Edmunds, 2000.

[2] C. Galiński, *Selected issues of aircraft construction*, Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw (in polish), 2020.

[3] S. Danilecki, Aircraft Design, Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw (in polish), 2000.

[4] W. Stafiej, *Calculations used in the design of gliders*, Warsaw University of Technology, Warsaw, (in polish), 2000.

[5] D. P. Raymer, *Aircraft Design: A Conceptual Approach*, AIAA, Playa del Rey, 2018.

[6] M.H. Saedrey, *Aircraft Design: A Systems Engineering Approach*, Daniel Webster College, New Hampshire, 2012.

[7] V. Devaraja Holla, *Knowledge Based Engineering (KBE): Key product development technology to enhance competitiveness*, Infosys Perspective, 2018, https://www.infosys.com/engineering-services/white-papers/documents/knowledge-based-engineering.pdf, accessed June, 24 2023.

[8] D. Yao, Z. Chang, J. Zhao and Y. Dou, Study on Key Techniques of Parametric Design System Based on Solid Works and KBE, *Applied Mechanics and Materials*, Vol. 71-78, 2011, pp. 3861-3867.

[9] E. Jayakiran Reddy, C. N. V. Sridhar i V. Pandu Rangadu, Knowledge Based Engineering: Notion, Approaches and Future Trends, *American Journal of Intelligent Systems*, 2015, 5(1), pp.1-17.

[10] T. Heikkinen, J. Johansson, F. Elgh, Review of CAD-model Capabilities and Restrictions for Multidisciplinary Use, *Computer-Aided Design and Applications*, 2018, 15(4), pp. 509-519

[11] W. Skarka, A. Jałowiecki, Automation of a Thin-Layer Load-Bearing Structure Design on the Example of High Altitude Long Endurance Unmanned Aerial Vehicle (HALE UAV), *Applied Sciences*, 2021, 11, 2645. https://doi.org/10.3390/app11062645.

[12] A. Jalowiecki, P. Klusek and W. Skarka, The methods of knowledge acquisition in the Product Lifecycle for a Generative Model's creation process, *Procedia Manufacturing*, 2017, Vol. 11, pp. 2219-2226.

[13] W. Skarka, Model-Based Design and Optimization of Electric Vehicles, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 566-575.

[14] M. Peciak, W. Skarka, Assessment of the Potential of Electric Propulsion for General Aviation Using Model-Based System Engineering (MBSE) Methodology. *Aerospace*, 2022, 9(2), 74. https://doi.org/10.3390/aerospace9020074.

[15] N.N., *The NACA airfoil series*, [Online]. Available: https://web.stanford.edu/~cantwell/AA200_Course_Material/The%20NACA%20airfoil%20series.pdf. accessed: 11 August 2022.