Conceptual design of a small 4-seater aircraft with hybrid propulsion system

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Abstract: The lecture develops the operational concept for the small 4-seater aircraft with hybrid propulsion system. From the operational concept will be derived the preliminary specification of the aircraft. With systematic application of methods of the aircraft conceptual design the small aircraft will be preliminary developed. The Aerodynamic and basic flight performance will be discussed. The lecture supported by the EFOP-3.6.1-16-2016-00014 project Research and development of the disruptive technologies in area of e-mobility and their integration into the engineering education.

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1. INTRODUCTION

All the major international bodies (as ICAO, EASA, ACARE), large leading organisations and institutions (for instance IATA, ONERA, TsAGI, etc.), as well as the aircraft producers are working on developing future safe, secure and sustainable aircraft with radically increased efficiency and dramatically reduced environmental impact. Nowadays, it seems the best and final solution is to develop the full electric aircraft. However, today this task is not solvable, because the limited performances of the energy storage (accumulators), technologies enabling generate clean energy on the board (for example by use of solar panels) and /or transferring the "clean" energy from ground to the aircraft board (for instant by micro waves). Therefore, the hybrid propulsion system may find their market place in this transition period.

This paper develops the operational concept for the small 4-seater aircraft with hybrid propulsion system. There will be used not only simple energetic and efficiency models, but more general approach including the safety security and passenger comfort, too. The investigation of the impact, including the compatibility, environmental (noise and chemical emission) impacts here will not specially investigated, because accepting that fact, the hybrid aircraft impact initially less than the conventional aircraft impacts.

From the operational concept will be derived the preliminary specification of the aircraft. With systematic application of methods of the aircraft conceptual and preliminary design the small aircraft will be preliminary developed. The Aerodynamic and basic flight performance will be discussed shortly.

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2. CONCEPT OF OPERATION

There are several approaches to define the concept of operation. The simple and probably most used term is "Concept of Operations (ConOps) – describes the way the system works from the operator's perspective" (System, 2010). Another term operational concept often used as similar term, while the operational concept is „a verbal and graphic statement of an organization's (enterprise's) assumptions or intent in regard to an operation or series of operations of a specific system or a related set of specific new, existing or modified systems" (Guide , 2012).

So, there is a simple definition: concept of operation is a document defining the characteristics of a proposed or developing system from the user point of view. More generally speaking, the concept of operation defines how to develop, implement and use of the proposed system with user (costumer) high complacence. It is used to communicate the quantitative and qualitative system characteristics to all stakeholders. Of, course, it is understandable, in our case, the user of the 4-seater small aircraft (in most cases private persons) needs aircraft, airport and services including the rent a plane and ATM, safe and secure assistances, etc.

In simple first order, the different between the concept of operation and operational concept can be defined as the first described the operation of a product like aircraft, while the second, the operational concept describe the operation of a system, a company. So, the operational concept defines a proposed system as the cost effective, safe, secure and affordable for the users like it is defined by NASA (Abbott, 2004; Future, 2002; Munoz, 2006) for small aircraft transportation system.

The concept of operation can be developed by different ways but as usually it must content

- statement of the goals and objectives of the developing system,
- strategies, tactics, policies, jurisdictions and constraints affecting the system,

- organizations, activities, and interactions among participants and all the stakeholders,
- clear statement of responsibilities and authorities delegated including the monitoring and regulations and actions in emergency situations,
- ways of using the system (including owning, renting, service, flying, ATM, etc.),
- specific operational processes for fielding the system,
- processes for initiating, developing, maintaining, and retiring the system.

The specification or characteristics of the system elements (like geometric, aerodynamic characteristics or flight performance of the new small aircraft, behaviors of the special airports) may not derive from the operational concept directly. The needs of user of the systems can determine a series of system elements, like fix and rotary wing aircraft with different types of engines (piston engine, propellered gas turbine, small gas turbine) and with different equipment and conform (VRS or ILS system, unpressurised or pressurized cabins, etc), as well as using the special airfields special airport or common airport with global traffic, and so on. However, the operational concept must define the common rules of using, relationships between the stakeholders, their responsibilities, etc. Such rules, as sharing the ownership, training and personal licensing of pilots, way of renting, integration of the traffic into the global air traffic system, etc. must be defined and built up on the same basis that must be defined by operational concept.

Of course, in case of well-developed operational concept the series of system elements can be defined and optimized. So, finally, on the basis of the operational concept we are able to preliminary define the mean characteristics of the system elements, like the typical aircraft (not one, 4 – 6 at least), the required avionics system, needing improvement or radical changes in the aircraft control systems, integration of the new aircraft into existing ATM, changes in regulations, establishing the training system, defining the rules for emergency situations, etc.

3. PRELIMINARY CONSIDERATIONS

At first we must clarify that the development of the personal small aircraft with hybrid propulsion systems does not equal to improving the general aviation. It is a radically new system that may use of existing system elements (as small aircraft, or airports) of the civil aviation and general aviation at the beginning of implementation of its operational philosophy. This is a new business needs further market needs evaluation.

The mean idea of developing the 4 seater aircraft with hybrid propulsion system is to develop a new

- 4 (or 6) seater safe and secure aircraft with
- acceptable total life cycle operational cost,
- best “door to door” time (speed),
- reducing the environmental impact (noise and emissions at the airport regions.

The European research project PPLANNE (2017) has analyzed the operational concept of the small and personal aircraft (Rohacs et al., 2011) There were characterized the requirements for developing the future small aircraft by indicators mas shown in table 1.

An example helps in understanding the role of indicators. Somebody has got information that his mother in law living for 400 km distance got heart attack (for example at 10.00 am). At first five minutes, he is talking with wife what to do (10.05). Next five minutes, he is looking for possible flight (ordering air taxi, checking the availability of aircraft owning together his friends or renting the small aircraft with or without the pilot, or any other possible way of travelling to visit the mother in law in hospital (10.10). He is ordering the flight and preparing service of aircraft for flight - 10.15). After that he is using 12 – 15 minutes for deleting next two days meetings, planned works and reorganizing his timetable (10.30). He is taking a taxi and travelling to airport (11.00). He is preparing himself for flight (renting the aircraft, checking the preparation of aircraft for flight, working with administrations, etc. (11.15). He is meeting his wife and children, passing through the security checking setting on board (11.30). He is starting the flight and flying (with developing small 4-seater hybrid aircraft piloted by himself) with cruise speed 260 km/h. 1 hour 45 minutes later he is landing on the target airport, where passing the formal process and going to the taxi ordered during flight (13.30). He and his family are traveling to the hospital and visit the mother in law at 14.00. So, in this example, the user reached door-to-door time 3.5 hours (the 30‘preparation is not included into this time) and door-to-door speed (with taking into another 30 km from city center to the airport and from airport to hospital) 430 km / 3.5 h = 122.86 km/h.

4. CONOPS AND AIRCRAFT DESIGN INPUT

This example is a short and well understandable description of the concepts of operation.

In more technical and short form of ConOps might be defied by the following major features:

- aircraft can be operated by private owners, air taxi or by service provider companies,
- the aircraft might be prepared for flight (by service providers) maximum 30 minutes,
- the aircraft will be operated at the small airport, where all the administrative tasks (including security checking of the passengers, loading the baggage, etc.) might be realized during 15 minutes,
- the aircraft uses electric power during take-off and climb,
- the cruise speed about 250 – 280 km /h,
- the flight time less than 3 hours (not required to have toilet on the board),
- cruise flight level: 70 – 90 FL (equals to 2000 – 3000 m, according to the standard atmosphere, that means not required to build pressurized cabin, or oxygen system),
- in case of using the hybrid propulsion system, engines might be switch off during descent,

Table 1. Applied indicators and their preliminary definitions

Name of indicator	Definition	Dependence	Threshold	Remarks
cost	total life cycle cost related to the one flying hour	- ownership (sharing) - aircraft performance - fuel prices - service provided - airport tax depending on environmental impact - taxation system (preferring the use of electric power)	operational cost of small aircraft below the operational cost of an upper middle size car	The aircraft developed by NASA SATS project members has reached this threshold already.
door-to-door time τ_{DD} or speed V_{DD}	time or speed of the full travel from door to door	- service provided - aircraft performance - distances of airports from city centers - city transport system	$V_{DD} = (2.1 + 0.0004\,R)R^{0.67}$ $\tau_{DD} = R / V_{DD}$ R - distance from door - to – door $[V_{DD}] \rightarrow$ km/h, $[\tau_{DD}] \rightarrow$ h, $[R] \rightarrow$ km	threshold is given as an example
safety and security	risk of accident, risk of fatal accident risk of criminal event risk of successful hijack	- aircraft performance - aircraft control system - air traffic control - cockpit instrumentation - pilot supporting system - pilot, aircraft and air traffic monitoring, emergency situation management - aircraft, airport and air traffic security system - security jurisdiction	risk of accident $\leq 10^{-5}$ risk of fatal accident $\leq 10^{-7}$ risk of criminal event $\leq 10^{-6}$ risk of successful hijack $\leq 10^{-10}$	the defined thresholds may too low, but all these are subjects of further discussions
demand	time of availability of the given aircraft on demand	- number of aircraft, - air taxi services - sharing the ownerships, - informatics system	$\tau_{ad} = 15 + 0.02 * R$ minutes R – door-to-door distance given in km	

- during landing the energy must be recovered,
- aircraft after flight service time should be less than 20 minutes,
- the electric systems must be saved from the cyber-attack,
- the aircraft must be kept on the land safe and secure.

This concept of operation and the analysis the indicators (Figure 1.) defined in Table 1. are the inputs for aircraft development, aircraft preliminary design.

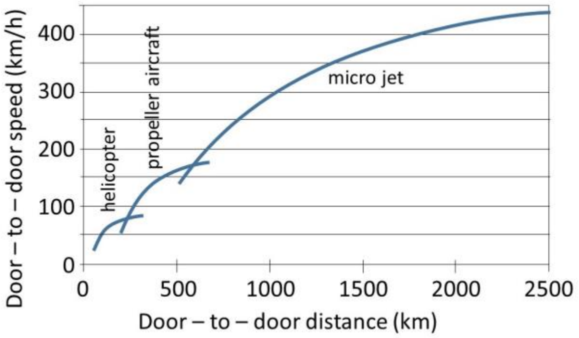

Fig. 1. Types of small aircraft defined by door-to-door distance and speed

The input data, as first design specifications for developing aircraft are the followings:

- 4-seater small (light weight) aircraft (with load 440 kg),
- two propeller hybrid propulsion system (with 15 or 45 minutes clear electric operational time),
- cruise speed: 200 – 260 km/ h, cruise flight level: 70 – 90 FL,
- flight time: maximum 3 hours and range: 400 – 500 km,
- other conditions:
  - aircraft will be operated from small airports with limited equipment,
  - by so called less-skilled pilots (owners having required licenses and knowledge, but limited practice),
  - with integration into the developing ATM system (SESAR),
  - and the operation safety and security levels must reach the thresholds defined in Table 1.

5. AIRCRAFT CONCEPTUAL DESIGN

The goal of the conceptual design is to define the series of different aircraft configurations that meet the design specification and to select and optimize the aircraft layout that is the best solution aircraft from aerodynamic and flight characteristics point of view (Raymer, 1992). A knowledge-based approach (Munjulury, 2016), is applied.

According to our practice (Hargitai, Lovas, 2004; Rohacs et al., 2010a,; 2010b; Bicsak, Jankovics, 2012), the preliminary design must be started by analysis of the markets and markets needs.

As part of the conceptual design, because hybrid and full electric aircrafts are in development phase only and we don't have enough reliable information available to use statistical approach to estimate weight of the aircraft, a weight estimation method, and models had to be built to see whether the a hybrid or a full electric aircraft is feasible at all.

The new propulsion system offers new ways to design aircraft, new approaches can be used, for instance a tandem tilt wing configuration with multi engine or propeller propulsion system, or a multi rotor configuration with or without wings, etc. At present, harmonizing the regulations with these novel configurations means challenge that many aircraft manufacturer cannot afford, not mentioning the user and social acceptance of new design.

Thus we have decided upon, in this very early stage, design a more conventional configuration, because we have experience with these configurations, there are enormous data available to estimate the weight of the structure, and likely with these estimated values the aircraft can meet up the requirements set up by the authorities.

Estimation of take-off mass of hybrid and full electric aircraft started with data collection. Collection of data of conventional aircraft representing the present and past of 4 seater piston engine aircraft. Collected data was used to analyze weight distribution, and validation of weight estimation model introduced later in this paper.

Mass data of more than 30 aircraft was collected by using operational and maintenance handbooks of aircraft and engines. The collection consisted 4-6 seater single- and multiengine piston aircraft. Nine of them were chosen for collecting and estimating distributed mass data. Table 2. represents mass data of 9 well known and popular aircraft. Major parameters e.g. maximum take-off mass, empty mass, commercial load, dry engine mass, maximum fuel mass are manufacturers' data. Weight distribution of aircraft parts were estimated by using statistical methods (Raymer, 1992). Summarizing distributed weight not giving back the maximum take-off mass, usually resulted in higher value, but it is close to it. The difference comes on one hand from the estimation method itself, and on other hand it is an error comes from the manufacturers' data, because the resulting mass of these aircraft loaded up with maximum commercial mass and maximum fuel capacity is higher than the allowed maximum take-off mass.

Analyzing the data, especially the ratio of structural mass and empty mass to maximum take-off mass, one can see that results are almost the same for every aircraft independently to the material used to build the structure. It requires more research but as an initial conclusion we can say that new materials did not result in lower weight, but give more freedom to the designer to design a more streamlined frame. It looks a correct assumption that a new aircraft will have the same weight distribution independently on the type of propulsion system, because if an aircraft have long full electric capability to fly, it

Table 2. Collected data of conventional aircraft

MASS GROUPS [kg]	**SR22T**	**SR22II**	**C177RG**	**C172N**	**C210**	**DA-40**	**DA-42**	**Mooney M20**	**PA-28R**
1. wing	173	173	135	111	183	122	175	163	120
2. fuselage	172	172	134	110	182	121	174	163	120
3. tails	39	39	30	25	41	27	39	37	27
4. undercarriage system	92	92	72	59	97	65	93	87	64
5. systems (control, instrumentation)	25	25	20	16	27	18	25	24	17
6. airframe (sum of 1-5)	501	501	390	320	530	353	507	473	348
7. propellers (with reductors)	143	118	87	77	114	88	290	118	88
8. dry engines	250	195	133	115	187	136	125	195	136
9. fuel	279	279	124	127	263	121	154	280	142
10. propulsion system (sum of 7 - 9)	672	592	344	319	564	346	569	593	366
11. commercial load	477	522	468	400	660	450	620	546	508
12. MTOW (catalogue)	1633	1633	1270	1043	1725	1150	1650	1541	1134
13. empty (catalogue)	1065	1009	802	649	1015	700	1030	995	626
14. number of engines	1	1	1	1	1	1	2	1	1
15. engine power [HP]	315	310	200	160	300	180	135	244	180
16. structural mass /total mass	0,30	0,31	0,32	0,31	0,30	0,31	0,30	0,29	0,28
17. empty mass /total mass	0,65	0,62	0,63	0,62	0,59	0,61	0,62	0,65	0,55
18. material	composite	composite	metal	metal	metal	composite	composite	metal	metal

will require lot of battery capacity which results in great battery weight. To ensure the strength of structure in accordance with regulation, it will result in higher structural weight. This conclusion can be kept in mind during conceptual design process, and offers a good way to estimate the structural weight, which is between 29 to 32% of maximum take-off weight

Research was made for electric aircraft as well. Three electric aircraft, that was not intended to participate in any electric aircraft competition or challenge, are highlighted. These tree were chosen because they already exist in a piston engine version with same geometric and aerodynamic properties. Therefore these versions are closer to a real, commercially competitive configuration than those were built for an endurance challenge where every part of the aircraft was designed to meetup the requirements of the competition.

First one is the Siemens Extra 330LE aircraft (fig.2.), which is a fully electric variant of the famous Extra 300 aerobatic family. The aircraft has already set up 3 world record. It is powered by a 260kW Siemens electric engine. The electric motor weighs 50kg. Its maximum take-off weight is 1000kg, almost the same to the piston engine version. It is important to mention that the manufacturer used the same airframe, with same, or nearly same limitations, that were certified in a piston engine version. Therefore it can carry a limited weight as battery, despite of the weight loss of the engine. The limited amount of battery results in 18.6 kWh capacity. Using this battery pack, the endurance of the aircraft is 15-20 minutes.

Fig. 2. Siemens Extra 330LE (Extra, 2017)

Second aircraft is the Siemens Magnus eFusion (fig.3.) two seater light sport aircraft. It uses a 60kW Siemens electric propulsion system. Its empty weight 450 kg and maximum take-off weight is 600kg. The endurance is about 15'.

Fig. 3. Siemens Magnus eFusion (Magnus,2017)

The third is Pipistrel Alpha Electro (fig.4.), which is the electric variant of the ultra-light, two seated Pipistrel Alpha Trainer aircraft. It has a 550kg maximum take-off mass, 350 kg empty mass and carries 126 kg battery packs with 20 kWh usable capacity. This capacity lets it able to fly up to 60 minutes endurance according to the manufacturer. Published user experiences report the endurance significantly less, depending on the used flight profile.

Fig. 4. Pipistrel Alpha Electro (Pipistrel, 2017)

This three example clearly show the main challenge that an aircraft manufacturer faces during the development of a fully electric aircraft and this is the low energy density of the available onboard energy storage systems. The information from battery manufacturers and data from aircraft manufacturers show that the energy density of a usable Lithium-ion battery system is between 150-180 Wh/kg. In the weight estimation process we used these values, because they well represents the level of available technology.

There is no applicable regulation for a final reserve of an electric powered aircraft. Currently the EU-OPS 1.255 is applicable for flights. According to EU-OPS 1.255 the fuel onboard after engine shut down must not less than the amount needed to fly for a period of 45 minutes (piston engine) or 30 minutes (turbine engine). Electric aircraft introduced before not fulfill these requirements.

The weight estimation process of different configurations requires a mission profile, which was derived from the operational concept of the system (fig.5.). Using the same mission profile in different configurations makes resulting masses comparable to support the decision making process to define the specifications of the propulsion system.

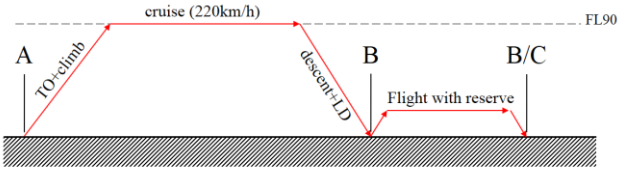

Fig. 5. Mission profile derived from operational concept

The mission profile consist of a take-off and climb segment, a constant altitude cruise at flight level 90 with average cruising speed of 220 km/h, it is followed by a constant speed descend (gliding) and a landing attempt, then a 45 minutes level flight at maximum endurance speed. The distance between point A and B (d_{AB}) was chosen to 400km in accordance with CONOPS. Other constraint was the time to reach cruise altitude, which was given as 15 minutes. Considering the cruising altitude, the average rate of climb cannot be less than 3.05 m/s (w_{cl}), which is an average value in this category.

Range between A and B is given with the following equation:

$$d_{AB} = V_{cl} \cdot t_{cl} \cdot (1 - \tau_{cl}) + d_{cr} + V_{des} \cdot t_{des} \cdot (1 - \tau_{des}) \quad (1)$$

Where d_{cr} distance covered during cruise, V_{cl} and V_{des} are the average ground speed during climb and descent, t_{cl} and t_{des} are duration of flight phase, τ_{cl} and τ_{des} are time fractions representing the maneuvering in the vicinity of airport.

The model uses flight mechanic equations to estimate the required engine power during each flight phases. Aerodynamic and geometrical characteristics were approximated by using of an average 4 seater aircraft configuration derived from collected data introduced before. The engine shaft power required from the engine was derived from steady rate of climb equation:

$$P_{eng_i} = \left(\frac{\mathrm{w}_i}{\mathrm{W_i}} + D_i \cdot V_i\right) \cdot \frac{1}{\eta_{prop_i} \cdot \eta_{trans_i} \cdot \zeta_i} \quad (2)$$

where w_i vertical speed, positive in climb, 0 in level flight, negative in descent $\mathrm{W_i}$ is the actual weight of aircraft, D_i is the drag force at given angle of attack, η_{prop_i} propeller efficiency, η_{trans_i} efficiency of transmission system, ζ_i power settings compared to maximum continuous power settings.

While the output power of an electric engine is constant with altitude, the opposite is true for combustion engines, therefore required power rating of the combustion engine (ICE) at sea level (P_{SL}), was determined with Gagg and Ferrar model (Gudmundsson, 2014), by using required ICE power (P_{ICE}) and density ratio (σ) in a given flight phase.

$$P_{ICE_i} = P_{SL_i} \cdot \left(\sigma_i - \frac{1-\sigma_i}{7.55}\right) \quad (3)$$

Battery capacity calculated by summarizing average electric engine power (P_{eng_i}), power required by aircraft systems (P_{aux_i}), efficiency factor of battery system (η_{elec}), safety factor (ξ_i) and time duration (Δt_i) of flight phase.

$$E_{batt} = \sum_{i=1}^{n} \left(P_{eng_i} + P_{aux_i}\right) \cdot \eta_{elec} \cdot \xi_i \cdot \Delta t_i \quad (4)$$

Knowing the required engine power, electric engine power, and battery capacity, masses of engines, battery and used fuel can be calculated. Take off mass comes after iteration from the sum of structural mass (m_{struct}), payload mass (m_{pay}), internal combustion engine mass (m_{ICE}), fuel mass (m_{fuel}), battery mass (m_{batt}), electric engine and its systems mass (m_{es}).

$$\mathrm{m_{to}} = m_{struct} + m_{pay} + m_{ICE} + m_{fuel} + m_{batt} + m_{es} \quad (5)$$

The model was used to estimate take off mass of a conventional combustion engine aircraft, a hybrid with 15 minutes long full electric flight capability, a hybrid aircraft with 45 minutes full electric flight capability and a full electric aircraft, using geometric and aerodynamic properties of an average aircraft.(Table 3.)

Table 3. Average aircraft

	Take-off mass	Battery capacity
Conventional	930 kg	-
Hybrid (15’)	1320 kg	32kWh
Hybrid (45’)	N/A	N/A
Full electric	N/A	N/A

The iteration process was not converging when the full electric time was 45 minutes or longer. It is because the model used average geometric and aerodynamics properties, which represents conventional aircraft. As a result of it, the required engine power, and used electric energy are high which results in high battery mass.

The optimal solution would be the deviation in geometric and aerodynamic properties from conventional aircraft to gliders, where the required power and energy consumed in every flight phases are lower. Using glider like aircraft emerges some operational problems:

- Increased aspect ratio increase wingspan. It makes ground movements, storage more difficult, or requires other pre- and post-flight operational processes (wing folding) and increase in structural weight, operational costs.
- Gliders have more streamlined cabin, that result in less space in the cabin, less comfort
- Increased wingspan reduces flight controllability, increased sensitivity to turbulences means less comfort
- High speed, and high aspect ratio means aero elastic problems. solving them means higher structural weight, active damping system, etc.

The more glider like an aircraft, the longer full electric flight time can be realized with it, but considering emerging operational problems it is not the right solution, but deviating the shape and dimensions to glider like properties is a reasonable way. The developed model was used to estimate take off masses for a more “glider like” aircraft. (Table 4.)

Table 4. “glider like” aircraft

	Take-off mass	Battery capacity
Conventional	912 kg	-
Hybrid (15’)	1200 kg	25 kWh
Hybrid (45’)	1700 kg	74 kWh
Full electric	N/A	N/A

Results shows that a 45 minutes full electric flight capable hybrid aircraft is feasible. The small change in conventional aircraft take off mass can be seen. It means that it uses less fuel but because the fuel mass was a small portion of total mass, its reduction does not result in large changes, since it has high energy density. The lower the energy density the higher the mass change. It can be clearly seen by comparing the result of table 3 and table 4 (120 kg change in case of hybrid 15').

6. CONCLUSIONS

In this paper, development of the operational concept for the small 4-seater aircraft with hybrid propulsion system was described. Not just simple energetic and efficiency models were used, but more general approach including the safety security and passenger comfort, too. The investigation of the impact, including the compatibility, environmental (noise and chemical emission) impacts were not in focus of this paper, it has been accepted as fact that a hybrid aircraft impact initially less than the conventional aircraft impacts.

Design input parameters were defined from the developed operational concept. Weight estimation model was developed and described to estimate take-off mass of aircraft using different propulsion concepts, according to the operational concepts introduced in this paper.

As a result of the developed model, hybrid aircraft with short clear electric operational time seems feasible at present technical level of energy storage systems, thus the concept of hybrid aircraft with 15 minutes full electric capability looks to be a reasonable choice as an alternative of conventional aircraft.

In long term, full electric and hybrid aircraft (with long clear electric operational time) seems feasible, but the main limit of these concepts is the low energy density of energy storage systems. A breakthrough in energy storage technologies is needed.

7. ACKNOWLEDGMENT

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