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Development of Disruptive and Sustainable Technologies, Concepts for Aviation

HAS Doctoral Thesis

Presented by

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Budapest, 2023

Acknowledgement

I would like to thank my colleagues at the Department of Aeronautics, Naval Architecture for their continuous help and support in various research projects at the national and international level, as well as establishing a friendly, pleasant working environment.

A special thanks goes to József Bokor, Péter Gáspár, István Varga, Ádám Török, Lászlóné Tánczos for their particular advices and discussion that helped me to progress with this thesis.

I express my gratitude to all of my previous supervisors, and managers (i) István Varga, Szalay Zsolt at the Budapest university of Technology and Economics, (ii) Ádám Egry at HungaroControl, (iii) András Levente Gál at the KTI Hungarian Institute for Transport Sciences and Logistics (iv) Vu Duong, Marc Brochard at Eurocontrol, (v) Ivan Lavellee at Sorbonne and (vi) Alexandre d'Aspremont at Princeton University for all the support and guidance that they have provided my throughout my professional career.

My sincere thanks go to my family, girlfriend and Maximilian for supporting and motivating me to complete this thesis, help to overcome the difficult moments and establishing the peaceful environment at home.

Abstract

Seeing the present difficulties of air transportation (in almost all KPIs, such as safety, security, efficiency, predictability, capacity), the stakeholders defined challenging visions and targets in the strategic research agendas and white papers. The ***problem*** is that the defined visions might only be met with the development and implementation of radically new, so-called disruptive technologies, which seeing their complexity require further more mature evaluation and support.

*The **overall objective** of this thesis is to develop advanced modelling techniques, supporting practices and philosophies for disruptive and sustainable technologies, systems and concepts.* This covers (i) the modelling of disruptive technology development (e.g. advanced demand modelling), (ii) the future technology development and deployment (including technology identification, selection, advanced techniques of radically new technology development and (iii) the evaluation and supporting framework definition (with e.g. total impact analysis, energetic evaluation, and advanced safety and security philosophies).

The ***hypothesis*** is that advanced modelling techniques, supporting practices developed in this thesis could help the development of disruptive technologies, systems and concepts, being required to meet the challenging requirements defined by the aviation related strategic agendas and visions.

Disruptive technology development is in focus of all high level strategic groups, policy makers, transportation research programs, key industrial players and the society, which makes the ***actuality*** of the research topic and objective unquestionable.

The ***overall result*** of the author is the contribution to the creation, investigation, test and implementation of future disruptive technologies and solutions helping to reach the ambitious targets of the aviation industry.

The developed methodologies were ***tested and demonstrated*** in various national and international research activities. Results clear showed that the proposed techniques provide an outstanding support for the development of disruptive technologies, systems and concepts.

The findings of the investigations performed are summarized in 5 ***theses***.

This thesis is a restructured and furtherly developed version of the former Habilitation Thesis of the author “Development of Disruptive Technologies and Solutions for Future Aviation, BME, Budapest, 2020”

The major results of the related research activities and the development of the core areas are summarized in the following theses.

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1. Introduction

1.1. Actuality

The history of air transport and generally the development of aeronautics might be approximated by “*S*” - curves known from innovation diffusion theory (Rogers, 2003).

In these days, after the first era related to pistons aviation, the second era, commercial aviation with gas turbines “*S*” – curve is about to end. Therefore, the stakeholders high level groups, leading institutions, aircraft producers, operators and policy makers developed challenging visions (NASA, 2002), (ACARE, 23011), for the future aviation segment (Strategic, 2011), FAA, 2016).

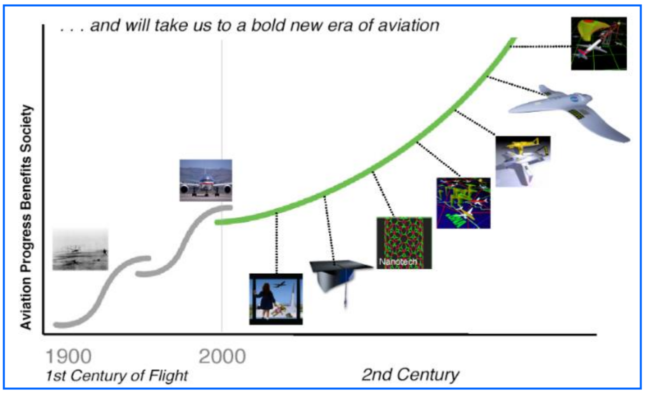


Figure 1. Areas having strong influences on the future aviation (NASA, 2002)

Seeing the limitations of the presently applied technologies and concepts, the established vision calls for ***disruptive concepts, radically new technologies***, on demand services and novel air vehicles, such as drones or supersonic commercial air transportation (see Figure 1.). In this environment, ***the adequate technology identification, selection, development, deployment, and the supporting framework establishment plays a crucial role.*** See for example the methodology developed and applied in the EU FP7 Gabriel project, (Gabriel, 2011 - 2014), (Rohacs & Rohacs, 2016), managed by the author of this thesis.

In this environment, researchers of countries with limited aeronautical industry and support in aeronautics research (like of Hungary) might contribute to the future aviation by (i) using existing technologies in new areas (like the development of drone applications), (ii) joining to major industry players (as Airbus, or DLR) and / or (iii) developing, studying and implementing disruptive technologies, radically new solutions.

In addition to the challenging key performance indicators such as safety, security, efficiency, capacity, predictability or flexibility, the importance of greening and the environmental friendly solutions continues to significantly grow. The global economy and societies face with significant new problems in environmental protection, climate change, circular economy, changes in global energy supply systems. These problems led to the definition of new inspiring targets in e.g. aviation related sustainability, environmental impact reduction or carbon neutralisation until 2050 (UN, 2015), (European Parliament, 2021), (ACARE, 2011), (ICAO, 2022). As a result, numerous research activities focus on greening, and the predicted HGH (greenhouse gas) emission (see Figure 2.). The future will be affected by a series of related aspects like the latest result of sciences and technologies, the availability of the required material and energy sources, the possible changes in the economic or social circumstances. Strategic planning should thus include the modelling of future states or the development process of the directly and indirectly linked governing aspects, framework. This could cover (i) the modelling of disruptive technology development (comprising e.g. an overall future aviation development and complex demand modelling), (ii) the future technology development and deployment (including technology identification, selection, advanced techniques of radically new technology development and (iii) the evaluation and supporting framework definition (with e.g. total impact analysis, or advanced safety and security philosophies.

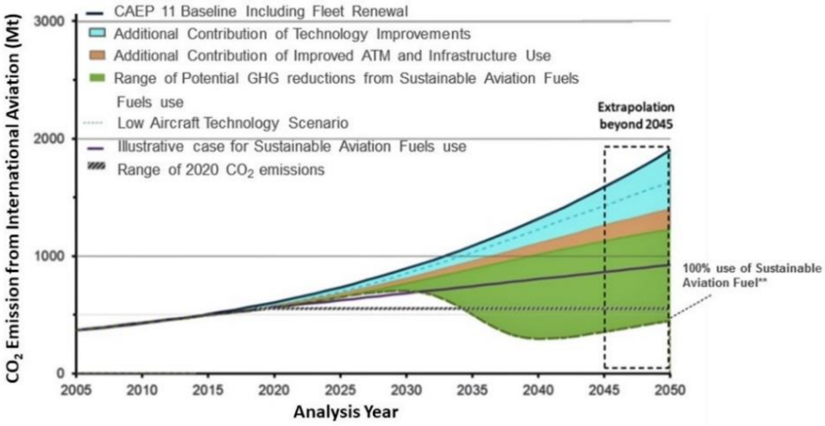


Figure 2. Greenhouse gas emission of international aviation
(Source: ICAO – International Civil Aviation: icao.int/environmental-protection/pages/climatechange_trends.aspx (CAEP 11 – Committee on Aviation Environmental Protection, information on 11th meeting)

These problems in fact represent the general process of developing new technologies and concepts, upon the elements specified in the Figure 3.

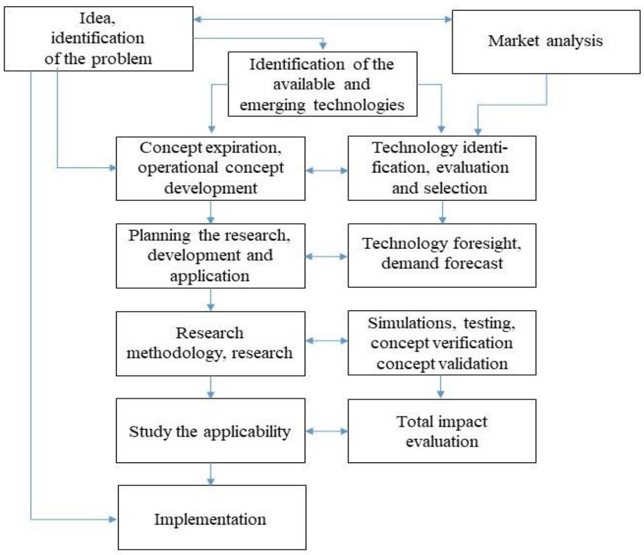


Figure 3. General process of developing new technologies and concepts

The topic of disruptive technology development might be seen rather complex, however,

(i) *high level groups of stakeholders and policy makers* defined ambitious objective that require radically new technologies and solutions,
(ii) *transportation research programs* – including aeronautics and air transportation – are heavily focused on disruptive technologies and solutions,
(iii) *key industrial players* are seeking for outstanding improvements (e.g. in efficiency, greenings, safety, security) and target their attention more intensively on pioneering ideas, since the presently available solutions cannot meet the requirements,
(iv) *society* – following the presently observed trends - is looking for green, sustainable solutions, with the potential of fully exploited alternative energy systems, which should be based on disruptive concepts.

The facts above on the amount of stakeholders being interested makes the actuality of the development of disruptive technologies and concepts unquestionable.

The author of this thesis developed his knowledge and competence at numerous top rated universities, at the SME, national and international governmental, research and industrial sectors, managing various national as well as international projects in the aspects outlined in this thesis. The author focused all of his academic scientific activities to disruptive air transportation. Firstly in his MSc (Rohacs, 2004a), he addressed personal air transportation vehicles, and advanced safety philosophies, concepts. In his PhD (Rohacs, 2007a), and advanced demand model was developed, which later was applied in numerous EU projects related to small aircraft transportation. Since the PhD, the author was involved and coordinated numerous national and international research projects aimed to develop radically new and disruptive technologies / concepts, solutions, systems, including even the related environmental, social, financial / business, regulatory aspects (see for example the magnetic levitation assisted take-off and landing concept). The most important finding were summarized in his Dr. - Habilitation thesis (Rohacs, 2020).

In addition, the author was also involved or coordinated numerous industrial and global strategic plan development activities, for example (i) Disruptive product and service portfolio strategy (HungaroControl, 2019), (ii) National Waste Management Strategy (Ministry of Innovation and Technology, 2020), (iii) Hungarian Drone Strategy (Ministry of Technology and Industry, 2022); (iv) Scientific Strategy (Hungarian Institute for Transport Sciences and Logistics, 2022), (v) Hungarian Air Transportation Strategy (Hungarian Institute for Transport Sciences and Logistics, 2022). These activities permitted to achieve an outstanding acknowledged knowledge in scientifically proved strategic planning, and the identification, evaluation, selection of disruptive solutions.

1.2. Objective

This thesis is the further developed version of the former Habilitation Thesis of the author titled "Development of Disruptive Technologies and Solutions for Future Aviation" defended in 2020" (Rohacs, 2020).

The overall objective of this thesis is to support the future disruptive and sustainable aviation development processes with adequate modelling techniques, supporting practices and philosophies. This covers

(i) the modelling of the disruptive technology development and general innovation process, such as (the development of an overall model of future aviation development advanced demand modelling),
(ii) the future technology development and deployment (including technology identification, selection, advanced techniques of radically new technology development and
(iii) the development of complex evaluation techniques and supporting philosophies, frameworks (with e.g. total impact analysis, energetic evaluation, and advanced safety and security philosophies).

The overall result of the author is the contribution to the creation, investigation, test and implementation of future disruptive technologies and solutions supporting the development of the future aviation segment. Altogether, the investigations led to the formulation of several governing ideas related to disruptive technology development:

- the development of future aviation requires *more precise modelling* to cover the introduction of the major radically new, emerging and future technologies,
- the accuracy of long-term forecasts could be enhanced with *innovation diffusion model technology techniques*,
- disruptive technology development require advanced *out-of-the-box concept generation* methods, and complex *technology selection, evaluation and assessment techniques*
- the integration of disruptive technologies and solutions (such as drones) to the future transportation systems *needs new approaches* (from the business model to the interoperability of the connected other transportation systems).
- the deployment of disruptive technologies require *new supporting framework, philosophies* (e.g. safety and security) and *complex impact assessment methods* considering technical, non-technical, social, financial and regulatory aspects (on the entire life-cycle)

This thesis is structured along the core areas related to disruptive technology development. These are described by the same structured approach including (i) the problem definition, (ii) the basic considerations, (iii) the developed solutions, (iv) the applicability (and examples) of the created solutions, (v) the conclusions and (vii) the results.

All the research activities outlined in this thesis were supported with national and / or international (EU supported) projects. Investigations were performed by high level professional methodologies (applied to research, model-formation, modelling, simulations, testing, impact evaluation) being combined with economic assessment and innovation development processes.

1.3. General methodology

The future state and global aviation development process could be captured with a simple, controllable stochastic model (Figure 4.). This starts with the identification and evaluation of the present. As it can be seen, the progress in sciences and technologies and other changes in required natural sources composes the mainly objective stochastic part in future development and determine the predicted (or predictable) future. It might be examined by technology foresights, forecasts and roadmaps techniques. On the other hand, the economy and society have a vision on the future that they (stakeholders) are expecting. This is the subjective part of the process, called as expected or desired future.

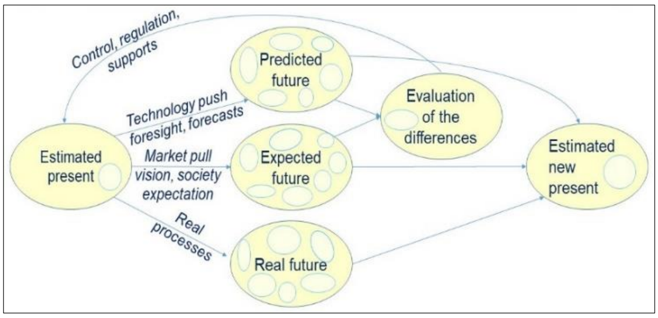


Figure 4. A simple controllable stochastic model of the future development processes.

The estimated difference between the predicted and expected future can be used to generate the required control actions, leading to the expected future. This control includes e.g. a vision generation, strategic goal development, resource allocation (technical and financial support), or supporting framework development (e.g. regulation, safety and security standards). This leads to the “real future”, which might be slightly different from the expected future state, due to e.g. technological, financial, social acceptance or regulatory limitations.

The simplified process might be modelled as controllable Markov process with continues time and discrete state. Of course the process might be improved by applying semi Markov process, hidden elements, or Markov chain with discrete time and space. In any way, the identification or determination of the required state change coefficients (defining the probability density of state changes) result to complex problems and investigations, discussed by this thesis.

The overall model might be created on the basis of innovation theory, with a systems engineering description approach, comprising probability and stochastic processes development theories. The sub-model elements should include various related disciplines, related for example to aircraft design, theory of flight, flight dynamics and control, demand and business models, economics, safety or security. In addition, the model should also comprise the indirectly linked explanatory variables, derived from (i) policy requirements and regulation, (ii) technology developments, (iii) available natural resources and (iv) market, society needs. These could be synthetized on a new level, which is deeply discussed in this thesis, and demonstrated at various examples.

2. Modeling disruptive technology development

2.1. Overall model of future aviation development

Problem

The management of aviation progress – along e.g. the strategic research plans, the society expectations, the socio-economical factors, the envisaged technologies, the available natural resources – is a complex duty, which should be supported with ***an overall innovation process model*** that comprises all major explanatory variables.

Basic principles

The forthcoming air transportation depends on (i) mainly objective aspects, processes as the appearance of new scientific theories, results, the development of new technologies, concepts, the availability of the required natural resources (materials and energy), the human and financial assets (IATA, 2013), (IATA, 2019), and (ii) subjective features, such as the demand of future system defined by the economy or social leaders (as reachable objectives) (ACARE, 2011), (IATA, 2021), (FAA, 2004), (SESAR, 2022). The basic terms affecting the future are briefly summarized in the grey text boxes on the side.

The study, investigation, simulation and management of future developments require competences (i) in basic sciences (material sciences, technology sciences, physics, mathematics), (ii) in integrated multi disciplinary approaches like biomimicry, (Shyam *et al.*, 2022) morphing technologies, (Ricci *et al.*, 2017), (Chu *et al.*, 2022), micro-electro-mechanical systems (MEMS) (Osiander *et al.*, 2017), (iii) in special subjects of aircraft design

Goal *– what you ultimately want to achieve*
Objective *– a way to achieve a goal*
Target *– a specified, realistic, measurable objective*
Vision *– (here) description of the future foreseen, thought and planned by imagination and / or wisdom*
Technology *– knowledge of input application aiming to reach the expected outputs / results*
Solutions *– using the combination or set of technologies to solve a problem or reach an objective*
System *– set of items working together as parts of hierarchically and functionally interconnecting network being available to perform a well defined task*
Aviation *– a special economic sector that develops, produces and operates air vehicles. It has two major parts: aeronautical industry and air transportation (including their development, optimisation, manufacture and recycle)*
Innovation *- use of new ideas, concepts, technologies or services for public good*
Innovation process - *is the entire process from concept inspiration, creation of new idea, through research, development, production, operation, until recycling*
Innovation process generation *- is the establishment of innovation process*
Innovation diffusion *- is the market penetration of the object (product or service)*
Indicator *– a variable selected and defined to measure the progress towards an objective*
Indicator data *– values used in indicators*
Indicator type *– nature of data used by the indicator (qualitative or quantitative, absolute or relative)*
Indicator system *– a process for defining indicators, collecting, analysing data and apply the results*
Indicator framework *– conceptual environment that links indicators to a theory, purpose or planning process*
Indicator set *– a group of indicators selected to measure the comprehensive progress towards the goal(s)*
Index *– a group of indicators aggregated into a single value*
Systems engineering *- is a set of engineering tools to develop the new products and / or services*
Phases of development and product life *– well definable parts of the development and product life that has a determining role in the system development and operation.*

and operations of aircraft, comprising their supporting sub-system (e.g. airport management) (Torenbeek, 2013), (Fageda *et al.*, 2018), (Budd and Ison, 2020), (Graham, 2023), (Galotti, 2019), and even (in) in innovation development techniques, such as innovation theory or systems engineering (Berry and Berry, 2018), (Christensen *et al.*, 2004), (NASA, 2017), (Sales, 2016), (Murman *et al.*, 2016).

The investigation and simulation of the processes developing the future aviation is a rather complex problem because there are too many aspects, factors affecting on the processes, while the information or data to perform the investigations are limited or unavailable. Numerous research activities aiming to cope with this problem, including the definition of future scenarios, or the development of advanced demand modelling techniques (Owen *et al.*, 2010), (Baldwin, 2017) (Terrenoire *et al.*, 2019). A large number of publications are based on general approaches, or a well-defined limited part of future technologies and services, which unfortunately require further efforts to translate them into applicable and solid series of actions (Wensveen, 2015), (Bala, 2021), (Farokhi, 2020), (Kousoulidou and Lonza, 2016), (Rao *et al.*, 2017). On the other hand, one of the most powerful and applicable methodology to define the future aviation was published by NASA, in the SRA titled "Vision 2040" (Liu *et al.*, 2018). It is an extensive work performed by the representatives of the academic, governmental, industrial and national laboratory bodies, organisations.

Technology brokering *- is the creation of the breakthrough innovations at markets fields being otherwise disconnected*
Emerging technology *– radically new technologies that might be available within 5 – 10 years*
Foresight *- is a knowledge (or sound judgment) of a future event that may or may not occur. (This is an act of looking forward. It provide the general inputs for technology policy).*
Forecast *– is the prediction of the future based on estimation techniques. It uses methods from simple trend analysis to complex models dealing with a large series of explanatory variables (drivers).*
Scenario *- is a synoptical collage of an event or series of actions and events.*
Roadmap *- is a plan or guide for future actions that matches the given terms of goals with technology solutions to help meet those goals.*
Business model *- rational of how the system (organization) may create, deliver and capture (economic, social, or other forms of) value – how to make a profit.*
Business plan *- a detailed plan setting out the objectives of a business,*
Strategy *- a method or plan chosen to describe the desired future, such as the achievement of a goal or solution to a problem.*
Sustainability *- meeting the needs of the present without compromising the ability of future generations to meet their own needs, balancing and integrating a prosperous economy, a quality environment, and social equity.*

The key thoughts of the NASA "Vision 2040" document (Liu *et al.*, 2018).
It defines a ***unique methodology*** based on
- the examination and state of the art of different states, called as present (S_p) and final / expected / end states (S_f),
- the estimation of the gaps in the redefined key element environments,
- the definition of the scope, fields, methods of investigations,
- the application of the available modern supporting methodologies, and
- the estimation, identification, evaluation and selection of the possible, recommended actions.

The Key Elements applied by this cited vision are the (i) models and methodologies, (ii) multiscale measurement and characterization tools and methods, (iii) optimization techniques, (iv) decision making and uncertainty quantification and management, (v) verification and validation, (vi) data, informatics and visualization, (vii) workflows and collaboration frameworks, (viii), education and training as well as (ix) computational infrastructure.
Sections of the key elements: definition – current state of the art – 2040 end state – gaps – recommended actions – relationships with order key elements.

Defined crosscutting themes: (i) data management, (ii) data analytics and visualization, (iii) information sharing and reusability, (iv) multidisciplinary collaboration, (v) institutional paradigms, (vi) benchmarking and business case, (vii) scalability and computational efficiency, (viii) linkage and integration, (ix) input/output confidence and reliability, (x) behaviour of materials and structures.
Result of the Vision 2040: roadmap developed for materials and (mechanical) systems.

The methodology of NASA "Vision 2040" (Liu et al., 2018) was generalised to study the entire air transportation segment, adapted to the hierarchically and functionally structured aviation system, reconsidered and redesigned for an overall model (while being applied for larger timeframe based on the available information and data).

Solution

Based on the NASA proposed methodology, future development might be defined according to the transfer from the present (S_n), to the future (S_f) state:

$$S_p \xrightarrow{TF} S_f \qquad (1)$$

where *TF* is a transfer function depending on the implemented actions.

Equation (1) should consider the following three major aspects:

- the states might be defined by using a series of indicators and indexes chosen specially on a goal and objective oriented basis,
- the transfer function leading to the future states should be identified / defined for each applied indicators, indexes
- the applicable models can be classified by the transfer functions / models

For the transfer functions, various available prediction models were investigated, from simple regression, or controllable stochastic techniques, to methods comprising deep learning and artificial intelligence.

The process of developing the future is recommended to be evaluated by an overall index, I_a, (index of aviation) total life cycle assessment (TLCA) related to the governing parameter. The assessment might be defined as cost, emission, greenhouse gas emission, or carbon dioxide emission, while for the governing parameter flight hours (for the aircraft), 100 passenger kilometre (100 pkm), or one tonne-kilometre (tkm) (for air transport) might be applied. For example total life cycle cost per flight hours (TLCC/h_f) or total greenhouse gas emission per 100 pkm ($TLCE_{GHG}$/100pkm) are sound relative indexes. Regarding the type of environmental impact, one might use the so-called direct impact – caused by the aircraft operations only – or the total impact that summarizes all the directly and indirectly associated affects. These indexes might be determined in form of annual total mass of emissions, or as contribution (in %) to the global emission caused by the aviation sector.

Based on these indexes, the development process of future aviation might be represented as a complex stochastic process $\{I(t)\}_{t\epsilon T} \rightarrow I(t)$. See an example at Figure 5., where the thin blue curves define the various aircraft categories (such as a mid-size commercial aircraft operated by the low-cost carriers, or a rotorcraft used as urban air taxi) for the given *I(t)* index (e.g. fuel consumption), while the thick ones give the upper and lower time-depending boundaries (of the index). The index is time dependent and could be given at time t with the distribution function $f\big(I(t)\big)$, showed with a red curve. As Figure 5 shows, the stochastic process $\{I(t,\omega): t\epsilon T\}$ flows in sample space $\omega\,\epsilon\,\Omega$. The red thick curve represents the mean of the process of changes of the selected index. As one might recognise, the stochastic process is non-stationer, thus the distribution function of the random values of indexes are time depending.

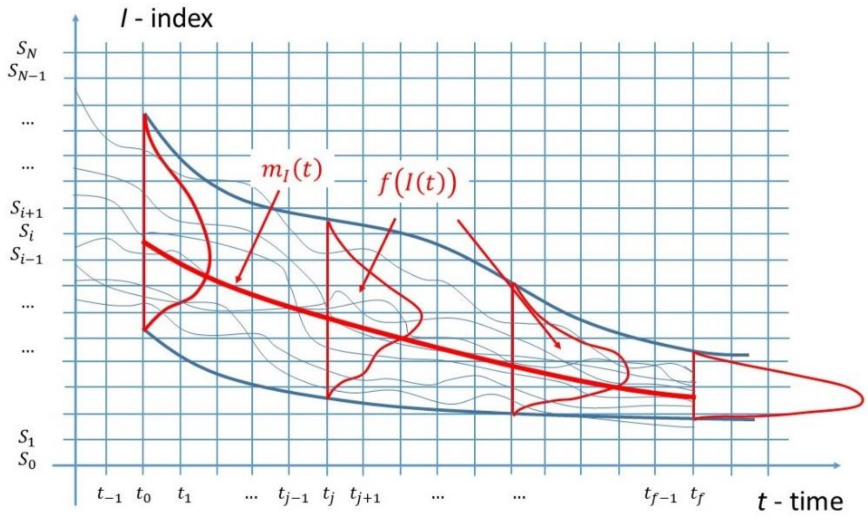


Figure 5. A process example that leads to the future state (explanation in the text)

Let's discretize the time period $\left[t_0, t_1, \dots, t_j, \dots, t_f\right]$, and state (example) space

$$S_i,\ i=1,2,3,\dots N;\quad S_i \cap S_k = 0,\ i \neq k\,, \tag{2}$$

in which "goodness" $S_p \to S_1$,

The process is monitored by the measurements $S_{j,i}$, $j,i = 0,1,2,\dots$ and sets of real values representing the general process I, $x_{r_{j,i}} \in I$, $r = 1,2,\dots,l, j,i = 1,2,\dots$. The investigation of the past data series showed the followings: indicator, I, at time steps represents deformated normal distribution, and „staying" the indicator process in given S_j sub space might be approximated by an exponential function. The *I* index might be defined for classes of aircraft fleets (as long- medium – short-haul aircraft, small aircraft for commercial aviation), which follows a normal distribution. Therefore, the process development, as changes in indicator, I, can be characterised by the transition probability density:

$$\lim_{\Delta t \to 0} \frac{P\{S_{j+1,k} = S_k | S_{j,i} = S_i\}}{\Delta t} = \lambda_{j,ik}\,, \qquad j\epsilon\overline{0,f}\,,\quad i,k\,\epsilon\overline{0,N-1}\,,$$
$$\lambda_{j,ik} \geq 0,\quad \forall j,i,k, \qquad \textstyle\sum_{k=0}^{N-1} \lambda_{j,ik} = 1, \quad \forall j,i\ . \tag{3}$$

Furthermore, the time steps are represented by their starting time, t_j, while the state elements as subspace between the $(S_{i+1} - S_i)$ showed as S_i might be defined by the mean value of changes for the investigated index as $x_{j,i} = \left(x_{j,i+1} - x_{j,i}\right)/2$.

This discretisation allows to introduce the probability of process realisation in the given state at the given time, $p_{j,i}(t_j, S_i)$ for j = 1, 2, …, j, …, f and i = 1, 2, …, i, …, N-1.

Applying these definitions, the mean or expected value, m_I, and the standard deviation, or variance, σ_I, of the investigated process, changes in chosen index can be defined such as follows:

$$m_I(t_j) = \sum_{i=1}^{N-1} p_{j,i}(t_j, S_i)\, x_{j,i}\,, \quad j = 1, 2, \dots f, \tag{4}$$

$$\sigma_I(t_j) = \sqrt{\sum_{i=1}^{N-1} p_{j,i}(t_j, S_i)\left(x_{j,i} - m_I(t_j)\right)^2} \tag{5}$$

Accordingly, the vector of probabilities

$$\mathbf{P}_j = \mathbf{P}(t_j) = [p_{0,j}(t_j, S_1), p_{1,j}(t_j, S_2) \dots, p_{i,j}(t_j, S_i), \dots, p_{N,j}(t_j, S_{N-1})]^T \tag{6}$$

are changed defined by the simple transfers from time „j” to time „j+1”:

$$\mathbf{P}_{j+1} = \mathbf{P}_{\boldsymbol{j}}\mathbf{C}_{j,j+1}\left(t_j, \mathbf{F}(t_j)\right), \tag{7}$$

where **TF** → **C** is a transfer (transition) matrix, or the matrix of transfer coefficients, **F** – is the vector of affecting factors.

The complex problem of modelling the entire process of future developments could be simplified to a technically easier model, with approximating the stochastic process of continuously time and space by the extensively applied stochastic process of discrete time and space. This process is a Markov chain, because the series of chain elements are not depending on the past, but on the current state:

$$\mathbf{P}_{j+1}(I_{j+1} = x_{j+1} | I_j = x_j, I_{j-1} = x_{j-1}, I_{j-2} = x_{j-2}, \dots, I_0 = x_0) = \mathbf{P}_{j+1}(I_{j+1} = x_{j+1} | I_j = x_j,)\,. \tag{8}$$

At this stage, the major problem of the proposed model is the estimation of the transfer matrix elements for each time steps. As preliminary investigations show, the transfer matrix elements are not equal to the elements of the transition probability density, and thus a general controlled process is recommended to be defined, based on the controlled transition density:

$$\pi_{j,ik} = \sum_{k=0}^{N-1} \mu_{j,iq}\lambda_{j,qk}\,, \quad \forall j\,, \quad \forall i, q, k \in \overline{0, N-1}\,, \tag{9}$$

where

$$\sum_{k=0}^{N-1} \pi_{j,ik} = 1, \quad \forall j, i\ . \tag{10}$$

Supposing that the controlled Markov chain is measurable, the Transfer matrix (**C**) might be determined from the following:

$$M[c_j] = \sum_{i=0}^{N-1}\sum_{q}^{N-1}\sum_{k=0}^{N-1} P_{j,i}\mu_{j,iq}\lambda_{j,qk}\ \left(c_{j,qk}^{D} + c_{j,qk}^{S}\right) + \sum_{i}^{N-1}\sum_{q=0}^{N-1} P_{j,i}\mu_{j,ik}c_{j,iq}^{d} = min! \tag{11}$$

where $c_{j,qk}^{D}$ - is the cost related to the measurement and identification of the state $S_{j,k}$ when the process shifts from $S_{j,q}$ to $S_{j,k}$ states,

$c_{j,qk}^{S}$ - is the cost related to the transition of the process from $S_{j,q}$ to $S_{j,k}$ states,

$c_{j,iq}^{d}$ - is the cost related to the transition of the process from $S_{j,i}$ to $S_{j,q}$

states under the applied control.

Seeing the number of strategic research agendas and other visions on the future of aviation, one might consider that the sector's development process is well defined. However, the estimation of the transfer matrix elements is problematic, since the available documents usually provide general visions, future requirements, or challenging guidelines, rather than exact details on the implementation of the emerging and future technologies. For example, the first targeted deadline for the introduction of electric aircraft passed many years ago, mostly due to the unforeseen limitations of the battery technology and resources. In addition, the NASA BluePrint vision (NASA, 2002) and the European Vision 2020 (ACARE, 2001) formulated at the beginning of century envisaged the so called more electric aircraft, while electric propulsion systems and fully electric aircraft configurations only appeared in the later visions as FlightPath 2050 (ACARE, 2011) or the updated Strategic Research and Innovation Agenda (ACARE, 2017). Step changes in process development are thus often caused by unforeseen external circumstances (e.g. crisis, covid, war) or pioneering concepts with low TRL, which gives the prediction a relatively high uncertainty. This problem could be solved with the annual estimation of the transfer matrix elements, which takes into account the technology foresights, roadmaps and realistic predictions on the most important affecting technologies and solutions (see results of further investigation in the following chapters).

Applicability

The assessment of the applicability of the proposed concept should be started by the evaluation of the present (at t_0) and the final (at t_f) states, being defined by the high level ambitious goals of the stakeholders, the society and the economy. Then, the transfer matrix elements must be determined for each time steps, each years. All the elements, $c_{j,k|t_i|t_{i+1}}$describe the transfer from one state S_j to any other S_k state over a step of time from t_i to t_{i+1} for all j = 1,2, …, k, …, f-1 and i = 1, 2, …, N-1.

The detailed investigation of aspects and effects influencing, determining the transfer function elements helped to formulate the following three possible approaches:

- study of all major factors influencing the future development,
- investigation of the hierarchical and functional systems, sub-systems and
- analysis of the available information, data.

Accordingly, the first approach – based on all major influencing factors – is developed, as shown in the Figure 6. As illustrated, four group of factors are defined, (i) natural resources, (ii) the market pull, (iii) the science and technology push and (iv) the policy, indexed as *nr*, *mp*, *stp*, *p* consequently. These are the four sub-coefficients, which could be used to determine the transfer coefficient upon the following:

$$c_{j,ik}|t_j|t_{j+1} = \prod_{l=1}^{4} c_{l,j,ik}|t_j|t_{j+1}\,, \qquad (12)$$

where *l* depicts the major factor groups.

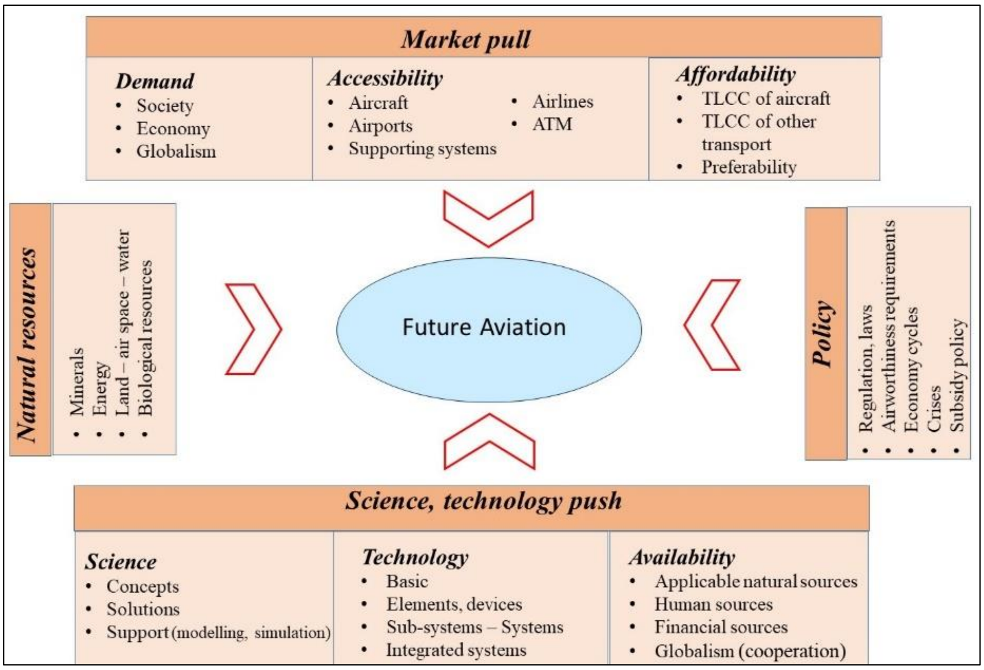
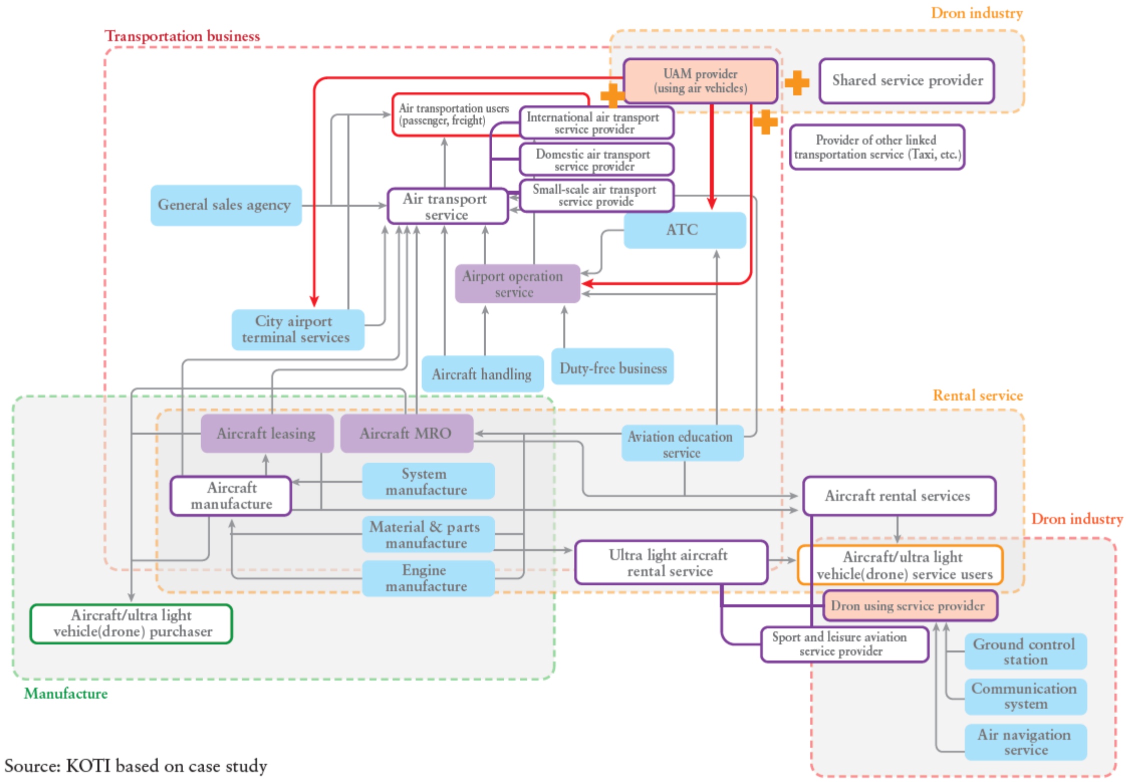


Figure 6. Major factors determining the development of future aviation.

The second approach is based on the hierarchical decomposition of the system to its core sub-systems, and distinguishing for example large commercial operators and low-cost carriers. Figure 7. illustrates a possible functional definition of the air transportation ecosystem, as defined by the Korean Transport Institute (Kim *et al.*, 2019). As illustrated, it is a rather complex layout, with numerous key stakeholders (e.g. aircraft manufacture bodies, aircraft and airport operators, ANSPs, policy makers, research organisation), and several sub-system components (such as communication, navigation, or. engine manufacture). In this case, the determination of the transfer matrix elements follows the same approach as defined at the equation (12), with the application of separated sub-system, elements.



Source: KOTI based on case study

Figure 7. General ecosystem of future aviation (developed by KOTI – Korean Transport Institute (Kim *et al.*, 2019)

The third applicable approach is based on collection, identification analysis and selection of the available information and the determination of the required coefficients accordingly. The available data should be based on various SRAs, technology and industry visions, roadmaps, research and policy papers, or various (e.g. socioeconomic) data banks. This methodology covers since the scientifically sound systematic reviews, simulation and prediction studies, and data mining, big data analysis (Dou, 2020).

Examples

The following chapters of this thesis deal with further investigation of the proposed general model. It studies the applicable indexes, major factors influencing the future, developing radically new technologies, solutions to reach the challenging goals defined by society and economy leaders and policy makers.

Two simplified examples for the application of the developed modelling methodology could be given. The first demonstrates how roadmaps might define the effects of technology development on the predictable process of future aviation. General roadmaps or specialised roadmaps of a particular domain are often optimistic visions on the future, published by large companies and organisations such as Boeing, Airbus, IATA, EUROCONTROL, FAA (IATA, 2013), (IATA, 2019), (FAA, 2022), (US DoD, 2005), (TE, 2022), (Hanlon, 2017). For this investigation, the technological roadmap published by IATA (International Air

Transport Association) (IATA, 2013) was selected. It contains several tables (see Table 1.) that provide promising information on the new concepts, technological solutions, their applicability to aircraft program, possible fuel reduction, technological readiness and their possible implementation date. As shown, numerous potential technologies and concepts were identified to lower the fuel consumption and thus the carbon-dioxid emission. While numbers are promising, real numbers depend on the actual fleet composition, traffic volume evolution, and several other socioeconomic, as well as regulatory factors. It is important to stress, that flying without the landing gear is one of the top rated concepts, which as also addressed by the EU FP7 GABRIEL project, coordinated by the author (Gabriel, 2011 - 2014), (Rohacs and Rohacs, 2016) (see chapter 3.1 and 4.2.).

Table 1. Typical information source on the technology roadmap (IATA, 2013)

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current development status (TRL #)	Availability of technology (calculated)
Aircraft Configuration	Truss-Braced Wing / Strut-Braced Wing		after 2020	10 to 15%	2	2028
	Hybrid-Wing-Body		after 2020	10 to 25%	4	2026
	Cruise-Efficient STOL		after 2020	< 1%	3	2027
	Morphing Airframe		after 2020	5 to 10%	3	2027
	Flying without landing gear		after 2030	10 to 20%	1	2032
Aerodynamics	Advanced Wingtip Devices	Wingtip Fence	retrofit	1 to 3%	9	2012
		Blended Winglet / Sharklets	retrofit	3 to 6%	9	2012
		Raked Wingtip	retrofit	3 to 6%	9	2012
		Split Winglets with scimitar tips	retrofit	2 to 6%	7	2022
		Spiroid Wingtip	after 2020	2 to 6%	7	2022
	High Lift Devices	High-Lift / Low-Noise Devices	after 2020	1 to 3%	4	2026
		Variable Camber Trailing Edge	before 2020	1 to 2%	9	2012
		Dropped Spoiler	before 2020	1 to 2%	9	2012
		Hinge-less Flap	after 2030	1 to 2%	3	2027
	Drag Reduction Coatings	Drag reduction coatings	retrofit	< 1%	9	2012
		Turbulent Flow Drag Coatings (Riblets)	retrofit	1%	8	2015
		Aircraft Graphic Films	retrofit	1%	9	2012
	Natural Laminar Flow		after 2020	5 to 10%	7	2022
	Hybrid Laminar Flow		after 2020	10 to 15%	7	2022

The second example deals with effect of economic, pandemic, or political crises on the development of future air transportation, according to the following 7 steps:

- study of the available information on the air transportation volume (that is getting double every fifteen years),
- evaluation of the effects of crises on air transportation (Figure 8.),
- determination of the general transfer matrix elements based on historical records,
- analysis of the recovery period related to the crisis: for example the effect and recovery time caused by covid are vastly different in size and time relative to any other crisis (see Figure 9.),
- identification of the crisis appearance based on the study and definition of well-known economic cycles (Kitchin inventory, Juglar fixed investment, Kuznets infrastructural investment and Kondratiev long waves),

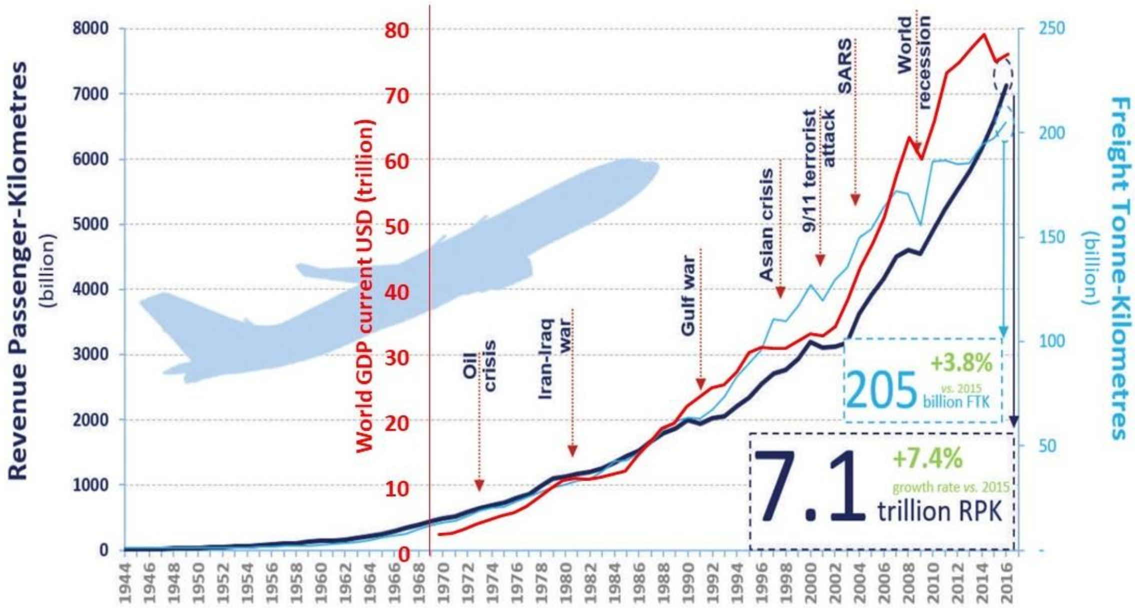


Figure 8. The direct link between air transport volume (ICAO, 2017a) and GDP grows.

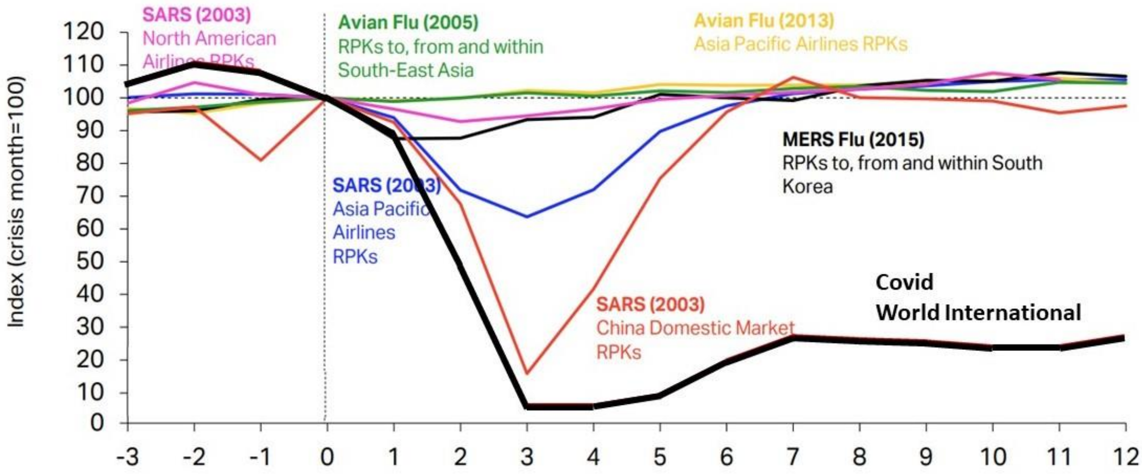


Figure 9. Impact of past disease and covid outbreaks on the aviation segment (combined figures published by (ICAO, 2023)).

- estimation of the changes in the transition matrix elements (7), (12).
- execution of the simulation (Figure 10.).

Figure 10 shows a simulation example. The model illustrated, even the complex effect of covid (e.g. longer recovery time could be considered, and thus provide more meaningful predictions. As found:

- could be easily adapted to special crisis as covid (by the optimal selection of the transfer matrix coefficients),
- could even consider the complex effect of covid (e.g. longer recovery time).

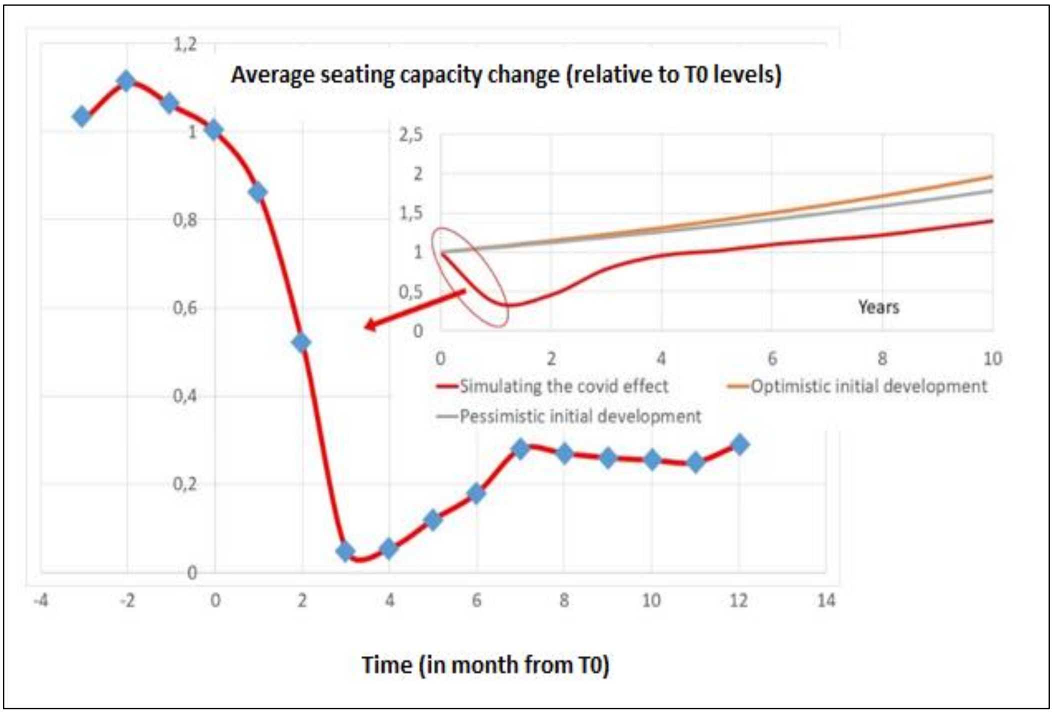


Figure 10. Effect of covid on future aviation determined by the developed methodology

Conclusions

Future as a period of time that is to come depends on (i) the availability of the natural resources (ii) the power sciences and technology push, (iii) the market need, market pull and (iv) the industrial strategic visions, objectives. As a consequence, the process have objective, random and subjective sides, which is a complex process, and that is difficult to model and simulate.

Seeing these circumstances, the proposed method firstly defined special indicators for the complex process identified. The changes of these indexes as a random process of continuous time and state was discretised and approximated by known stochastic process of discrete time and state space, a Markov chain. Finally, the methodology to define the transfer matrix elements was determined.

The applicability of the proposed method was investigated and discussed in the following chapters of this thesis.

Summary

I summarised the available information on the possible modelling and simulation techniques related to the future development of aviation in a general Markov chain model, which approximates the development processes with discretised time and state space.

- The model requires a sophisticated determination of the annual transfer matrix.

- I defined the framework and structure of the major factors – influencing the future development – along the hierarchically and functionally structured system of the aviation industry
- The determination of the transfer matrix elements was solved for several future developments, such as the effect of small aircraft development, the use of maglev to assist the aircraft take-off and landing operations, and the integration of drone in the smart city environment.
- The model and annual transfer matrix estimation were tested and demonstrated with different examples, such as using roadmaps for technology evaluation, or the recovery of the air transportation traffic volume after the crisis generated by covid.
- The methodology and the simulation model is the generalized developed improved version of the model developed by myself at EUROCONTOL, used in my PhD thesis, and numerous other EU research project (PPlane, FORSAT, FOROT, FORJET).

2.2. Demand modelling – applied to small aircraft transportation

Problem

The strategic planning and management of future aviation, and disruptive solutions, require ***advanced demand modelling techniques***, in order to establish sound and mature business models, and market projections.

Air transportation development does not follow the classical product or service diffusions theories, usually faced with lack of data, and thus cannot be forecasted with the classic prediction methods. Advanced demand modelling thus require a new approach and methodology.

Basic principles – study the future

The progress in sciences and technologies pushes and the demand in future aviation pulls the development. The stakeholders' representatives, policy makers working on the industry visions, white papers, managing and policy developments should be supported with sound technology foresights and demand assessments.

Four problems related to small aircraft demand forecast was identified (by FORSAT – Forecast of Small Aircraft Transport project of CleanSky 2) (FORSAT2035, 217-2018):

- The known forecasts might overestimate the real demand and they are rather based on industry feelings (Figure 11.),

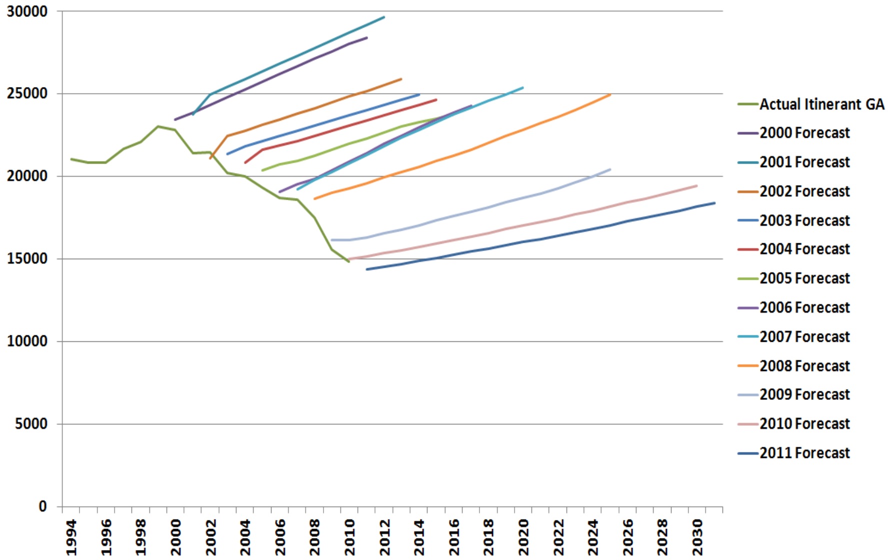


Figure 11. Forecasts of itinerant general aviation operations at all US towered airports (Shetty & Hansman, 2012)

- The demand does not depend on the usually observed major drivers (like GDP or populations) (Figure 12.). For example:
  - As shown in pink colours, even with growing GDP, when oil prices are higher, total small aircraft operations are lower, while these operations are not highly dependent on fuel prices.
  - The recovery after a crisis is usually happens earlier and faster than predicted by the industry experts.

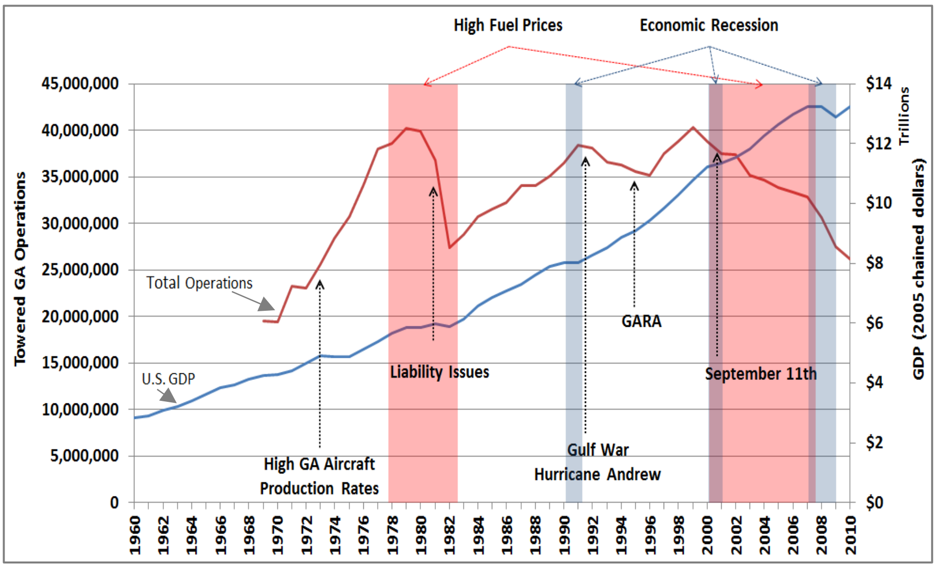


Figure 12. Influences of the economic factors on the general aviation (Shetty & Hansman, 2012)

- The inputs required for demand forecast have serious constraints, as false or missing data (Figure 13.),

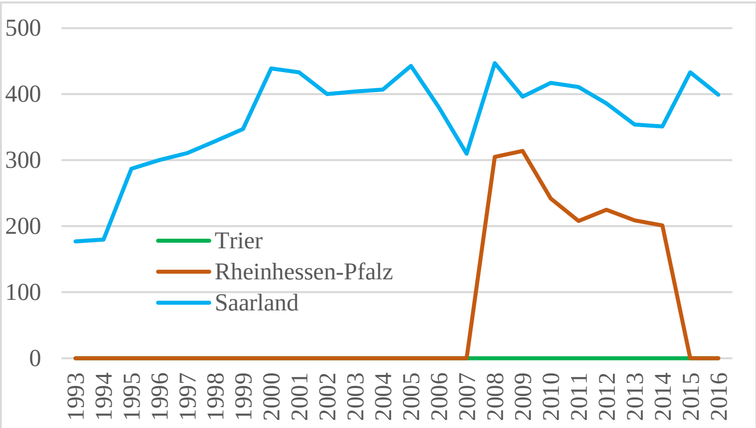


Figure 13. Historical data-series on the number of air passengers (in thousand) of the selected German regions
(source NUTS2 (EUROSTAT, 2018)) demonstrating the available inputs (Saarland), partly available records (Rheibnhessen-Phalz) and completely missing data (Their) (Rohacs et al., 2018)

- There is a lack of information on the technology progress (dummies) initiating step changes in small aircraft development (such as the needs in electric aircraft and their possible introduction to the market).

Solution - Methodology for demand estimation

In Europe, the first extensive forecast studies on small aircraft were performed by EUROCONTROL, aiming to identify and predict the influence of small aircraft on air traffic management (ATM). These studied the results of the NASA AGATE (Advanced General Aviation Transport Experiments), NASA SATS (Small Aircraft Transportation System) megaprojects and assessed the numerous models for demand forecast. The initiatives were dealing with the possible use of known forecasting methods (like regression or gravity models), analysed and developed further models / methods, like Markov approximation, or the estimation of the interaction of the civil air traffic with new small aircraft transportation.

The first results at EUROCONTROL (Rohacs, 2004b, 2005a, 2005b, 2006a, 2006b, 2007b, 2007c) were summarised in a PhD thesis (Rohacs, 2007a). The methodology developed was later applied by the EU supported EPATS (EPATS, 2007) and SAT-Rdmp (SAT-Rdmp, 2010 - 2012) projects (see Figure 14.). The projections were given by simple quantitative econometric model, based on a log-linear or logit models.

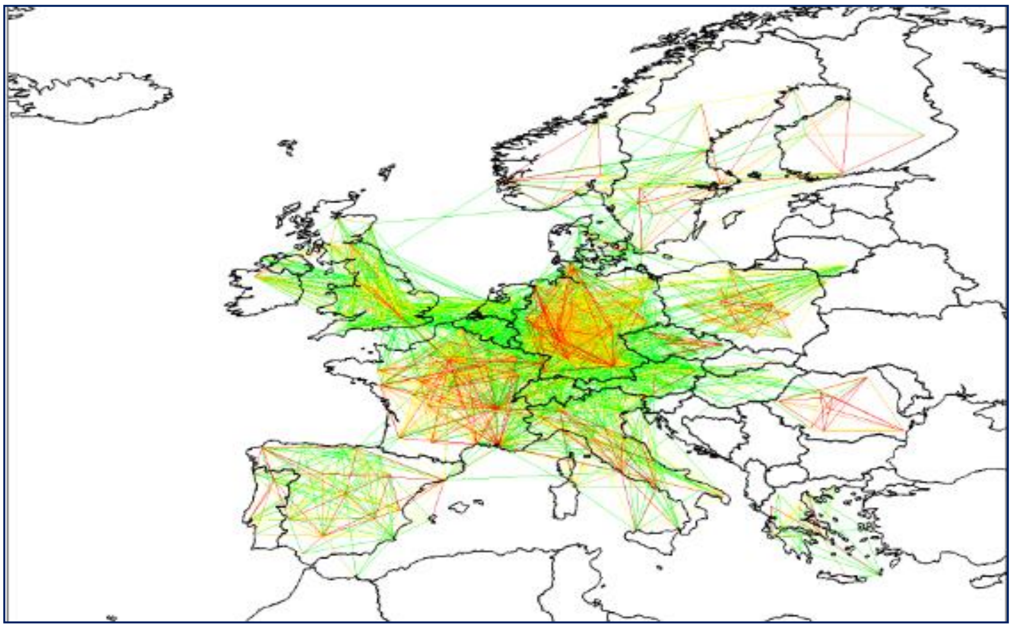


Figure 14. Prediction of small aircraft transportation flights routes for 2035, coloured by the number of daily flights (Ghijs & Rohacs, 2013)

A *log-linear* (or double-logarithmic) model specifies the logarithm of the traffic volume as a linear function of the logarithms of independent variables.

$$\ln(D) = \alpha + \beta_1 \ln(X_1) + \beta_2 \ln(X_2) + \cdots + \beta_N \ln(X_N)\,, \tag{13}$$

where D – is the demand, α is a constant, $\beta_1, \beta_2, \dots, \beta_N$ are the so called elasticities that measures the responsiveness of the dependent variable to a change in an independent variable, $X_1, X_2, \dots, X_N$ are the variables.

The main drawback of the log-linear model is that each elasticity is invariant across all data points, which is powerless in considering unexpected events and novel factors driving the demand.

The *logit models* consider the market shares of alternative transport modes, and thus assessing the mode shift behaviour from road to air transportation. It extends the log-linear form to allow a mixture of categorical and common independent variables and to estimate one or more categorical dependent variables, such as the followings:

$$\ln\left(\frac{S_i}{S_m}\right) = \alpha_i + \sum_{k=1}^{K} \left(\beta_{ik} \frac{X_{ik}}{X_{mk}}\right) + \sum_{n=1}^{N} \gamma_{ik} X_n\,, \tag{14}$$

where S_i/S_m is the ratio of demand *i* to base mode *m*, X_{ik}, X_{mk} are respectively the k^{th} attribute of mode *i* and the base mode *m*, X_n is the n^{th} common variable to all modes, $\alpha_i, \beta_{ik}, \gamma_{ik}$ are the model parameters.

These techniques are however found less appealing, seeing that both rely on a statistically adequate number of past observed records – which are limited if not fully unavailable for disruptive technologies and concepts (Laplace et al., 2011).

Seeing the limitations of the generally applied quantitative methods, other advanced techniques were analysed and developed by the author. The demand of a product – like small aircraft – can be evaluated and characterised by specially formed indicators as *state variables*, together as state vector, $\mathbf{x}$. In this case, dependent variable (demand or market requirement, total cost) might be defined as state vector elements. The changes in state vector is determined by the governing indicators, as GDP, regulatory environment, technology development, as „control" input, $\mathbf{b}(t)$, while the real process is distributed by random values, process, space, being summarized in a noise vector, $\xi(t)$. Mathematically this could be formulated as:

$$\dot{\mathbf{x}} = \mathbf{\Phi}(\mathbf{x}, t) + \mathbf{b}(t) + \mathbf{\sigma}(\mathbf{x}, t)\xi(t) \ , \tag{15}$$

where $\mathbf{\Phi}$ is the deterministic vector describing the rate of change of the state vector $\mathbf{x}$ (as the product of the state and time increment functions); $\mathbf{b}$ is the vector of control effects; and finally $\mathbf{\sigma}$ is the transfer matrix describing impact of the noise disturbance on the state vector $\mathbf{x}$. This equation by replacing the state vector $\mathbf{x}$ by $\mathbf{x} = \mathbf{m}_{\mathbf{x}} + \Delta\mathbf{x}$, the equation (21) could be statistically linearized in the area closed to $\mathbf{x} = \mathbf{m}_{\mathbf{x}}$:

$$\dot{\mathbf{x}} = \frac{d}{dt}(\mathbf{m}_{\mathbf{x}} + \Delta\mathbf{x}) = \mathbf{F}(\mathbf{m}_{\mathbf{x}}, t) + \mathbf{U}(\mathbf{m}_{\mathbf{x}}, t)\Delta\mathbf{x} + \mathbf{b}(t) + \mathbf{\sigma}(\mathbf{x}, t)\xi(t) \tag{16}$$

where $\mathbf{U}(\mathbf{m}_{\mathbf{x}}, t)$ is the sensitivity matrix, i.e. the matrix of partial derivatives of the (vector) function $\mathbf{F}(\mathbf{x}, t)$ respectively to state vector $\mathbf{x}$, determined at $\mathbf{x} = \mathbf{m}_{\mathbf{x}}$.

Research discovered that this class of models could be applied for relatively simple projections, but the exploitation of these techniques is rather limited for disruptive products or concepts, due to the lack of relevant data. In addition, the prediction model in a generalized form is powerless, since the system should reflect special, complex characteristics influencing the demand (e.g. cultural habits, accessibility, importance of greening). These attributes might depend on the regulatory aspects or the application of the novel technologies, which defines rather a complex system with internal coupling and discrete (step) changes.

Seeing the uncertainty related to a new concept or product, a new approach was developed by the author, based on *innovation diffusion theory* (Rohacs, 2007a). This technique is based on the idea of describing the demand – instead of simple econometric models – by a more suitable method and an S-curve, which considers the market penetration of the new product or system (see Figure 15). This approach might better represent the relationship between the technology or product adoption and time, since the new technology or product covers numerous market penetration and adoption phases (e.g. innovators, early adopters, early majority late majority, laggards), with different characteristics (e.g. purchase power, technology openness).

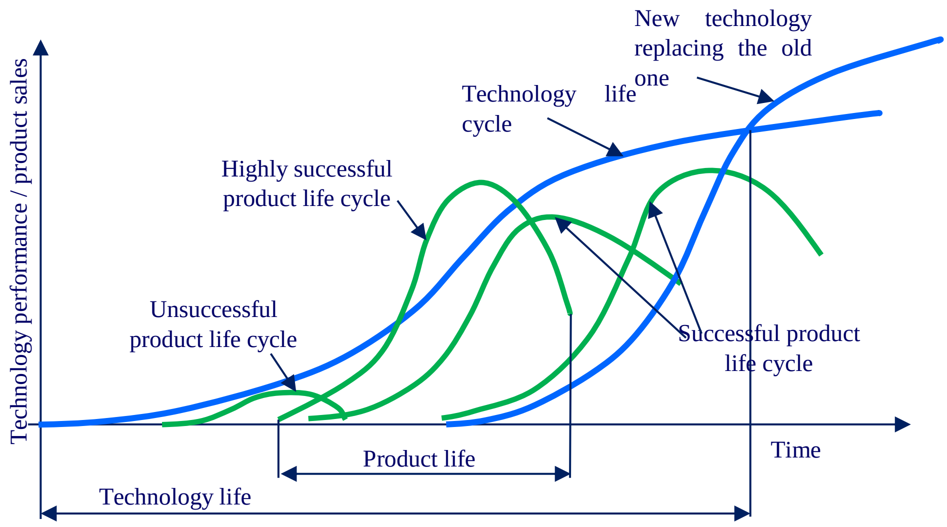


Figure 15. The basic approach based on the S-curve of technology, product life and market penetration.

To describe S-curves, numerous formulas are available, but this thesis recommends the widely used Gömpertz curve, mostly due to its flexibility:

$$VO = S * \exp[-a * \exp(-b * v)]. \tag{17}$$

This model estimates the dependent variable (this time the vehicle ownership per capita: *VO*) at the simulation time *t*, with a saturation level *S*, two model coefficients *a* and *b* and a major independent variable, *v*). While this techniques is capable to capture the real market processes and cope with items without past records, it still require variables on the expected market saturation level, the starting point of the S-curve and the duration of the market penetration. To overcome this problem the author combined the innovation theory approach with the so-called *Travelling Money Budget* (TMB). This, instead of a simple economic approach, considers the proportion of income that the society is willing to devote for traveling. As observed, it is highly a function of given socioeconomic and country specific factors, but usually remains unchanged even in unpredictable events (Zahavi *et al.*, 1981). Accordingly, a given product or technology becomes available on the market (which is the starting point of the S-curve), when its total operating cost reaches the traveling money budget.

Finally, seeing that the real market demand of a disruptive product or item is highly depending on other indirectly linked supporting circumstances (e.g. disruptive business model, new regulatory environment, advanced safety & security philosophies), a new systematic approach was developed and applied to forecast the small aircraft, rotorcraft and business jet segments (in the FORJET, FORROT and FORSAT EU projects) (FORJET2035, 2017-2018), (FORROT2035, 2017 – 2018), (FORSAT2035, 2017 – 2018), (Rohacs et al., 2018). This new approach has the following novelties:

- selecting the drivers after their detailed evaluation (including the reliability and sensitivity),
- selecting the input records (historical and available forecasted data of drivers – sources of statistical information centres, large data sources as World Bank, Knoema, IMF, OECD, Visiongain, or large institutions, international organisation as ICAO, IATA, NASA, Airbus, Honeywell),
- introducing a special method to harmonise the missing or possibly false input data,
- developing a driver identification, evaluation and selection method,
- integrating the demand forecast depending on the accessibility (airport density, provided service as air taxi) and affordability (price of using small aircraft),
- combining the forecast of drivers, available forecast methods (like autoregressive or autoregressive with exogenous term) with “S”-curve (Gömpertz model) in short- and long-term modelling (Figure 16.),
- proposing a basic methodology composed of 5 core steps (Figure 17.),
- introducing dummies and economic cycles to modify the forecast results and
- finalizing the results to estimate the required numbers of aircraft.

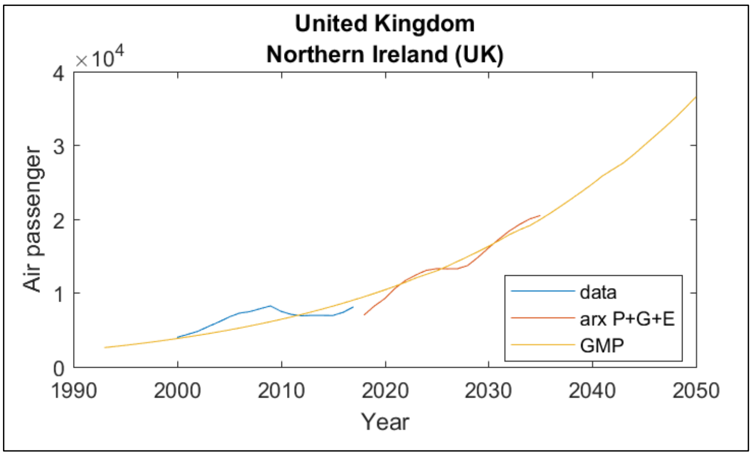


Figure 16. The role of Gömpertz curve in forecasting (Rohacs et al., 2018), (FORSAT2035, 2017 – 2018)
(Here arx – autoregressive endogenous models were applied where P is the population, G stands for the GDP and E reflects the education ratio)

The developed methodology is based on using:

- $d_i(t_0 - t)$ and $d_i(t_0 + t)$, $i = 1, 2, \dots, n$) selected input drivers as historical $(t_0 - t)$ and forecasted $(t_0 + t)$ data,
- f_j , $j = 1, 2, \dots, m$ harmonisation functions (or models),
- d_{m_k} , $k = 1, 2, \dots, p$ – dummies taking into account the appearance of new technologies and
- e_{c_l}, $l = 1, 2, \dots, q$ effects of economic cycles.

$$\left(D_{pkm}(t_0 + t), D_{\frac{a}{c}}(t_0 + t), \dots\right) =$$
$$= \phi(d_1(t_0 - t), d_2(t_0 - t), \dots, d_n(t_0 - t) \tag{18}$$
$$d_{1_f}(t_0 + t), d_{2_f}(t_0 + t), \dots, d_{m_f}(t_0 - t),$$

$$f_1\left(d_1(t_0-t), d_2(t_0-t), \dots, d_n(t_0-t)\right),$$
$$f_2\left(d_1(t_0-t), d_2(t_0-t), \dots, d_n(t_0-t)\right), \dots,$$
$$f_m\left(d_1(t_0-t), d_2(t_0-t), \dots, d_n(t_0-t)\right),$$
$$d_{m_1}(t_0+\tau_1), d_{m_2}(t_0+\tau_1), \dots, d_{m_p}(t_0+\tau_1),$$
$$e_{c_1}(t_0+t), e_{c_2}(t_0+t), \dots, e_{c_q}(t_0+t))$$

Here is an example for the harmonisation functions: the demand generation value (*Dgv*):

$$Dgv = \sum_{i=1}^{n} c_i \delta_i, \tag{19}$$

where c_i are the coefficients defining the role of different factors at the regional level air trips, δ_i is like a Kronecker symbol defining the activity of the given factor (it is equal to 1 once the given factor characterises the regional developments and air trips, and zero if not), $i \rightarrow$ factors as business, agriculture, industry, trade, science and technology, tourism, airports (this last equals to 1 once the region have medium or large size airport(s)).

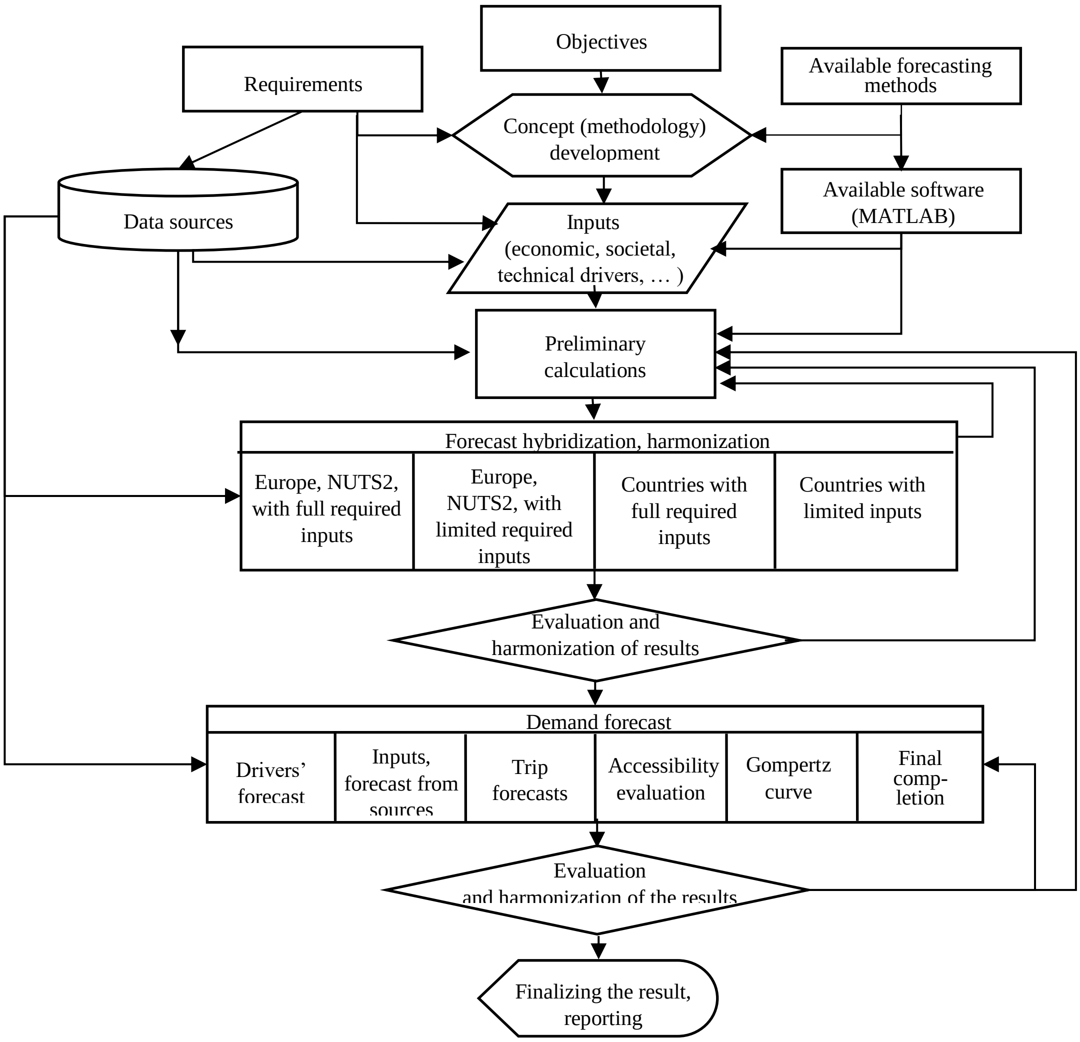


Figure 17. The applied general methodology of passenger demand forecast for the small aircraft segment (Rohacs et al., 2018),, (Wangai, et al., 2019b)

For example the *Dgv* developed for Germany is

$$Dgv = 0.75\,\delta_{\text{business}} + 0.12\,\delta_{\text{agriculture}} + 0.24\,\delta_{\text{industry}} + 0.54\,\delta_{\text{trade}} + \\ + 0.42\,\delta_{\text{science and technology}} + 0.48\,\delta_{\text{tourism}} + 0.45\,\delta_{\text{airports}}\ . \tag{20}$$

Using this technique, the demand generation values equal to 0.6, 1.11 and 2.52 for Trier, Rheinhesse-Paltz and Saarland respectively (Figure 13.). By taking into account these values and the population data on air passengers related to the Saarland region, the basic indicator $\left(I_{ap_b}\right)$ might be converted to the other two regions such as:

$$I_{ap} = I_{ap_b} \frac{I_p}{I_{p_b}} \frac{Dgv}{Dgv_b} + \varepsilon \tag{21}$$

where I_p – is the indicator on the population of the regions, index b related to the basic indicators or values and ε is the white noise with standard deviation 10 thousands air passengers.

The dummies were estimated from the available foresight data and roadmaps developed for different regions.

Applicability

This shortly described methodology was applied in numerous large EU supported and national projects. Firstly, in the EPATS project (Epats, 2007), with a Eurocontrol contract, and with an improved version in the SAT-Rdmp project (SAT-Rdmp, 2010 – 2012) (see Figure 18). Later, the methodology was also used in the EU Pplane (Pplane, 2009 - 2012) and Esposa (Esposa, 2011 - 2014) projects.

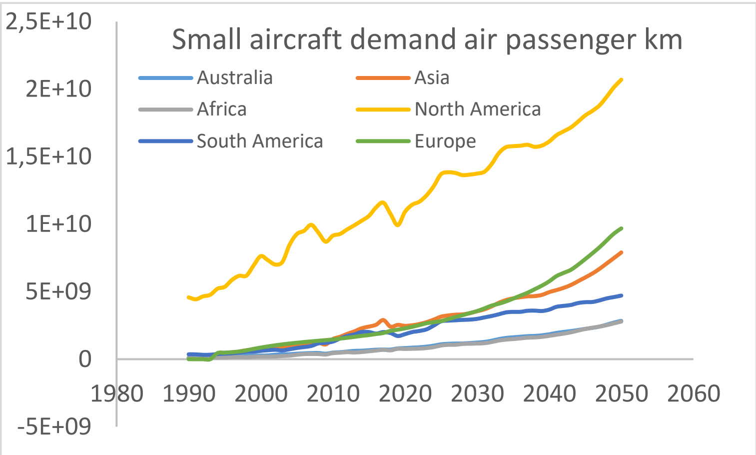


Figure 18. Summarised results of the small aircraft demand in form of passenger kilometres.

The methodology was used to forecast the non-cooperative targets (SINBAD project (SINBAD, 2007 - 2010)) and the Hungarian UAV demand as well (Rohacs, 2008).

The developed technique (as available in 2020) was completed in the FORSAT (FORSAT2035, 2017 – 2018) (Figure 18.) FORROT (FORROT2035, 2017 – 2018) and FORJET (FORJET2035, 2017 – 2018 (Figure 19.) projects (the forecasting team was managed by author). It was adequate for the FORSAT project, as it provided results for the NUTS2 level. On the other hand, its implementation to the FORROT and FORJET projects was powerless due numerous difficulties: (i) the number of small business jets is rather marginal, (ii) the drivers were difficult to be identified, (iii) the usual drivers like the GDP had no determining role, and (iv) the business jet specific drivers are difficult to capture (e.g. the country level registration of the small business jet mostly depends on the possible tax optimisation structures).

The developed methodology and its application was applied in the EPATS (EPATS, 2007), SAT-Rdmp (SAT-Rdmp, 2010 – 2012), (Laplace, 2011), , (Ghijs & Rohacs, 2012), (Ghijs & Rohacs, 2013), Pplane (Pplane, 2009-2012), Esposa (Esposa, 2012 – 2014) and Sindbad (SINBAD, 2007 – 2010), (Rohacs, 2008) projects. It gives the basic approach to FORSAT, FORROT, FORJET PROJECTS, (Rohacs et al., 2018) and was published in several papers, (Rohacs, 2004b, 2005a, 2005b, 2006a, 2006b, 2007a, 2007b, 2007c), (Rohacs, et al., 2005, 2006), (Törő et al., 2018), (Wangai et al., 2019b, 2019c).

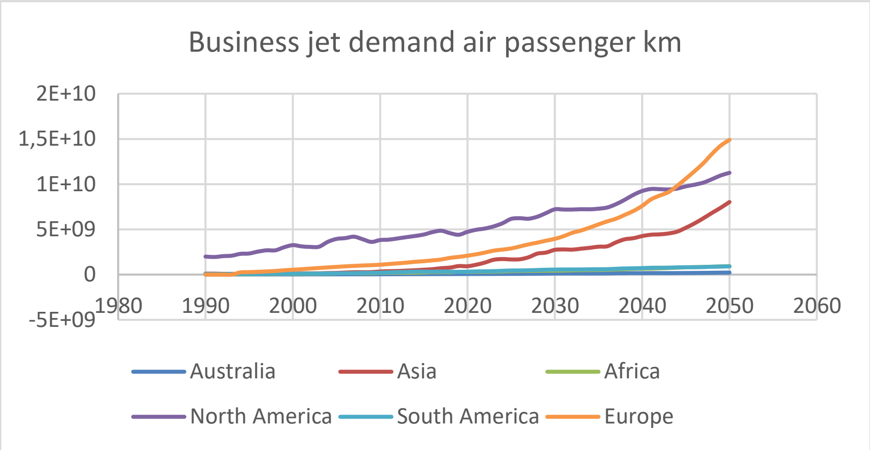


Figure 19. Summarised results of the business jet demand (in passenger kilometres).

Examples

The developed methodology was also applied to several special cases. Figure 20. demonstrates how technological dummies, the introduction of electric and hybrid small aircraft in 2024/25 might radically increase the demand of small aircraft at the Hamburg NUTS-2 region.

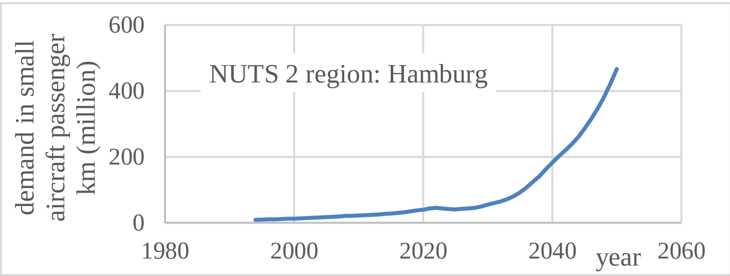


Figure 20. Changes in small aircraft demand induced by electric and hybrid electric aircraft in the Hamburg NUTS-2 region (FORSAT2035, 2017 – 2018), (Törő, 2018)

The methodology was also applied to other transportation mean, to railway transport. The concept was validated by Japan’s historical data (Figure 21.) and records published by (Chester and Horvath, 2009). The methodology was applied to forecast Kenya railway transport (Wangai *et al.*, 2020), (Wangai, 2020) for strategic planning (Figure 22.).

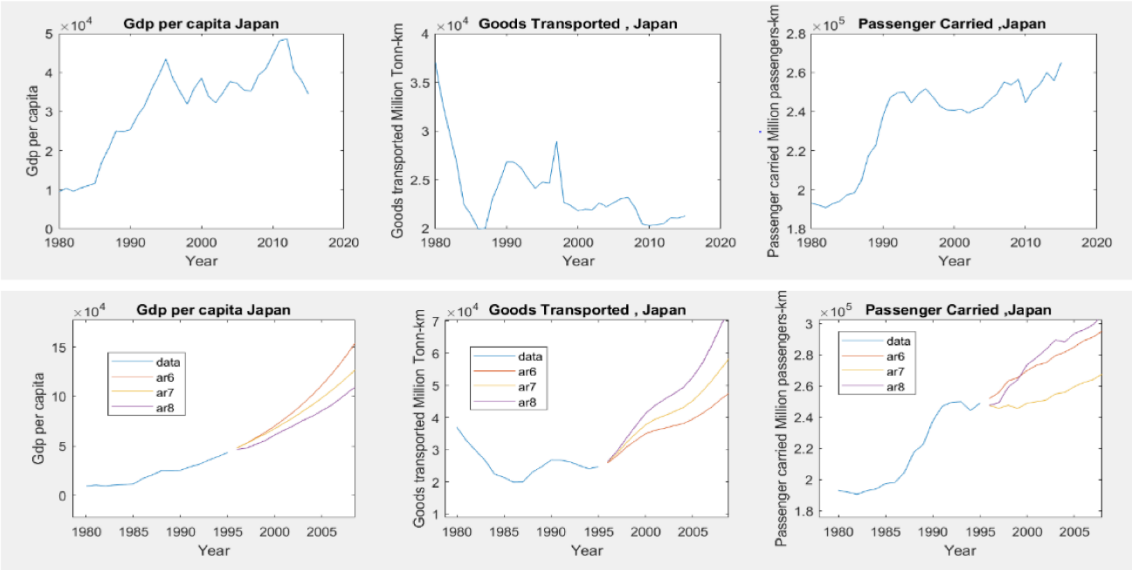


Figure 21. Concept validation using Japan's historical data.

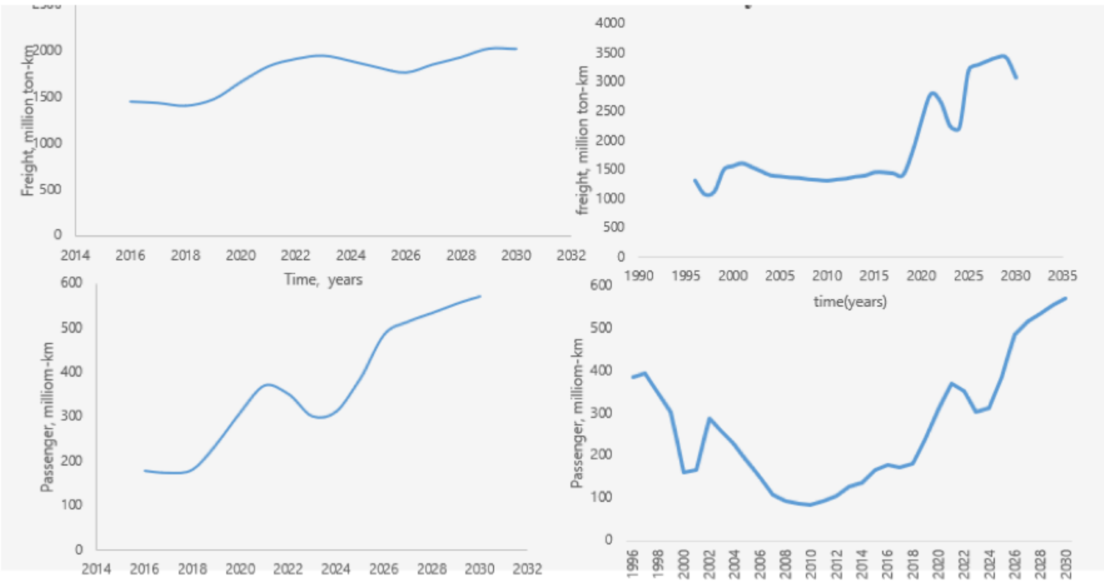


Figure 22. Harmonized demand estimation for freight (upper) and passenger (lower), Kenya railways

Conclusions

After the detailed investigation of the available techniques related to long term disruptive technology forecast, a special methodology was developed, based on the proposed 5 steps summarised in the Figure 17.. This introduces the following major novelties:

- Use of indirectly linked drivers, based on e.g. social, financial, safety, security or regulatory aspects,
- Application of dummies and economic cycles (to capture variables even with high uncertainty),

- Adjustment and harmonisation of the missing or possible false input records,
- Extension of the generally used techniques with more realistic market features based on the market penetration S-curve (Gömpertz curve).

The methodology was used in numerous national and EU funded projects, lastly in the Clean Sky 2 JTI programme (see FORSAT, FIRROT, FORJET projects), and acknowledged by the stakeholders. It supports the modelling of disruptive concepts, both in the technology-push or market pull environments.

Summary

I improved the forecasting methods described in my PhD thesis and I summarised them into a new complex methodology adapted to small aircraft transportation systems.

- The methodology defines the selection of specific drivers, uses the historical and available forecasted data (related to the drivers),
- It harmonizes the input data series, estimates the technology dummies, effects of economic cycles and
- It utilizes a complete five step forecasting method combined with Gompertz curves and advanced socioeconomic constraints (like TMB)
- The proposed methodology was used in numerous research projects, and demonstrated that it could highly support the estimation of market – pull factors in the modelling the future aviation development processes.

2.3. Thesis I

I improved the generally used **forecasting methods**, with advanced demand modeling techniques (applicable for disruptive solutions), based on the following major novelties: (i) using realistic market penetration S-curve, (ii) introducing advanced socioeconomic factors like accessibility, affordability and traveling money budget, (iii) integrating the high level visions available in the technology foresight and roadmaps to better capture the uncertainty linked to the future development of the industry.

- I developed a **special forecasting technique for disruptive technologies** with unavailable past records (such as small aircraft), based on the following 5 step approach (see Figure 17): (i) the selection of specific drivers, (ii) the preliminary assessment of the technological, economic or social effects, (iii) the forecast of the independent variables, (iv) the harmonization of the missing or possible false input records, and (v) the prediction based on a realistic market penetration curve.
- I coupled the forecasting technique with a **market penetration S-curve**, to more realistically capture the relationship between the technology / product adoption and time, and reflect the various market penetration phases (e.g. innovators, early adopters, early majority late majority, laggards), with different characteristics (e.g. purchase power, technology openness):

$$VO = S * \exp[-a * \exp(-b * v)]$$

where VO is the vehicle ownership (or demand) at the simulation time t, with a saturation level S, two model coefficients a and b and a major independent variable, v (in most cases thai is the time).

- I created a special forecasting methodology based on an **annually adjusted transfer matrix** and a controlled Markov chain approximation technique to cope with the lack of data on the future development of the aviation sector by the technology foresights and roadmaps given in the strategic research agendas.

$$m_I(t_{j+1}) = \sum_{i=1}^{N-1} p_{j,i}(t_j, S_i)\, \mathbf{C}_{i.j,j+1}\left(t_j, \mathbf{F}(t_j)\right)\, x_{j+1,i}\,, \quad j = 1, 2, \ldots f,$$

where m_I is the average expected value of the I index at t_{j+1}, $j = 1, 2, \ldots f$ (discretised) time step, $p_{j,i}$ – is the probability of staying at the investigated stochastic process of aviation future development evaluated by the I index in S_i state (S_i, $i = 1, 2, 3, \ldots N$; $S_i \cap S_k = 0$, $i \neq k$) as sub-space of I index, $\mathbf{C}_{i,j,j+1}$ is the „i"- column vector of 3D transfer matrix at j, $j+1$ time step, $\mathbf{F}$ is the vector of factors affecting the future aviation development process, $x_{j+1,i}$ is the determining elements of S_i subspace at t_{j+1} time step (see Figure 5).

- The developed forecast method based on a market penetration S-curve was validated by projecting car ownership records in the past for numerous decades. Results clearly indicated that the projected ownership data followed a regular product S-curve, with marginal deviations from the past real observed data. The developed methodologies were also applied in various large-scale international projects, comprising different disruptive concepts, such as the projection of flying without a landing gear, which clearly demonstrated the applicability and the acknowledgement of the developed techniques.

Most important publications related to Thesis I:

- Wangai, A. ; Macka, M. ; de Graaff, Travascio L. ; Solazzo, M. A. ; Rohacs, D. ; Vozella, A.: "Developing a general methodology for forecasting the demand in small personal aircraft". *Inderscience Publishers. International Symposium On Sustainable Aviation* (ISSA-2019). ISBN:9786058014008 pp. 84-91, 2019
- Wangai, A. W. ; Dung, N. D. ; Rohacs, D.: "Forecast of electric, hybrid-electric aircraft". *Proceedings of International Symposium on Electric Aviation and Autonomous Systems*, pp. 26-31, 2019
- Rohacs, D.: "Kisrepülőgépek elérhetőségének nemlineáris hosszútávú előrejelzése: Long-term Prediction of Small Aircraft Accessibility". *Repüléstudományi Közlemények 19* Különszám pp. 1-8., 2007
- Rohács, D.: "Non-linear prediction model for the European small aircraft accessibility for 2020: Az európai kisrepülőgépek elérhetőségének nemlineáris előrejelző modellje 2020-ra". *PhD értekezés*, BME, 2007.
- Rohacs, D.: "Non-linear probabilistic prediction of the Small Aircraft accessibility: A European model for the piston, turboprop and jet Aircraft". In: *Transport Means 2007* : Proceedings of the11th International Conference, Kaunas, Litvánia : Kauno Technologijos Universitetas, 291 p. pp. 43-46., 4 p, 2007
- Rohacs, D.: "The Effect of Income and Total Operating Cost on Small Aircraft Accessibility in Europe: a prediction for 2020". In: *Proceedings of the 5th Innovative Research Workshop and Exhibition* : EUROCONTROL, pp. 9-13., 2006.

3. Disruptive and sustaining development and deployment

3.1. Identifying, selecting, and developing disruptive technologies and concepts

Problem

There is no adequate method for the identification, evaluation, selection and development of disruptive technologies, while the future aviation targets require radically new techniques, concepts and systems.

Basic principles - Definition and classification of technologies and solutions

Technology is a set of knowledge, human, energy, financial resources, tools, machines, organizational methods, human actions to support products or services developed for public goods (Dosi, 1982) (Montobbio, 2003).

The development of the new technologies appears in three different forms. The first type – called as sustaining technology – brings enhancements on a shorter term and by sustaining the existing solutions and concepts (Rothwell, 1994), (Dodgson, et al. 2002). Higher innovation level is reached by the second type, the so-called disruptive technologies (Christensen, 1997). These destroy the existing systems and develop new solutions, which could be disruptive form a technology (e.g. developing an entirely new technology) or from a market (e.g. focusing on a new market, or with a different business model) point of new. The proposed solutions overcome the existing technologies, initiate radical changes in the given area of economy and a step change in the technological level (Norman, 1998) (Kroo, 2004). Finally, the third type of new technologies is the subversive technologies that cause radical changes on the society level. These are often refered as radical technologies that bring distruptive solution for both the technology and the market in the same time.

Basic principles

Technology and / or solution selection could be classified in the following three major groups:

- selection of existing alternative sustaining technologies, solutions, products, services,
- selection of radically new, disruptive technologies, solutions for further product, service development or deployments in existing systems to radically improve the system performance,
- selection of major technologies, solutions that have a determining role in the future (aviation) development.

In first case, the technology selection is a relatively simple task that could be performed with for example multi-criteria decision making techniques (Hwang and Yoon, 1981). The method is based on (i) the definition of measurable criteria performance to evaluate the alternatives, (ii) the selection of the attributes as inherent characteristics of the alternatives and (iii) the description of the objectives as design space. The multi-criteria decision making could be based on various general methods such as decision matrix, Poreto frontier, direct assignment, eingenvector or entropy, or even on several new approaches as fuzzy sets, genetic algorithm. These lasts are extensively applied in air transportation (Dožić, 2019), even in rather specialised problems as the UAV flight planning (Yang and Yoo, 2018).

The second group, the selection of radically new technologies needs a complex approach, since the performance and reaction of the market on the new solution is unclear. For such cases, the technology identification, evaluation and selection (TIES) is a central problem of the development and application of disruptive technologies and solutions. Probably, the most known and applied TIES method was developed by Kirby (Mavris & Kirby, 1999), (Kirby, 2001).

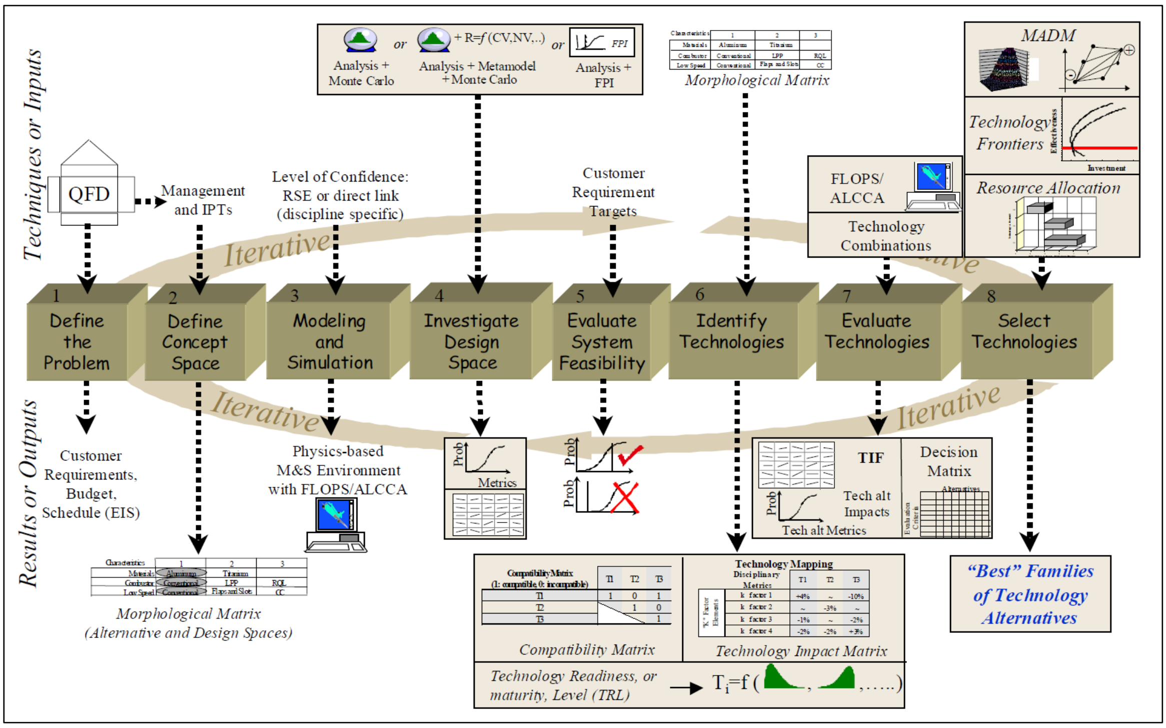


Figure 23. Developed technology identification, evaluation and selection process (Kirby, 2001)

This TIES (Figure 23.) integrates a set of different methods (such as quality function deployment, concept and design space definition, morphological matrix, design – management – integrated product teams, modelling and simulations, operation optimization system, advanced life cycle cost analysis, Monte Carlo simulation, fast probability integration, technical metrics, "k" factors, compatibility matrix, technology impact matrix, technology mappings, decision matrix, multiple attribute decision making, technology readiness level, technology frontiers, resources allocation) into one unique and generally applicable methodology. This approach combines the mathematical models, physics – based simulation, with non-mathematical methods as "k" factors and the systematic approaches. The TIES technique as presented in the Figure 23. is proposed to select disruptive or radically new technologies (see follow-up chapter).

The third group, the selection of major technologies, solutions determining the future is a new and very complex task, and which is out of the scope of this thesis.

Solution - technology identification, evaluation and selection

The existing general TIES techniques have severe difficulties, mostly linked to the fact that there is limited information on the radically new technologies, and their possible application. Therefore, the classical TIES technique was adapted to the selection of the radically new technologies and a new methodology was developed for the evaluation of the new solutions (see Figure 24.).

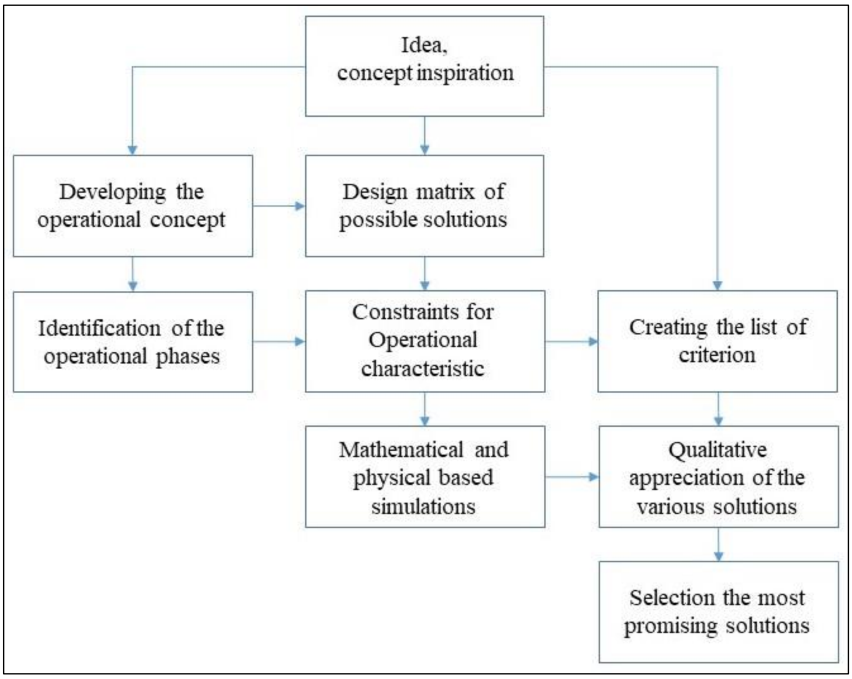


Figure 24. The developed methodology of identification, evaluation and selection of radically new technologies and concepts.

The methodology was based on the author's accumulated practice gained in numerous national and international research projects addressing disruptive technologies (e.g. (EPATS, 2007), (SINBAD, 2007 – 2010), (SafeFly, 2007 – 2010), (Corvus, 2008 – 2010), (PPlane, 2009 - 2012), (Gabriel, 2011 – 2014), Innovate, 2011 – 2014), (Esposa, 2011 – 2014), (Idea-E, 2017 – 2020)). The proposed framework can be shortly described such as the following:

Step 1. Introduction and study of the concept

Generation of the concept, development of the concept applicability, description of the operational concept, study of the regulatory environment, evaluation of the market, social, and financial needs.

Investigation and selection of the applicable technologies, solutions leading to the envisaged product or service (according to the operational concept).

Step 2. Definition of the basic criteria, objectives and constraints

Three types of criteria might be defined or created to evaluate the new technologies, solutions and / or products, services:

- general criteria – indicators determining the future development: total life cycle cost, relative energy consumption, total life cycle emission, noise, sustainability, safety, security, market and society needs, society acceptance;
- specific criteria – parameters, performance of technologies and solutions and /or products, services as technology /product life predicted, availability of the required materials, cost of building the production line, factories, service providing centers;
- comparative criteria – indicators permitting the comparison of the analogical technologies, solutions or product and services being competitors on market, such as physical characteristics, performance of the technology and solution alternatives.

The objectives – usually derived from the operational concept –might be formulated in objective functions, which should be optimized.

The constraints can be estimated on the basis of physical, operational conditions, economical and social needs.

Step 3. Evaluation, estimation of the criteria – preliminary work

- Creation of the decision matrix containing the alternatives $(y_1, y_2, \dots, y_j, \dots, y_m)$ for each criteria $(x_1, x_2, \dots, x_i, \dots, x_n)$.
- Estimation of the decision matrix elements, scores

$$\mathbf{D} = \left(d_{i,j}\right)_{(n\,x\,m)} = \begin{bmatrix} d_{11} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nm} \end{bmatrix} \quad (22)$$

- Standardization of the decision matrix.

  For disruptive technologies, the most promising solutions are leading to minimized cost, fuel consumption, emissions, and maximized safety, security. If the decision matrix elements were estimated by evaluation scores (for example by using 10 classes of merit, with 10 being the best), the decision matrix can be applied without any special standardization. In this case, the following formula might be used to determine the standardized elements, d_{ij}^s,

$$d_{ij}^s = d_{ij} / \max_i \left(d_{ij}\right), \quad i = 1, 2, \dots, n,\ j = 1, 2, \dots, m\ . \quad (23)$$

  Once the decision matrix elements are based on measurable values or changes in the given criteria (in %), the following standardization could be used:

$$d_{ij}^s = \left|\Delta d_{ij}\right| / \max_i \left(\left|\Delta d_{ij}\right|\right), \quad i = 1, 2, \dots, n,\ j = 1, 2, \dots, m\ . \quad (24)$$

Here Δd_{ij} means changes in criteria (in %). Actually, the $\max_i(|\Delta d_{ij}|)$ can be determined as the difference of the maximum expected and minimum accepted changes in the indicator – criterion (in percentage of change).

This methodology proposed to use 2% as the minimum acceptable value of changes (see definition of constraints).

- Creation of the weighting coefficients for the criteria $(w_1, w_2, \dots, w, \dots, w_n)$, that depend on the consideration of physical objective conditions, regulatory requirements, economic and social needs as well as (subjective) expectations.

Step 4. Selection of the most promising technology, solution for further deployment.

Once using the first type of standardization (29), the selection can be based on the following simple function maximizing the selected criteria goodness:

$$y_s = \max_j \left(\sum_{i=1}^{n} w_i d_{ij}^s \right) \quad (j = 1, 2, \dots, m)\,. \tag{25}$$

In case of using the relative changes in indicator-criteria, the maximum average value may represent the selection in a more comprehensible form for the users:

$$y_s = \max_j \left(\frac{1}{n} \sum_{i=1}^{n} w_i d_{ij}^s \right) \quad (j = 1, 2, \dots, m)\,. \tag{26}$$

For disruptive solutions, the comparison of the existing and the proposed new products and services and their alternatives increases the role of sound and well-defined criteria. In such cases, the criteria vectors are recommended to be divided into two vectors $(x_1, x_2, \dots, x_i, \dots, x_n)$ and $(z_1, z_2, \dots, z_k, \dots, z_q)$. The decision matrix, *D*, is and the weighting coefficient vectors are also divided into two parts. Accordingly, the introduced novel selection method could be given as:

$$y_s = \max_j \left(\sum_{i=1}^{n} w_i d_{ij}^s + \sum_{k=1}^{q} w_k d_{kj}^s \right) \prod_{k=1}^{q} \delta_k(z_k) \quad (j = 1, 2, \dots, m)\,, \tag{27}$$

$$y_s = \max_j \left(\frac{1}{n} \sum_{i=1}^{n} w_i d_{ij}^s + \frac{1}{q} \sum_{k=1}^{q} w_k d_{kj}^s \right) \prod_{k=1}^{q} \delta_k(z_k) \quad (j = 1, 2, \dots, m)\,, \tag{28}$$

where $\delta_k(x_k) \rightarrow \delta_k(z_k)$ is a symbol, working with analogy to the Kronecker symbol, and thus being one if $(z) \in \{z_{k,min} \div z_{k,max}\}$ and zero otherwise. Here $\delta_k(x_k) \rightarrow \delta_k(z_k)$ means that *z* might be a special characteristic, performance like flight risk.

Applicability

The developed methodology was applied in the EU FP7 L1 research project titled the "Integrated Ground and on-Board system for Support of the Aircraft Safe Take-off and

Landing study (GABRIEL)" (Gabriel, 2011 – 2014), (Rohacs & Rohacs, 2013b, 2014b). The author of this thesis was the technical manager of the project. This out-of-the-box initiative investigated how magnetic levitation might be used – as a ground-based power – to support the aircraft take-off and landing processes (Truman & Graaff, 2007), (Rohacs & Rohacs, 2015). The methodology introduced here on the selection, development and deployment of disruptive technologies was used in the concept generation, and also along the conceptual design, verification / validation duties (Rohacs & Rohacs, 2014b, 2016).

This project assessed the possible improvements of the aircraft take-off and landing processes (Rohacs, et al., 2012b), (Rohacs & Rohacs, 2014a), (Vos, et al., 2014). Altogether 15 different possible methods were studied to reduce the energy required for the aircraft take-off and landing phase. These covered for example (i) the high altitude airport concept served by special lift or aerostatic ships, (ii) the cruiser – feeder approach, (iii) the use of individual electric engine UAV accelerators, or electric catapults, and (iv) the application of magnetic levitation technology.

It was found that the use of magnetic levitation technology is the most promising technology to radically increase the energetic efficiency, while cutting the environmental impact at the airport vicinities. Furthermore, 7 more detailed alternative maglev related concepts were created, such as (i) using conventional or adapted smaller landing gears with the maglev track, (ii) removing the landing gears and magnetically hovering the aircraft along the runway, or (iii) applying a dedicated maglev accelerated ground sledge and a cart for the ground movements. These possible solutions were tested against four major groups of criteria as greener air transport (noise, emission, aircraft weight, performance, operational cost, energy reduction), complexity (reliability, availability, maintainability, airport capacity, complexity), safety (safety, impact of cross-wing emergency landing, security) and concept requirement at the airport (transition period, integration to the airport operation, required investments) (Schmollgruber, et al., 2012). The investigations performed suggested to use a configuration based on a cart with gears and a sledge being levitated above the maglev track (Figure 25.).

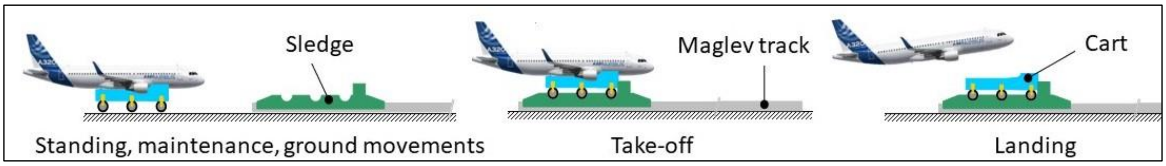


Figure 25. Operational concept of the Gabriel project (achieved by the developed technology identification, evaluation and selection methodology).

Once the framework of the proposed operational concept was available, the next task was to analyse and select the most appropriate magnetic levitation technology (Schmollgruber, et al., 2012), (Rogg *et al.*, 2013) (Rogg, et al., 2013). From the existing and mature magnetic levitation systems (Lee *et al.*, 2006) and developments, the followings found to comply with the defined requirements: (i) EDS SCM: Electrodynamic Null-Flux with superconducting magnets, (ii) EDS PM: Electrodynamic Combined Flux with permanent magnets in Halbach Arrays, named "Inductrack System", (iii) EMS LSM: Electromagnetic levitation with synchronous longstator propulsion, and (iv) EMS LIM: Electromagnetic levitation with Linear Induction Motor (Rogg *et al.*, 2013), (Rohacs and Rohacs, 2016).

These maglev systems were evaluated by using a multicriteria decision analysis (Table 2) and physical simulations.

Table 2. shows that the evaluation for a mid-size aircraft (like A320), according to numerous predefined criteria, resulted in the selection of the Electrodynamic Levitation technique with Permanent Magnets in Halbach Arrays, often called as the Inductrack concept.

Table 2. The evaluation results of the candidate maglev technologies

Criterion	Priority Factor	Result of the Preliminary Evaluation without Priority Factor				Result of the Preliminary Evaluation without Priority Factor			
		EDS SCM	EDS PM	EMS LSM	EMS LIM	EDS SCM	EDS PM	EMS LSM	EMS LIM
Levitation Capability	3	8	8	4	2	24	24	12	6
Speed / Acceleration Capability	3	7	9	8	3	21	27	24	9
Complexity of Guideway	2	4	7	6	7	8	14	12	14
Complexity of Vehicle	2	3	9	4	2	6	18	8	4
Electrical Power to be Installed	3	7	8	6	4	21	24	18	12
Energy Consumption per Launch	2	7	9	7	5	14	18	14	10
Levitation at Standstill / Take Off- and Landing Velocity	1	3	5	10	10	3	5	10	10
Magnetic Stray Fields 0,5 m Above Magnets	1	0	7	10	10	0	7	10	10
Safety Suspension System	3	10	8	10	10	30	24	30	30
State of Development / Development Risks	1	9	5	10	10	9	5	10	10
Potential of Further Development	1	6	6	3	3	6	6	3	3
Operation/Maintenance easy – difficult (assessment)	2	5	8	6	6	10	16	12	12
						152	**188**	**163**	**130**

This was also in line with the performed physical simulations (Figure 26.).

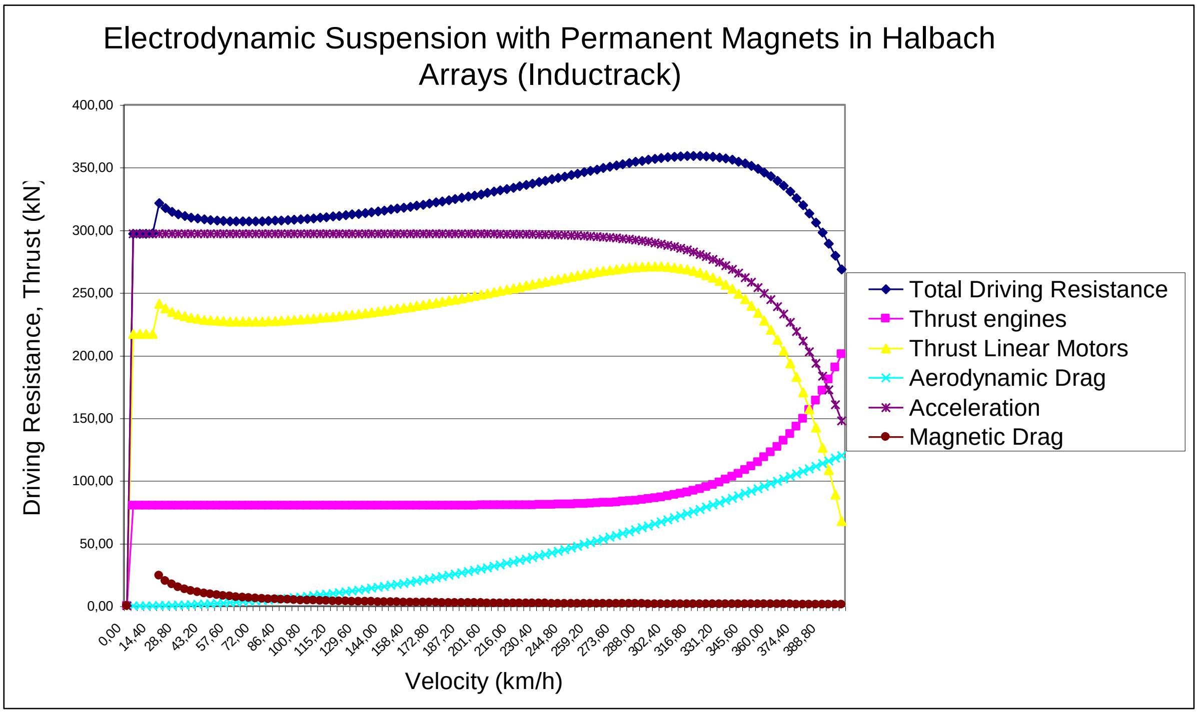


Figure 26. Evaluation of EDS PM technology for reaching 400 km/h take-off speed.

In the selected EDS PM technology, the levitation is performed by an electro dynamic difference flux system with permanent magnets. The sledge is accelerated and decelerated by an electrical synchronous long primary motor, which is supplied by converter units with variable voltage, current and frequency. The main components of the GABRIEL ground system are the guideway, magnetically levitated sledge/cart system, power chain, linear propulsion, controlling and supervision equipment. Figure 27. shows a cross section of the guideway and the levitation frames of the sledge. It is a rather complicated configuration, but this is necessary to meet the following GABRIEL requirements: (i) maximum speed 75 - 110 m/s, (ii) acceleration from 2 to 4 m/s² and (iii) thrust from the engines of the aircraft from 0 to 100%.

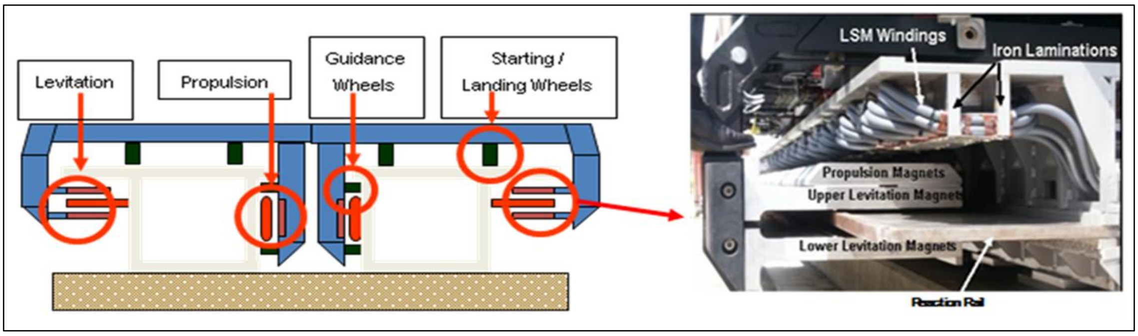


Figure 27. GABRIEL ground system, the cross section of the guideway and the sledge.

Note: The chosen magnetic levitation technology has a series of advantages and disadvantages. One of the interesting and important disadvantages is related to the source of the required material. More particularly, to construct the magnetic levitation systems, rare materials are required, such as the Neodymium. Permanent magnets, used in levitation systems, usually consist of a material, composed of Nd2Fe14Bo (Neodymium, iron, boron), which has the best performance of all permanent magnetic materials developed up to now, with its permanent field of 1,4 T; energy density of 300 kJ/m³ and coercivity of 1.000 kA/m.

There is a huge demand for neodymium, as these magnets are widely used in all branches of electric and electronic industry as well as for electric automobiles and wind energy generators. The main mining areas of neodymium are in China. It may be difficult to predict the availability and the market price on the long run. The development activities in the field of permanent magnetic materials should be observed, with the aim to replace neodymium by a less rare but equivalent material. Moreover, these magnets are not easy to handle, because of the strong magnetic forces, and thus require special skills and tools.

Examples

Other application of the developed methodology is related to (i) the conceptual design of a cargo UAV resulted in unconventional forms of structural solutions (IDEA-E, 2017 - 2020), (gal, et al., 2018), (ii) the concept development of personal aircraft (PPlane project (Rohacs, et al., 2011)), (iii) the development of the Corvus Racer 540 (Corvus 2008 – 2010), and (iv) the system development of optimized energy mix generation for residential buildings (MATE, 2022), (Rohacs, 2023a).

Conclusion

As showed in various projects and research activities, the proposed methodology (i) could be used in different domains with alternative level of innovation, (ii) might be easily adapted to the domain specific requirements (e.g. assess total life cycle cost evaluation, (iii) is based on the definition of design criteria and the use of a design Matrix of alternative solutions, which (iv) could be qualitatively evaluated to find the most promising alternative.

Summary

I adapted and developed the technology identification, evaluation and selection method to the selection and development of disruptive technologies and radically new solutions (systems, products and services).

- This method is based on the development of a design matrix (of the potential solutions), its evaluation (upon the operational phases, as well as the weighted scores of operability and other selected criterions) and using the methods of multi criteria decision making modified to the selection of the radically new technologies and solutions.
- The proposed method was applied in the technology identification, evaluation and selection process related to the Gabriel project, which clearly illustrated how such complex disruptive initiatives could be supported with ease, and how much the project results are dependent on the appropriate technology selection and evaluation.
- The proposed methodology was also applied to develop a smart map showing the locally availability renewable energies and propose the optimal energy generation mix for residential, public and industrial buildings.

3.2. Using out-of-the-box approach for the development of radically new solutions – the Gabriel concept

Problem

The challenging requirements defined in the air transportation related strategic agendas and roadmaps (ACARE, 2011), (IATA, 2021), (ICAO, 2022) ***require disruptive and radically new technologies***, since the sustaining developments are only leading to marginal improvements.

Basic principles

The methodology described shortly below, was created in the EU FP7 project titled "Integrated Ground and on-Board system for Support of the Aircraft Safe Take-off and Landing study (GABRIEL)", and coordinated by the author of this thesis (Gabriel, 2011 - 2014), (Rohacs & Rohacs, 2014b, 2016). In the development of maglev assisted aircraft take-off and landing processes, European research activities are globally outstanding (Baterin, et al., 1997), (NAVAL, 2016)..

The Gabriel project investigated how magnetic levitation might be used – as a ground-based power – to support the aircraft take-off and landing processes. Such radically new disruptive technologies and solutions might be developed by out-of-the-box approaches (Truman & Graaff, 2007), (Rohacs & Rohacs, 2015). The methodology introduced here on the selection, development and deployment of disruptive technologies was used in the concept generation, and also along the conceptual design, and concept verification / validation duties (Rohacs & Rohacs, 2014b).

In the development of maglev assisted aircraft take-off and landing processes, European research activities are globally outstanding (NAVAL, 2016), (Batenin, Bityurin, Ivanov, Inozemzev, & Gorozhankin, 1997).

Solution – proposed methodology

The created and proposed methodology is summarized in the Figure 28. As illustrated, is has five major steps:

1. Idea development and concept inspiration: according to the financial, market and regulatory expectations, based on the latest result of sciences and technologies.
2. Concept development: including (i) the assessment of the stakeholders' understandings on the mission and operational objectives (expectations), (ii) the problem definition (including the technical, non-technical, social, financial and regulatory aspects), (iii) the study of the available, enabling, emerging and future technologies, (iv) the estimation of effects of new technologies and solutions on the proposed solution, (v) the operational concept development, and (vi) and identification of the mission success criteria.
3. Theoretical investigations: comprising the conceptual design and the technology selection methodologies

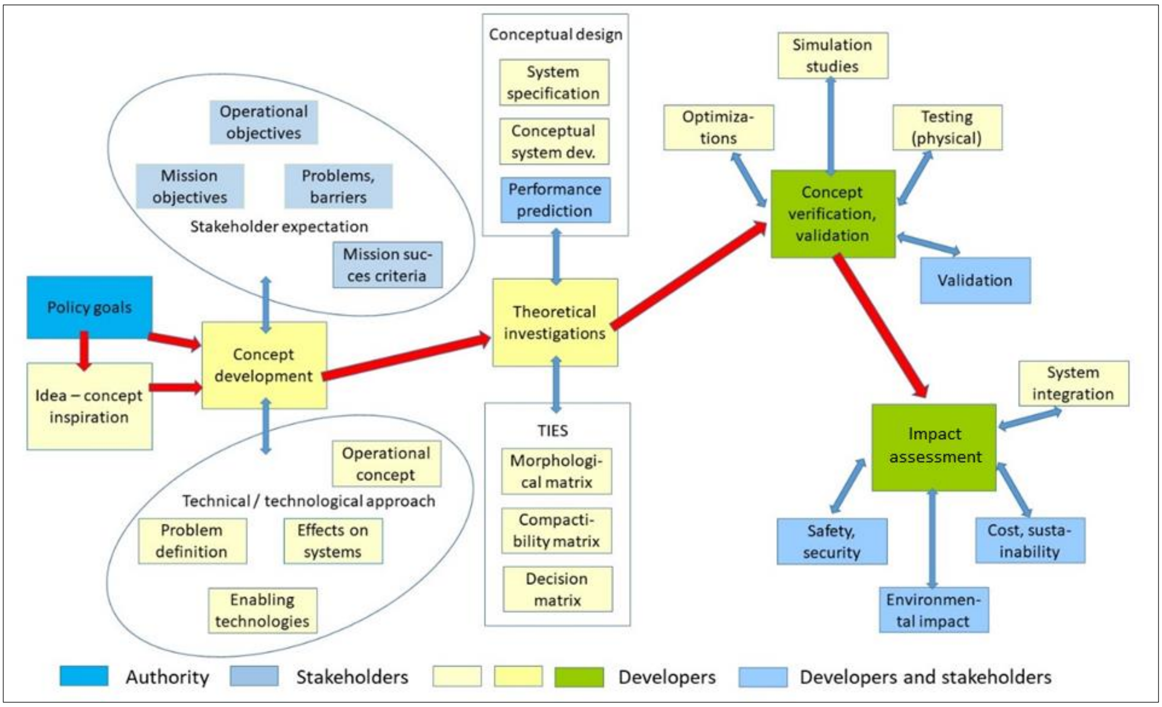


Figure 28. The proposed concept development and validation methodology (where TIES stands for technology identification, evaluation, selection)

4. Concept verification and validation: based on various simulations or physical tests, and even on consultations with the stakeholders
5. Impact analysis: details assessment of the results regarding e.g. financial, environmental, safety, security, social or regulatory aspects.

Applicability

The Gabriel consortia introduced an original idea (see chapter 3.1.) and intended to show the feasibility based on existing and well-applied methods (Rohacs, et al., 2012a, 2012b), , (Schmollgruber, et al., 2012), (Rohacs & Rohacs, 2014b) and generally utilized the methodology described (Figure 29.). Due to the unusual solutions, numerous original and new scientific methods were elaborated and applied. Some of them are outlined by this thesis, such as the development of the disruptive technology identification, evaluation and selection (chapter 3.1.) effects of MagLev technology on aircraft geometry (Majka, et al., 2013). security risk prediction of the radically new solutions (Rohacs, et al., 2014c) and total impact analysis (Majka 2016). Other related problems, such as the physics-based modelling of the acceleration, deceleration of the sledge by magnetic levitation technology, the concept development, the selection of maglev supporting system, the conceptual design of the Gabriel concept, the study on aircraft aerodynamics and flight performance, especially the take – off and landing performance of the undercarriage-less aircraft, or the redesign of the aircraft without an undercarriage (Figure 30.) (Rogg, et al., 2013), (Schmollgruber, et al. 2013, 2015), the complex simulation of aircraft motion (Figure 5.), the study of the precision landing in simulation and in the developed small demonstration models (magnetic track and UAVs) were solved by a standard scientific approaches

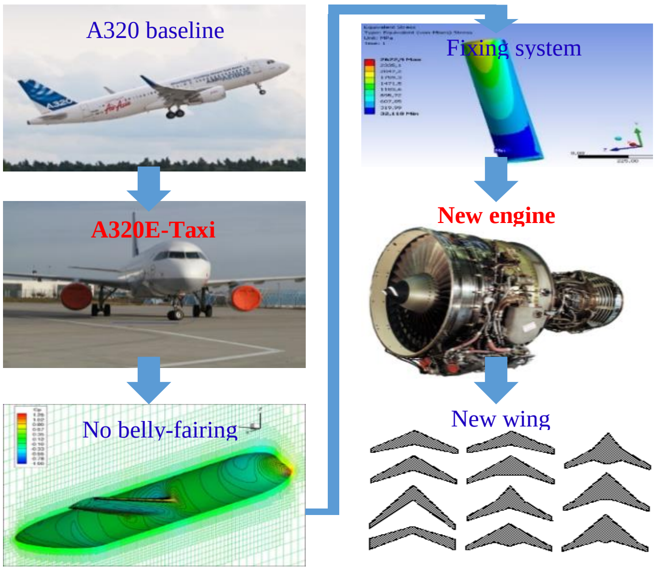


Figure 29. The optimization process of the adapted aircraft (Schmollgruber, et al., 2013)

One of the most interesting study was conducted in the development of a so-called rendez-vous system, being responsible to permit landings on the maglev levitated sledge (see Figure 30.). The original target was to reach a landing accuracy of ± 1 m in any direction. Therefore, a dedicated control system was developed, which harmonized the motion of the aircraft and the sledge moving on the maglev track. The motion control was based on measuring the relative distance between the aircraft and sledge, and a special supporting system (Pool, et al., 2013), (Rohacs, et al., 2014b), (Siepenkötter, et al., 2014).

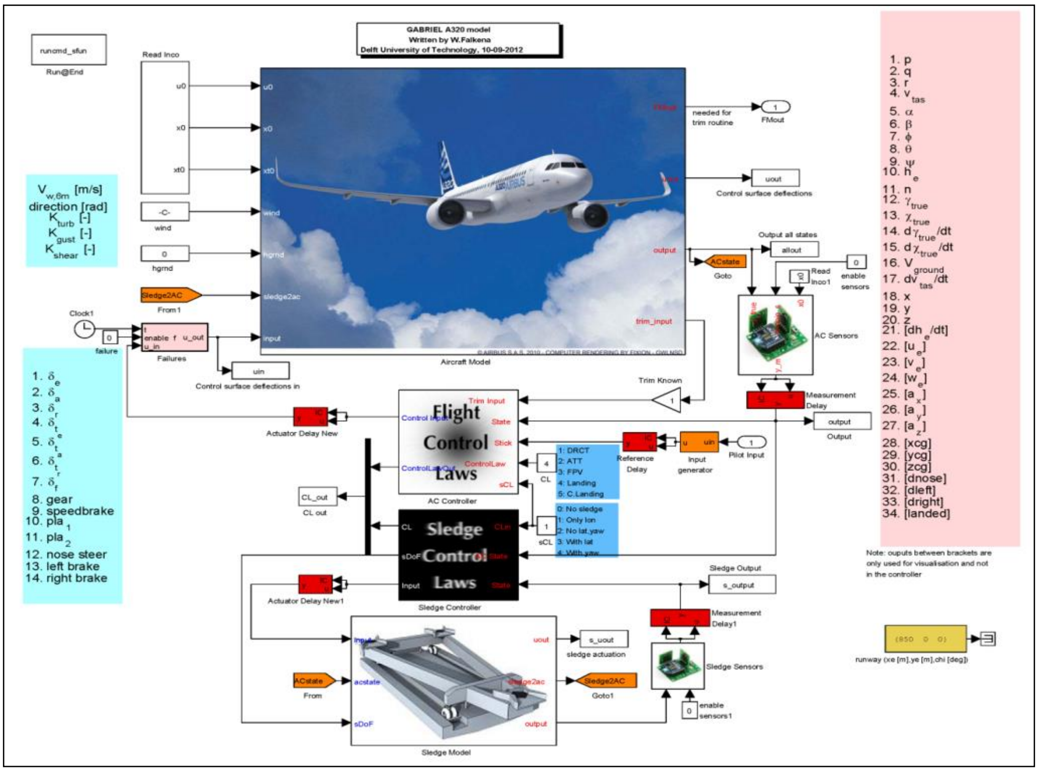


Figure 30. Simulation study on rendezvous control: landing of aircraft on the moving sledge (Pool, et al., 2013), (Rohacs, et al., 2014b)

The control system was based on optical sensing (Figure 31.). The concept was tested and validated in simulation, and seeing the critical importance of the system, also in real physical environment with a dedicated maglev track and a UAV.

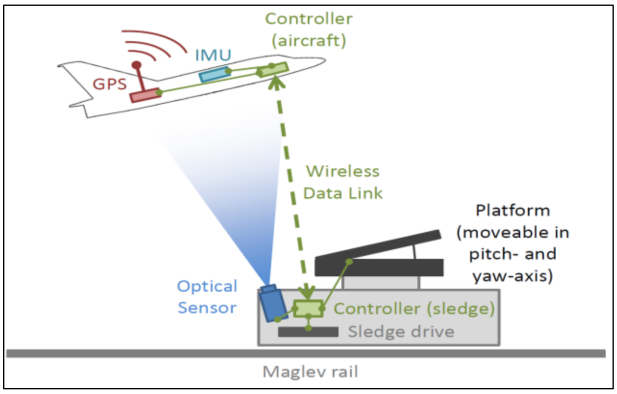


Figure 31. Principle of the rendezvous control system (Pool, et al., 2014)

Another important novelty of the project is the developed pilot support system to facilitate the rendezvous operation (Figure 32.).

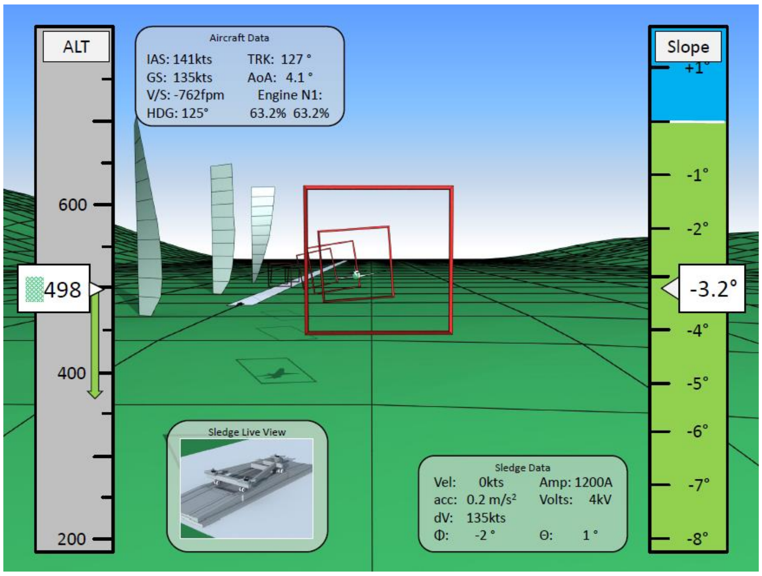


Figure 32. The proposed supporting information screen for the rendezvous concept (Schmollgruber, et al., 2014)

In addition to the concept development, implementation, and validation, a detailed impact analysis was also performed.

The final conclusion of the project were the followings:

- the envisioned maglev assisted TOL processes are technologically feasible (as demonstrated with the experiments), while also meeting the requirements (e.g. in accuracy),
- the deployment of the concept is safe and secure,
- the concept brings substantial benefits:
- the reduction of aircraft weight and fuel consumption is 9.3 and 18.1 % respectively (in case of mid-size passenger aircraft),

- the reduction of noise during the take-off and the landing phase is -64% and 19%, respectively,
- the emitted emissions are reduced over all phases of flight, but especially over the take-off by 38-58% (depending on the take-off scenario implemented),
- the cost-benefit ratio is positive, cost savings of up to € 1,467.26 per flight could be reached (on a typical European flight with a mid-size passenger aircraft).

Examples

The methodology was applied to the development and management of several projects including Esposa (Esposa, 2011 - 2014), SafeFly (SafeFly, 2007 - 2010), IDEA-E (IDEA-E, 2017 - 2020) or the smart map development of optimized energy mix generation for residential buildings (MATE, 2022),

Conclusion

The proposed new approach for the development of radically new, disruptive solutions brings the following benefits:

- include the assessment of the stakeholders' understanding on the mission and operational objectives (expectations) in the operational concept definition (to evaluate whether / how the concept could be used and define potential problems, limitations),
- perform detailed theoretical investigation to (i) identify, evaluate, and select the potential technologies, and (ii) provide the conceptual design of the system,
- make complex impact assessment from various financial, environmental, safety, security, social or regulatory aspects, and cross-check how these are in line with the preliminary defined expectations,
- generate outstanding results, while also meeting the social, industrial, regulatory and other requirements,
- support the public acceptance of the concept and the results (due to their early involvement in the development process).

Summary

I proposed a new method for the development of out-of-the-box technologies, systems and concepts, which could highly support the development of outstanding results related to disruptive developments and the progress towards the ambitious targets defined in the air transportation related strategic agendas and roadmaps.

- The developed technique is based on a 5 step approach, covering (i) concept inspiration, (ii) concept development, (iii) theoretical investigations, (iv) validations, verifications, and (v) impact assessment
- The methodology was demonstrated in the Gabriel, and SafeFly, Esposa, and smart map projects
- The methodology enabled for the author to make a major contribution to the development of the Gabriel project (at the concept development, feasibility study,

concept validation and impact assessment). The Gabriel concept was further developed by several other theses (Schmollgruber, 2018), (Sibilska-Mroziewicz, 2018), (Wu, 2019).

- The results showed that the techniques can generate outstanding results, with eased public acceptance and while meeting all other KPIs (such as safety, security, efficiency, sustainability), which could thus facilitate the development of out-of-the-box results.

3.3. Conceptual design of electric and hybrid aircraft

Problem

Seeing the stakeholders challenging visions and requirements in sustainability (ACARE, 2011), (IATA, 2021), (ICAO, 2022), electric / hybrid aircraft configurations are under extensive development. While this could be a promising concept towards greening, the specific energy (kWh/kg) of the available accumulator cells / battery packs are unfortunately very low. The energy available in 1 kg kerosene can only be stored in 10 – 12 kg of batteries, which in addition has other specific problems, such as thermal instability, aging, external force damage. Due to the smaller specific energy of the batteries, electric aircraft has higher take-off mass or dramatically reduced range (see point 4.2.). In addition, in a conventional propulsion system the aircraft gets lighter over the flight (since fuel is burned), unlike electric aircraft where landing and take-off weight is equal. To overcome these problems, the literature suggests to use electric propulsion systems with the so called low hybridization, thus employing the fully electric modes in a maximum of 12 % of the flight (Antcliff, et al.), (Rohacs & Rohacs, 2020a). Seeing these complexities, ***electric or hybrid aircraft require adapted or improved conceptual design processes***.

Solution – New conceptual design methodology

At first the identified problems / barriers of the new technologies (e.g. specific energy, weight, technology readiness level, expected lifetime) and the possible operational concepts supporting the electric and hybrid – electric propulsion systems (e.g. where and how these aircraft could fly) were analyzed to assess all primary data being required for aircraft design (Kuhn, 2012), (Thackeray, et al., 2012), (Gal, et al., 2018), (Rohacs & Rohacs, 2019).

Regarding the aircraft design, it is a multidisciplinary nonlinear optimization process with large series of constraints. These last represent the details of various domains, and thus could be grouped for example to legal, economic, technological, mechanical, aerodynamic, flight mechanics, dynamics, flight performance, flight dynamics, stability and control areas.

The aircraft development includes three major iteration / optimization phases (Raymer, 2012) (i) the conceptual, (ii) the preliminary and (iii) the detailed design.

The first, the conceptual design, deals with the proof of concept, multidisciplinary dynamic and fluid design that investigated a large number of alternatives to find the good aircraft configuration according to the defined requirements or other constraints. The methods of conventional conceptual aircraft design (Raymer, 2012), (Torenbeek, 2013), (Roskam, 2015, 2017), were adapted to electric and hybrid aircraft design duties, by several institutions, universities and research organizations (Pornet *et al.*, 2015), (Pornet and Isikveren, 2015), (Antcliff *et al.*, 2016), (Stückl, 2016), (Hoelzen *et al.*, 2018), (Voskuijl *et al.*, 2018), (Brelje and Martins, 2019), (Finger *et al.*, 2020). The applied methodologies include three groups of improvements: (i) the reformulation of the operational concept and mission, (ii) the correction of the weight/mass formulas and (iii) the enhancement of the aircraft performance (range) determining methods.

The conventional and the adapted conceptual design of electric, hybrid – electric aircraft are based on the mass balance (Figure 33.). Instead of equation (56), the mass balance equation is used as some of the relative masses of components (mass related to the aircraft take-off mass).

$$M_{TO} = M_a + M_{sy} + M_{ps} + M_f + M_b + M_{pl} + \cdots = M_{TO}\frac{M_i}{M_{TO}} = M_{TO}\sum_i \bar{M}_i \,, \tag{29}$$

where $\bar{M}_i$ is the i – th type of the relative mass, mass fraction, and subscribes *a*, *sy*, *ps*, *f*, *b*, *pl* represent the airframe, systems (expect the propulsion system), propulsion system (expect batteries), fuel (kerosene), batteries and payload respectively.

The mass fraction calculations are the core element of traditional aircraft design efforts, based on semi-empirical formulas that uses geometrical characteristics, material properties, technological and structural solutions (see for example the, (Torenbeek, 2013), (Roskam, 2017).

The mass or weight (W) balance equation (29) is characterising the feasibility of the conceptually designed configuration, since the relative masses are function of the available scientific design methods, technologies, production process or culture. Accordingly, the sum of the relative masses defines the following three possibility: (i) if $\sum_i \bar{M}_i > 1$, than the aircraft with the predefined performance cannot be built in the given production environment, (ii) once $\sum_i \bar{M}_i < 1$ than even better aircraft with better performance might be built, while (iii) $\sum_i \bar{M}_i = 1$ means that the best aircraft is made.

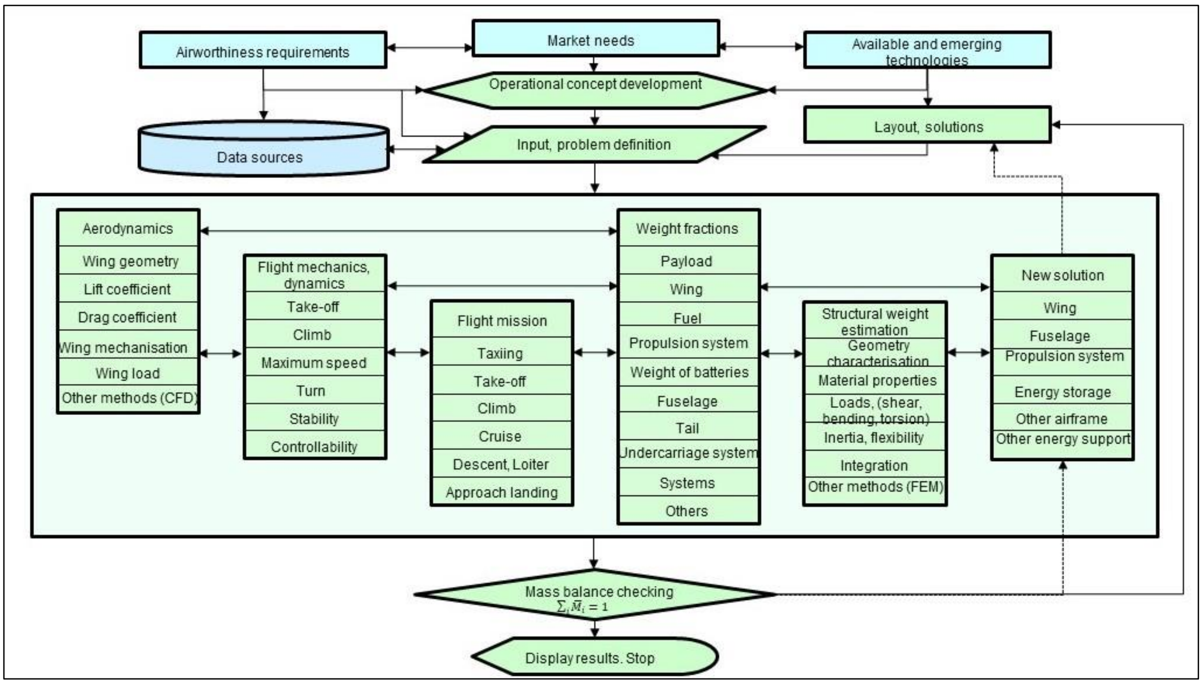


Figure 33. The core elements influencing the weight balance calculation

In the electric or hybrid configurations, it is clear that the aircraft weight / mass increases dramatically, due to the low specific energy of batteries. This problem might be solved by a new approach to the conceptual design and the development of unconventional solutions (e.g. lightweight structure, integrated and distributed propulsion systems) (Gal, et al., 2018), (Rohacs & Rohacs, 2019).

Accordingly, the required energy and power used in different flight segments was added to the conceptual design methodology, as energy unity equation defining the sum of relative energy of flight mission segments:

$$e_{efm} = e_{TA} + e_{TO} + e_C + e_{CR} + e_{DE} + e_{LO} + e_{AL} = e_{efm} \sum_i \bar{e}_i \,, \quad 1 = \sum_i \bar{e}_i \,. \tag{30}$$

where e – means energy, $\bar{e}_i$ stands for the energy fraction while the subscribes, *efm, TA, TO, C, CR, DE, LO, AL* define the energy used in the (entire) flight mission for the taxi, take-off, climb, cruise, descent, loiter and approach / landing phases.

Then, a range equation and a methodology for range calculation was developed for the electric and hybrid – electric aircraft configurations, according to Breguet definition as introduced already in chapter 4.2. (Rohacs & Rohacs,, 2020a) (see equation (59)). The novelties introduced were integrated into one methodology (Rohacs & Rohacs, 2019), (Sziroczak *et al.*, 2020), as illustrated in the Figure 34.

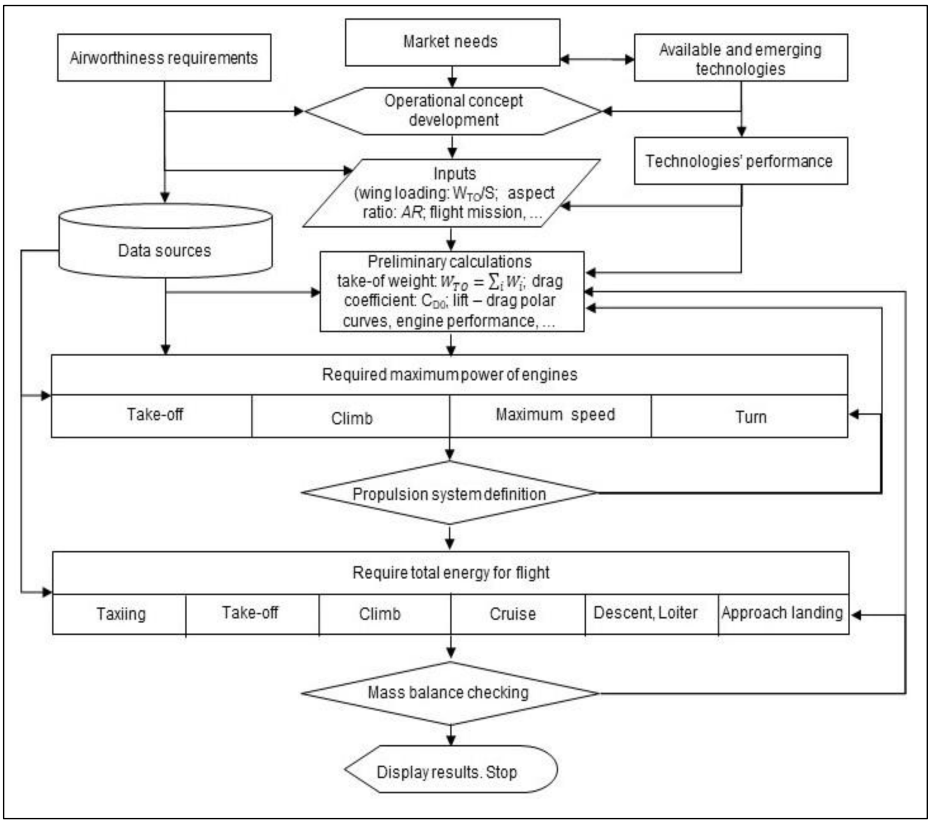


Figure 34. The developed new approach – based on the total impact performance index – to the conceptual design of electric, hybrid – electric aircraft.

The assessment of the required power or energy could be based on traditional flight mechanics, flight performance analysis techniques (McCormick, 1994), (Roskam and Lan, 1997), (Eshelby, 2000), (Miele, 2016). For example, the required power could be assessed from the weight reduction depending on the flight performance. In case of cruise flight (constant level, constant speed, i.e. steady level flight),

$$T = D, \quad L = W, \quad T = D\frac{L}{L} = \frac{W}{\frac{L}{D}} = \frac{W}{k} \tag{31}$$

the change in weight (during the cruise flight) equals to

$$\frac{dW}{\mathrm{dt}} = -TSFC\ T = -TSFC\ \frac{W}{k}, \qquad (32)$$

where T is the thrust, L- is the lift, D is the drag of the aircraft, k is the lift drag ration (defining the aerodynamic goodness of the aircraft) $TSFC$ is the thrust specific fuel consumption.

By separating and integrating the equation

$$\mathrm{dt} = -\frac{k}{TSFC}\frac{dW}{W}. \qquad (33)$$

the time of cruise flight might be determined as

$$t_{CR} = -\frac{k}{TSFC}\ln\frac{W_{CR_{initial}}}{W_{CR_{final}}}. \qquad (34)$$

The required energy for cruising equals to

$$e_{CR} = \eta_{fCR} e_{Df} TSFC\ T_{CR}\ t_{CR} = TSFC\ T_{CR}\frac{R_{CR}}{V_{CR}} \quad \left(or\ e_{CR} = -\eta_{fCR} e_{Df} k T_{CR} \ln\frac{W_{CR_{initial}}}{W_{CR_{final}}}\right), \qquad (35)$$

where η_{fCR} is the total efficiency coefficient for cruise flight (energy used by aircraft per energy storage by fuel used for flight), e_{Df} energy density of used fuel

Note: in case of developing the electric aircraft using these methods for calculation of the power and energy fractions is rather simple. Major different is that the mass of aircraft will not change during the flight.

Applicability

The author of this thesis participated in numerous national and international EU projects focusing on disruptive small aircraft development (e.g. (EPATS, 2007), (PPlane, 2009-2012), (SafeFly, 2007 – 2010), (IDEA-E, 2017 – 2020)). The methodology introduced here was developed in the framework of the IDEA-E and applied to the conceptual design of a 4 - seater electric, hybrid aircraft and a special cargo UAV. As found in the project, the performance of the 4-seater aircraft, and more particularly the relative payload (commercial load) could be increased by 250 %, once the proposed conceptual design approach is used (see Figure 35. and Figure 42.).

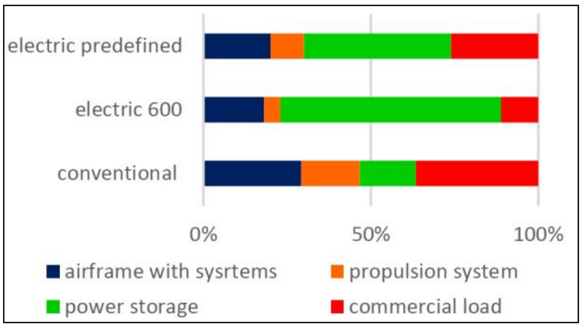


Figure 35. The ration of various aircraft components based on the developed conceptual design methodology (Gál *et al.*, 2018)

(conventional aircraft like Cessna 172, electric 600 electric aircraft with accumulator capacity of 600 kWh)

In another application, the proposed methodology was used in the conceptual design of a cargo UAV, which gave a disruptive aircraft configuration that could carry 150 kg of payload to 100 km of distance over 90 minutes of flight time (IDEA-E, 2017 - 2020). To reach this, the following series of extra constraints were defined (Gál *et al.*, 2018), (Sziroczak *et al.*, 2020):

- the structural mass (as relative empty mass without the elements of the propulsion system) must not go over 0.2;
- the relative mass of batteries should be less than 10 %;
- the commercial load should be greater than 40 %;
- the aircraft must use fully electric mode under 500m of altitude;
- the electrification factor must be below 0.2; and
- the power of the aircraft must permit to fully recharge the batteries during the cruise phase.

The design resulted in the aircraft configuration as illustrated in the Figure 36., with the following characteristics (with 150 kg of cargo): length: 4.7 m; wingspan: 7.6 m; wing area: 9.4 m^2; take-off mass: 350 kg, take-off distance: 60 m. The unconventional form results to considerably reduced empty weigh, but the parasite drag (drag at zero lift) is about 30 – 40 % higher relative to a conventional aircraft with resembling weight and size.

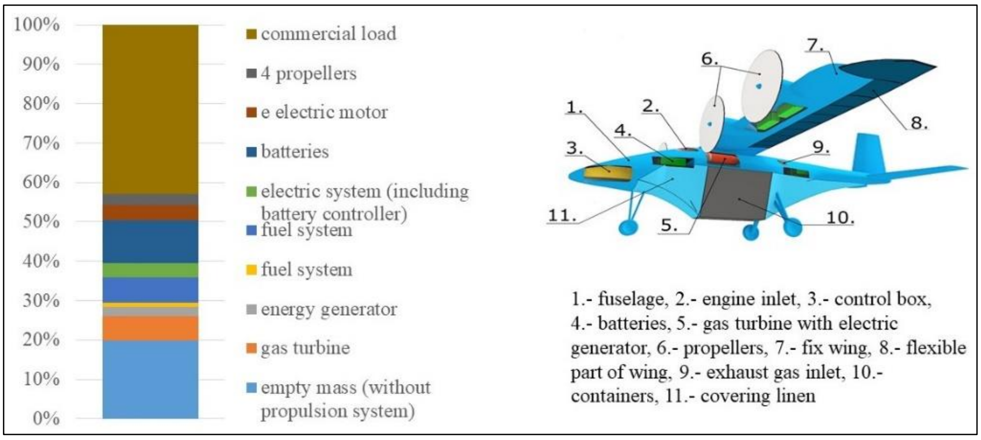


Figure 36. Weight breakdown and layout of the developed small cargo UAV based on the proposed methodology.

Examples

The developed new approach to the conceptual design was used in various research projects, such as the national IDEA-E initiative addressing the disruptive electric and hybrid small aircraft concepts (Gál *et al.*, 2017a), (IDEA-E, 2017 - 2020), and other investigations assessing the real benefits of electrified propulsion systems (Rohacs and Rohacs, 2019), (Sziroczak *et al.*, 2020).

Electrification in general, and the development of radically new, and unconventional aircraft concepts to reach the ambitious objectives of carbon neutral aviation (ACARE, 2011), (IATA, 2021) is an extensively addressed area in air transportation. Radically new configurations, propulsions systems are published by almost all major players, which clearly shows the evidence for the actuality and the importance of the proposed methodology.

Conclusions

The developed and proposed new approach to aircraft conceptual design methodology has the following major novelties:

- adaptation of the conventional conceptual design methodology to the electric /hybrid aircraft development based on the iteration of the required maximum power and energy being required for the predefined flight mission,
- introduction of four core types of inputs (related to the given electrified concept):
    - performance records derived from the developed operational concept (as number of seats, range, cruise speed) and airworthiness requirements (as take-off distance, rate of climb);
    - predefined constrains (for example legal or economic requirements with their deducted extra constraints on the mass and energy balance;
    - technical, technological characteristics of the propulsion system (like hybridization factor, propulsion system efficiency, or battery specific energy;
    - aerodynamic and flight performance data (as polar curve diagrams).
- generation of original new solutions based on out of the box concepts.

Summary

I developed a new methodology – based on the total impact performance index – to the conceptual design of disruptive concepts and more particularly to electric, hybrid – electric aircraft configurations.

- The developed approach is based on the interaction of the required maximum power and energy for the predefined mission, as well as the introduction of four core types of inputs related to electrified configurations (performance records being derived from the concept, predefined constraint related to electrification, technological characteristics of the propulsion system, and the aerodynamic records)
- The use of the proposed methodology was demonstrated in numerous research activities
- The results achievable with the proposed methodology show outstanding benefits (e.g. 250% higher payload), compared to conventional conceptual design techniques

3.4. Integration of drones in the smart city transportation system

Problem

Since the last couple of years, small unmanned aerial vehicles (UAV), drones are exponentially developing. While the business and social added value of the potential services provided are evident, ***it is unclear how these flights could be integrated in the urban / smart city traffic, and air transportation system***. Possible solutions to overcome the problem could cover e.g. (i) new techniques to control the classified drones and an advanced unmanned traffic management system (UTM), (ii) disruptive conflict detection and resolution methods for all dynamic (e.g. other airborne or ground-based vehicle), semi-static (e.g. crane) and static objects (e.g. buildings), (iii) new communication, navigation, surveillance systems, (iv) adapted and improved regulatory environment, and (v) various supporting elements (e.g. test and certification base, pilot training).

Basic principles

According to the forecasts (SESAR, 2016), drones by 2025 might reach 27 thousand movements a day in Hungary, which could represent a 72 billion HUF market. These numbers are more than challenging, since regulations are only provide a general framework, the drone movements and flight profiles are complex, the use of the existing systems for the commercial air transportation are powerless due to their budget, development time, human involvement, capacity, and reliance on other systems.

In the view of the problems defined above, numerous industry experts are working on the development of the segment, covering for example drone specific airspace (Figure 37.), air traffic management, highly automated conflict detection and resolutions (DLR, 2017), (Rios, 2018), (Low, 2017) areas.

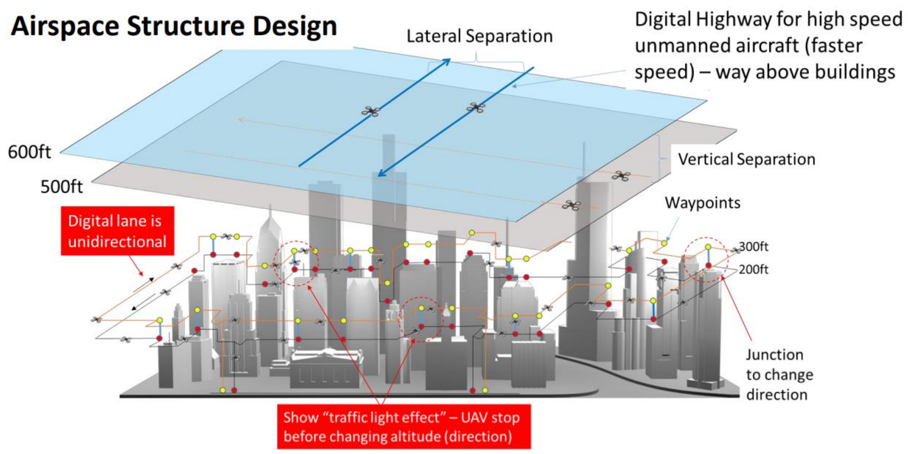


Figure 37. The recommended solution for airspace design developed by the National University of Singapore (Low, 2017)

Solution

The review of the related investigations show that the integration of drones in the urban traffic environment requires at least the followings:

- development of the urban “flight route” concept and layout,
- deployment of advanced models and supporting technologies for the traffic management of drones,
- deployment of an unmanned traffic management system,
- evaluation, development and deployment of concepts integrating and connecting drones with other related transportation systems (and especially autonomous cars, facing with resembling problems in e.g. the communication, navigation and surveillance areas).

This investigation focused on the development of advanced traffic management models. For the safe motion of drones several techniques were developed in the literature. An innovative example is the drone following model, as evaluated e.g. by Eurocontrol, Airbus, and numerous other research institutions. The core idea of this is to continuously composing and decomposing group of drones flying in the same direction (by distinguishing a leader and followers) and control groups instead of individual drones to save capacity / workload, for example in the required conflict management and communication (Nguyen & Rohacs, 2019a). For this concept, a dedicated drone following model was made, based on Markov chain representation of stochastic differential equation:

$$a(t) = \dot{v}(t) = f(v,t) + \sigma(v,t)\eta(t)\,, \tag{36}$$

$$a[k+1] = b_{dv}(v_{n-1}[k] - v_n[k]) + b_{dx}\{(x_{n-1}[k] - x_n[k]) - \Delta x_{pd_n}\} + \varepsilon[k]\,, \tag{37}$$

where *a*, *v* are the acceleration, and speed of the drones, *t* is the time, *x* is the distance between the drones, $f(x,t)$ the direction of changes of the stochastic process, η is the noise, $\sigma(x,t)$ defines the scattering of the random process (transition function of noise), *n* is the number of drone in row (*n* = 1, 2, … , *n*, … , *m*), *k* – is the number of calculation steps, *x* - is the distance between the drones, vb_{dv}, d_{dx} are the model parameters (constants), Δx_{pd_n} is a predefined distance for *n*-th drone, *ε* random value of disturbing the process.

The typical results are shown in the Figure 38.

Seeing the number of the envisaged drone movements, another investigation was focusing on the potential conflicts and their resolution. Previous investigations coordinated by the author already defined and preliminary tested an active conflict management system for small aircraft (Rohacs & Jankovics, 2010a, 2010b, 2012a), which was further developed to a complex system for drones. The proposed concept is based on on-board units and a central interface, which collects the GPS based positional information sent by the drones, to identify, resolves the conflicts, and send the new flight paths coordinates back to the UAVs. It is a fully automated system, which however has a user interface to monitor the flights and setup certain options. For the resolution, numerous alternatives are available (e.g. vertical, horizontal deviation, or speed intervention), thus the management is based on user defined preferences. The investigations defined the system requirements, made the technical specification, analysed the potential technologies, defined the operational concept, implemented the software and hardware parts of the proposed system, and demonstrated the concept at various occasions. These showed the applicability of the concept between drones, and also between air and ground vehicles (Sziroczak & Rohacs,, 2021, 2022) (Figure 39.). Results showed that the concept is technologically feasible, and meet the basic requirements, however require more mature communication technique due to potential interference with other systems. It is also clear, that the developed concept could solve the conflict arising between all the ground and air-based static, semi-static and dynamic objects, which thus could significantly support the envisaged drone related products, services in the smart city environments.

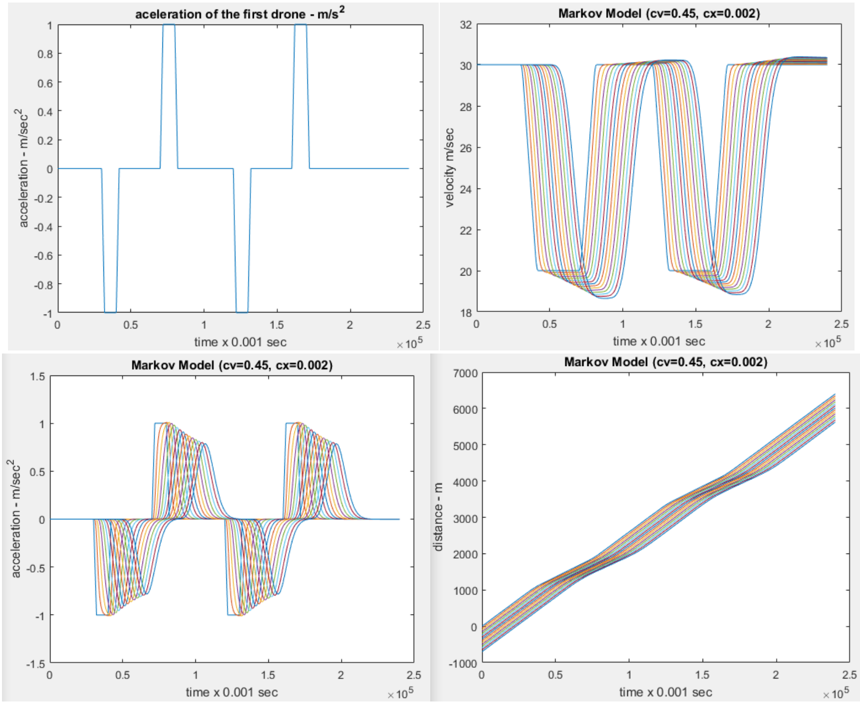


Figure 38. Simulation results of the drone following model

Figure 39. The developed conflict management system (upper left: the user interface, upper right: the onboard equipment, lower pictures: demonstrations at ZalaZone, (Sziroczak & Rohacs, 2022))

Application

Drone integration studies in Hungary dates back to 2007, with a specific traffic forecast (Rohacs, 2008), recommendations on the possible regulation framework, safety, security threats and the classification of non-cooperative targets (Balk, et al., 2007), (Rohacs, 2010a), (Rohacs, et al., 2010a).

Later, the author was involved in two projects (CDR, 2011), (LC-CDR, 2011 - 2012) dealing with the development of conflict detection and resolution systems for UAVs (Rohacs & Jankovics,, 2010a, 2010b, 2012). Dedicated passive and active conflict detection techniques were developed and tested. In the Smartpolis EU funded project, drones were defined as integrated parts of the coming smart city urban environment (Rohacs, et al., 2016b, 2016c).

Since 2017, the author of this thesis booklet is coordinated numerous drone related research activities: (i) the general development and implementation of drones (SPACECOM, 2004 - 2005), (Rohacs & Rohacs, 2011a), (Baburin, et al., 2013), (Rohács & Rohács, 2014 - 2015), (ATM, 2014 - 2015), (Gal, et al. 2018), (Rohacs & Rohacs, 2019), (Rohacs, et al., 2020), (Sziroczak, et al., 2022), (ii) the integration of drones in the urban traffic environment (Nguyen & Rohacs, 2018a, 2018b, 2019b., 2021), (Szarvas, et al. 2019), (Dobi, et al., 2019), (Rohacs, et al., 2020), (iii) the development of the complex USPACE functionalities, and more particularly the conflict detection and resolution methods (Szullo, et al., 2017), (Dobi & Rohács, 2018), (Dobi, et al., 2018), (Nguyen & Rohacs, 2018b, 2019a), (iv) the development of business models and operational concepts for various drone applications Nguyen, et al., 2020, 2021), (v) the development of advanced methods automating the drone traffic management (Nguyen, et al., 2020, 2021), (Sziroczak,& Rohacs, 2021), (vi) the definition of the DroneMotive concept, and (vii) as the president of the Hungarian Drone Coalition, the definition of the Hungarian Drone Strategy.

Until now, the developed methods introduced here were validated in simulation environments. At this stage, drones operated at the department of Aeronautics, Naval Architecture and Railway Vehicles are prepared for real physical tests (for example to assess the interaction of drone and autonomous vehicles).

Conclusion

The drone related investigations clearly showed that:

- the industry is facing with numerous problems, since just a marginal part of the entire ecosystem is present, which is mostly linked to drone design and preliminary concept definitions
- the amount an nature of the problems require a collaborative approach, beside ad-hoc developments without an aggregate strategy
- traffic management cannot be solved with the large commercial air transportation techniques, due to their cost, capacity, human involvement, regulatory environment
- the developed drone following model is technologically feasible, and could significantly help to solve the capacity related problems related to drone traffic management

- the proposed model could be also used in other related transportation system, and especially in autonomous ground vehicles.

Summary

I adapted and developed disruptive methods (as conflict detection and resolution tool, drone following models) to facilitate the integration of drones in the air transportation system, as well as in the smart city environment.

- The proposed drone following model is based on the idea of continuously composing and decomposing group of drones flying in the same direction (by distinguishing a leader and followers) and control groups instead of individual drones to save capacity
- The developed conflict management technique is based on a central interface, which collects the positional information sent by the drones (or other vehicles), resolves the conflicts and send the new deconflicted routes accordingly back to the vehicles
- The experimental development of the proposed conflict management system was demonstrated in numerous occasions at the ZalaZone proving ground (e.g. ZalaZone Innovation days II, III) in between various airborne and ground-based vehicles
- As demonstrated, the developed methodology permits conflict management between any equipped static (e.g. buildings), semi-static (e.g. crane), or dynamic objects (e.g. other airborne or ground-based vehicle),
- The simulation (for the drone following) and demonstration (for the conflict resolution) results showed that the proposed techniques could significantly help to support drone traffic management, and overcome the safety and capacity related problems.

Thesis II, III, IV

Thesis II.

I adapted and **developed a technology identification, evaluation and selection method** (TIES) to the selection and development of disruptive technologies as well as radically new solutions – including the development of out-of-the-box technologies, systems, concepts – which could lead to outstanding results and thus to progress towards the ambitious targets defined in the air transportation related strategic agendas, roadmaps.

- I **developed a TIES method**, based on (i) the definition of a design matrix (of the potential solutions), (ii) the evaluation of the potential solutions, (upon the operational phases, as well as the weighted scores of operability), (iii) the selection of sound criterions, (iv) the formation and estimation of the decision matrix, (v) the selection of the radically new technologies, solutions, using multi-criteria decision making techniques.
- I proposed a **concept development and concept validation technique** related to the radically new technologies, solutions, products or services (see Figure 28), based on a 5 step approach, covering (i) concept inspiration, (ii) concept development, (iii) theoretical investigations, (iv) validations, verifications, and (v) impact assessment that utilizes a life cycle phases approach comprised of extensive stakeholder cooperation, multi-disciplinary modelling and simulations, stakeholder and regulatory environment alignment.
- The developed method was validated in two expert workshops, by extensively assessing all alternatives and comparing the results with the proposed concept. Relative to other techniques, the proposed methods are more powerful in capturing meaningful radically new solutions, due to (i) the feedback from the complex impact assessment and constraints, (ii) the extensive multi-criteria evaluation process, and (iii) the involvement of the stakeholders and regulatory alignment in the development stage. The proposed method was demonstrated in several national and international projects, such as the EU FP7 L1 GABRIEL research project (with the author being the technical manager), *which was globally the first project* assessing, developing, and validating the concept of using maglev as a ground-based power to assist the commercial aircraft take-off and landing processes.

Most important publications related to Thesis II:

- Rohacs, D.: “Technology and solution-driven trends in sustainable aviation”. *Aircraft Engineering and Aerospace Technology 95 : 3 (SI)*, pp. 415-430., 2023.
- Wangai, A.W., Rohacs, D. and Boros, A. (2020b), “Supporting the Sustainable Development of Railway Transport in Developing Countries”, *Sustainability*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 9, p. 3572, doi: 10.3390/su12093572, 2020.
- Kinzhikeyev, S.; Rohács, J.; Rohács, D.; Boros, A.: “Sustainable Disaster Response Management Related to Large Technical Systems”. *Sustainability* 12 : 24 pp. 1-25. Paper: 10290 , 25 p., 2020.
- Gal, I ; Jankovics, I ; Rohacs, J ; Rohacs, D.: “Diszruptív technológiák fejlesztése, azonosítása, értékelése és kiválasztása – járműfejlesztési sajátosságok” In: Péter, Tamás (szerk.) IFFK 2017 : XI.

Innováció és fenntartható felszíni közlekedés, Budapest, Magyarország : Magyar Mérnökakadémia (MMA) pp. 109-117, 2017.

- Rohacs, D ; Rohacs, J.: "Magnetic levitation assisted aircraft take-off and landing: (feasibility study – GABRIEL concept)". *Progress in Aerosapce Sciences 85*, pp. 33-50, 2016.
- Rohács, D.: "The GABRIEL project". In: Rohács, D.; Kisgyörgy, L.; Horváth, Zs. Cs. - *Magnetic levitation and its experimental use in rail and air transportation*. Győr, Magyarország : Universitas-Győr Nonprofit Kft., pp. 75-95. 2015.
- Rohacs, J ; Rohacs, D.: "The potential application method of magnetic levitation technology – as a ground-based power – to assist the aircraft takeoff and landing processes". *Aircraft Engineering and Aerospace Technology 86* : 3 pp. 188-197. , 2014.
- Rohacs, D ; Voskuijl, M ; Siepenkotter, N.: "Evaluation of Landing Characteristics Achieved by Simulations and Flight Tests on a Small-Scaled Model Related to Magnetically Levitated Advanced Take-Off and Landing Operations". In *Proceedings of the 29th Congress of the International Council of the Aeronautical Sciences (ICAS),* Bonn, Németország : 2014.
- Rohacs, J. ; Rohacs, D. ; Jankovics, I. ; Voskuijl, M. ; Sibilski, K.: "Possible Solutions to Take-Off and Land an Aircraft". *Deliverable D2.4. Integrated Ground and On-Board system for Support of the Aircraft Safe Take-Off and Landing – GABRIEL, EU Project Number 284884*, 2012.

Thesis III.

I have improved the **conceptional design of new disruptive concepts and aircraft,** by adding new **energy balance condition** and **optimization for tiotal impact performance index** and applied to developing the electric, hybrid – electric aircraft configurations.

- I proposed a **new condition to the conceptual design process of electric aircraft**, which considers the required energy of the given flight segments, in order to facilitate the more meaningful comparison and assessment of various green and energy-efficient alternative propulsion technologies and concepts:

$$e_{efm} = e_{TA} + e_{TO} + e_C + e_{CR} + e_{DE} + e_{LO} + e_{AL} = e_{efm} \sum_i \bar{e}_i \ ,$$

$$1 = \sum_i \bar{e}_i \ .$$

where e – means energy, $\bar{e}_i$ stands for the energy fraction while *i* subscribes, *efm, TA, TO, C, CR, DE, LO, AL* define the energy used in the (entire) flight mission for the taxi, take-off, climb, cruise, descent, loiter and approach / landing phases. (Comment: accordingly, the sum of the relative energies defines the following three possibility: (i) if $\sum_i \bar{e}_i > 1$, than the aircraft with the predefined performance cannot be built in the given production environment, (ii) once $\sum_i \bar{e}_i < 1$ than even better aircraft with better performance might be built, while (iii) $\sum_i \bar{e}_i = 1$ means that the best aircraft is made.)

- I developed dedicated **new techniques to calculate the energies required** for the different flight segments, like for the cruise phase:

$$e_{CR} = \eta_{fCR} e_{Df} TSFC \ T_{CR} \ t_{CR} = TSFC \ T_{CR} \frac{R_{CR}}{V_{CR}} \quad \left(or \ e_{CR} = -\eta_{fCR} e_{Df} k T_{CR} \ln \frac{W_{CR_{initial}}}{W_{CR_{final}}} \right) \ ,$$

where η_{fCR} is the total efficiency coefficient for cruise flight (energy used by aircraft per energy storage by fuel used for flight), e_{Df} energy density of used fuel, *TSFC* is the thrust specific fuel consumption, *T* – required thrust, *t* is the time, *R* – is the range, *V* – is the speed of aircraft, *W* – weight. The η_{fCR}, e_{Df}, *TSFC,* T_{CR}, *W* depends on the applied design, production, operation technologies, methods, solutions, which thus – relative to other models – captures with ease the specific features of green propulsion (e.g. energy density, fuel vs battery weight).

- The proposed energy calculation method was validated with measured datasets of a physical electric propulsion system laboratory unit, with batteries being recharged by a small gas turbine.
- Results indicated that the use of the proposed methodology and the redefined new constraints related to electric and hybrid – electric aircraft configurations (e.g. energy density of the batteries, available prime resources) permits to increase the commercial load by 250 %, compared to conventional conceptual design techniques (see figures 35 and 36.) (Considerable reducing the negative effects of – presetly - very low energy density of accumulators).

Most important publications related to Thesis III:

- Rohacs, J. ; Kale, U. ; Rohacs, D.: “Radically new solutions for reducing the energy use by future aircraft and their operations”. *ENERGY 239* Paper: 122420, 2022.

- Kale, U.; Jankovics, I.; Nagy, A.; Rohács, D.: “Towards Sustainability in Air Traffic Management”. *Sustainability* 13: 10 Paper: 5451, 2021.
- Sziroczak, D.; Jankovics, I.; Gal, I.; Rohacs, D.: “Conceptual design of small aircraft with hybrid-electric propulsion systems”. *ENERGY 204 p. 117937*, Paper: 117937, 2020
- Rohacs, J. ; Rohacs, D.: “Energy coefficients for comparison of aircraft supported by different propulsion systems”. *ENERGY 191 p. 116391* Paper: 116391, 2020
- Rohacs, J.; Rohacs, D.: “Conceptual design method adapted to electric/hybrid aircraft developments”. *International Journal of Sustainable Aviation 5*, pp. 175-189., 2019

Thesis IV.

I adapted and developed **disruptive methods** (as a conflict detection and resolution tool, drone following model) **to facilitate the integration of drones** in the future transportation system, including various air-borne and ground-based autonomous vehicles.

- I proposed a **drone following model**, based on the idea of continuously composing and decomposing group of drones flying in the same direction (by distinguishing a leader and followers) and control groups instead of individual drones, in order to save capacity and human workload, based on a Markov chain representation of stochastic differential equation:

$$a(t) = \dot{v}(t) = f(v,t) + \sigma(v,t)\eta(t)\ ,$$

$$a[k+1] = b_{dv}(v_{n-1}[k] - v_n[k]) + b_{dx}\{(x_{n-1}[k] - x_n[k]) - \Delta x_{pd_n}\} + \varepsilon[k]\ ,$$

where *a*, *v* are the acceleration, and speed of the drones, *t* is the time, *x* is the distance between the drones, $f(x,t)$ direction of changes of the stochastic process, η is the noise, $\sigma(x,t)$ defines scattering the random process (transition function of noise), *n* is the number of drone in row (*n* = 1, 2, … , *n*, … , *m*), k – is the number of calculation steps, *x* - is the distance between the drones, b_{dv}, d_{dx} are the model parameters (constants), Δx_{pd_n} is a predefined distance for *n*-th drone, ε random value of disturbing the process.

- I developed an **active conflict management technique for autonomous vehicles** based on a central interface, which (i) collects the positional information sent by the drones (or other vehicles), (ii) resolves the conflicts and (iii) send the new deconflicted routes accordingly back to the vehicles.
- The proposed drone following model was validated in matlab fast time simulation environment, which showed that relative to other drone management techniques in the literature (e.g. superhighway concept) it demands lower workload, could facilitate beyond visual line of sight operations, while not requiring new airspace definition concepts. The conflict management system was demonstrated in numerous occasions at the ZalaZone proving ground between various airborne and ground vehicles. Relative to other techniques, the proposed solution (i) provides conflict management between any equipped static (e.g. buildings), semi-static (e.g. crane), or dynamic objects (e.g. other airborne or ground-based vehicle), (ii) facilitates the connection with other autonomous ground centers due to its core central interface, and (iii) permits the use of advanced conflict assessment and even multi-objective resolution models due to the high computational power of the central interface.

Most important publications related to Thesis IV:

- Sziroczak, D.; Rohacs, D.; Rohacs, J.: "Review of using small UAV based meteorological measurements for road weather management". In: *Progress in Aerospace Sciences 134*, Paper: 100859 , 20 p., 2022.
- Sziroczák, D.; Rohács, D.: "Conflict Management Algorithms Development Using the Automated Framework for Autonomous Vehicles". In: *Proceedings of The First Conference on ZalaZONE*

Related R&I Activities of Budapest University of Technology and Economics, BME, Budapest, pp. 89-93., 2022.
- Sziroczák, D.; Rohács, D.: “Automated Conflict Management Framework Development for Autonomous Aerial and Ground Vehicles”. *ENERGIES 14* : 24 Paper: 8344 , 2021.
- Nguyen, D. D.; Rohacs, J.; Rohacs, D:: “Autonomous Flight Trajectory Control System for Drones in Smart City Traffic Management”. In: *ISPRS International Journal of Geo-Information* 10 : 5 p. 338, 2021.
- Yildiz, M.; Bilgiç, B.; Kale, U.; Rohács, D.: “Experimental Investigation of Communication Performance of Drones Used for Autonomous Car Track Tests”. In: Sustainability 13: 10 p. 5602, 2021.
- Nguyen, D.D. ; Rohacs, D.: “Air Traffic Management of Drones Integrated Into the Smart Cities”. In: 32nd Congress of the International Council of the Aeronautical Sciences, ICAS 2021, Paper: 0456, 2021.
- Nguyen, D.D.; Rohács, J.; Rohács, D.; Boros, A.: “Intelligent Total Transportation Management System for Future Smart Cities”. *Applied Sciences-Basel* 10 : 24 Paper: 8933 , 31 p., 2020.

4. Evaluation and supporting framework development related to disruptive technologies

4.1. Total impact analysis

Problem

The investigation of the future aviation development process require ***overall complex indexes to evaluate the future development states, technologies, concepts***.

Seeing the problems of air transportation, the stakeholders defined challenging visions and targets in the strategic research agendas and white papers. It is also clear that these cannot be reached with the marginal modification of the present systems and sustaining innovation, and thus radical innovation and out-of-the-box approach are required. Once radically new concepts are designed, it is crucial to deeply investigate the various options and their impact, with a so-called total impact analysis.

Possible solution: develop concepts that take into account all effects (e.g. safety, security, greening, social acceptance) by a unique and well-applicable methodology.

Basic principles (of total impact analysis)

The policy makers need objective information about the general impact of the coming novel systems / concepts. Seeing the importance of this duty, in the last 40 - 60 years, new approaches were introduced and applied to impact analysis, which could be classified in the following three groups:

- life cycle (total life cycle) effects (emissions, cost) calculations – that are used to analyse and evaluate the impact of a product (e.g. vehicle);
- externality – external cost assessment of using, operating the given product, transportation mean, or type of vehicles;
- sustainability assessment – that evaluates the use of the resources as long term effects limiting or reducing the possibilities of the future generation.

There are numerous high level sophisticated solutions to calculate the life cycle emissions (Chester & Horvath, 2009), (Messagie, et al., 2013), costs (Asiedu & Gu, 1998), (Hellgren, 2007), (Furch, 2018), (Jun & Kim, 2007), determine the externality (Buchanan & Stubblebine, 1962), (van Essen, et al., 2008), study the interactions of transport externality and transport economy (Santos, et al., 2010), (Anas & Lindsey, 2011) as well as interconnections of externality and environmental assessment (Norris, 2001), (Profilidis, 2014). However, *there is no solution for an aggregate assessment* – covering all the group effects listed above together – with a general or integrated performance index.

Sustainability is the ability to be maintained at a certain rate or level. The most commonly used definition of sustainability is (WCED, 1987) "… meeting the needs of the present without compromising the ability of future generations to meet their own needs…". Based on this approach, sustainability creates a balance between the economy, environment, and society (Wangai *et al.*, 2020) and can be applied for the overall evaluation of the development processes.

In the literature, sustainable transport and their development was investigated from various directions. The combustion process was studied with numerical methods Bicsák, et al., 2010). New, simple dynamic model was suggested for the dispersion of motorway traffic emissions (Csikós, et al., 2015). General estimation method was elaborated for transport mode emission evaluation (Tánczos & Török, 2006). The sustainable transport strategic development was defined (Michelberger & Nádai, 2010). The linkage between the climate change and Hungarian road transport was analysed (Török & Tánczos, 2007). The transport efficiency (Rohacs, 2010), intermodal change (Rigo, et al., 2007) and multi criteria decision making problems were investigated to better understand the basic processes in transportation systems.

Numerous articles deal with the definition of special indicators or indexes to evaluate sustainability (Litman, 2007), (Joumard and Gudmundsson, 2010), (Upham *et al.*, 2003), (Janic, 2016) in general, or focused on a particular range of interest, such as fuel (Zhang *et al.*, 2020). For example, a special sustainable transport performance index was developed (Rohács & Simongáti, 2007), (Simongáti, 2010). The role of high level, state management in environment sustainability was studied (Kinzhikeyev, et al., 2017). The developed competences were used in the evaluation of new technology impacts (Rohács, 2006a, 2013), (Schmollgruber, et al., 2014), (deGraaff, et al., 2014), (Rohacs, et al., 2013). The review of the applied techniques and especially a large number of various indicators show that *there is no single and globally acknowledged index or methodology for sustainability assessment* (Rohacs & Rohacs, 2020b). It is also clear that sustainability (and its evaluation) is determined by its dependence on the geographic location (distance from natural resources), global supply chain, economic culture, social convention, and even the size of the investigated systems. As a result, sustainability is evaluated by a unique set of indicators and indexes (Litman, 2021), (Bugayko and Shevchenko, 2020) that might be applied to a particular domain like airports (Koç and Durmaz, 2015) or airlines (Zieba & Johansson, 2022), but usually being weak in overall sustainability assessment such as (i) covering legal regulation, (ii) requirements definitions, (iii) aptitude tests, (iv) authorization procedures, design, planning, building, operation, recycling. Regarding the segment (e.g. design, operation, recycle) of the investigations, most of them evaluate sustainability on the life cycle basis, and perform life cycle cost or life cycle emission assessment (Calado *et al.*, 2019), (Pohya *et al.*, 2018). The life cycle approach is applied to the entire air transportation system (Schmitt & Gollnick, 2016), including the aeronautical industry, aircraft, airlines, air navigation service airports, passengers and cargo, and all the connected systems as global supply chain, general transportation system. It is however observed that some indexes are technology-driven and only focus on (i) the operational segment (Scholz *et al.*, 2022), (ii) one single technology or (iii) class of technologies (Timmis *et al.*, 2015), (Ther Air, 2021).

These works together with several fascinating uses of the life cycle impact estimation methodologies (Chester & Horvath, 2009), (van Essen, et al., 2008), (Mailbach, et al., 2008), with the available input data (EUROSTAT, 2016), (OECD, 2018), the additional information on the impact of the infrastructure or specific system elements (Horvath & Matthews, 2005), life cycle assessment of pavements (Santero, et al., 2010) or – as a special example - toxic effects of brake wear particles (gassr, et al., 2009) enabled to make a further step in the generalization of the impact evaluation, and the total impact calculation as *total impact life cycle cost* (TILCC).

Solution - Index for total impact evaluation

The total impact assessment could be given by two alternative techniques, discussed in the followings.

In the first, the total impact is classified in five large groups:

- safety and security – inducing direct and short time impact as accidents;
- environmental impact (chemical emission and noise) – generating direct and indirect medium and long term impact on people, nature, living world;
- system characteristics – system management, management of the operation processes, that – for example – cause congestions;
- system support – infrastructure, supply chains, upstream and downstream processes that have considerable effects on the environment, society,
- use of resources – defined as loosing effects, such as the use of land, minerals resources.

This paper recommends to use a simplified and unique index to evaluate the total impact, in form of total costs covering all life cycle effects of the transportation system related to the unit of transport work (pkm, or tkm):

$$TPI = \frac{TLCC}{TLCW} = \frac{TOLCC}{TLCW} + \frac{TILCC}{TLCW} = TOPI + TIPI \quad , \tag{38}$$

where *TPI* is the total performance index, *TOPI* is the total operation performance index, *TIPI* total impact performance index, *TLCC/TOLCC/TILCC* are the total / total operational / total impact *LCC* (life cycle cost) and the *TLCW* is the total life cycle work.

The *TOPI* as the operational cost of the given vehicle, given transportation mode is well known and applied by the owners, operators, service providers. It plays a determining role in the users' selection of the vehicle, transportation mode and transportation chain. On the other hand, *TIPI* deals with the externality. This is the index that might be used in impact assessment.

The *TIPI* summarizes all the impacts:

$$TIPI = \sum_{i=1}^{n} TIPI_i = \frac{\sum_{i=1}^{n} TILCC_i}{TLCW} \quad , \tag{39}$$

where $i = 1, 2, \ldots n$ define the different group of impacts. According to the transportation systems, i = safety and security; environmental impact; system peculiarities; system support; use of resources.

The *TIPI* for group of impacts can be determined as the following sum of the different effects:

$$TIPI_i = \frac{\sum_{j=1}^{m} \sum_{k=1}^{l} \sum_{q=1}^{r} N_{j,k,q}\, p_{j,k,q}\, I_{j,k,q} \sum_{v=1}^{u} o_{j,k,q,v}\, c_{j,k,q,v}}{TLCW_i} \qquad \forall i \quad ,$$

$$TLCW_i = \sum_{j=1}^{m} \sum_{k=1}^{l} \sum_{q=1}^{r} N_{j,k,q}\, W_{j,k,q} \tag{40}$$

where $j = 1, 2, \ldots m$ depicts the subgroup of impacts, while $k = 1, 2, \ldots l$ defines the transport means, , $q = 1, 2, \ldots, r$ represents the types or groups of the given transport system, $v = 1, 2, \ldots, u$ identifies the different forms of consequences, *N* is the number of sub-sub-group elements contributors to the impact, like number of vehicles defined by *q*, *p* is the parameter of the given types or group of system elements causes the investigated effects, *I* is the impact indicator of the given system element, *o* the outcomes / consequences of impact defined by *I* or caused by the events, situations associated with the *I* indicator, *c* is the conversation coefficient for calculating the (external) cost and *W* is the work done during the investigated period defined by *p*. it means, if the *p* is the parameter of function given in form of average annual unit, then the *W* should related to the year, too. For example, if the *N* defines the number of vehicle and *p* is the annual average utilisation of the vehicles, then the *W* equals to *p*.

Another more general form might be applied to define the total sustainable performance index (*TSPI*) (see Figure 40.).

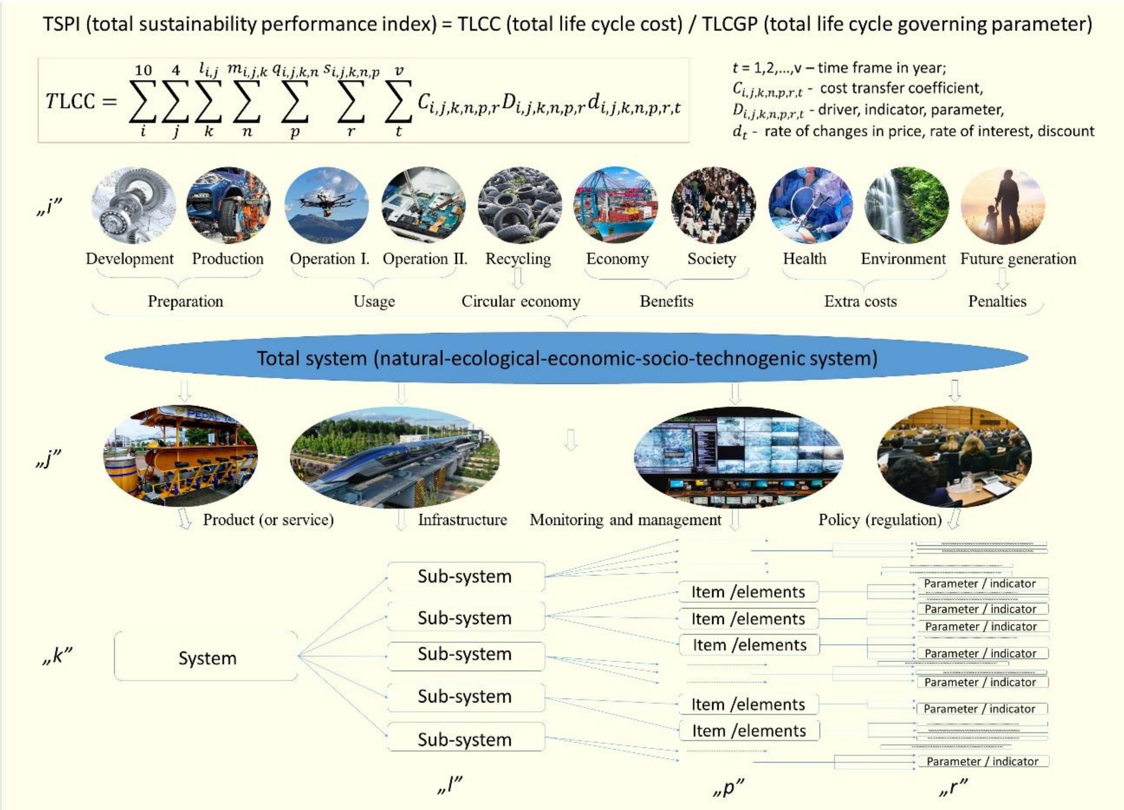


Figure 40. The concept and structure of the developed Total Sustainable Performance Index – TSPI

The available various techniques can be synthetized into a new total sustainable performance index (*TSPI*) – estimated on the system level (like transportation system, smart city, production plant, food service), as the total life cycle cost (*TLCC*) defined with user goals – to evaluate the chosen item, product, service related to the chosen total life cycle governing parameter (*TLCGP*), such as working hour, calendar hour (year), running distance in km (100 km):

$$TSPI = \frac{TLCC}{TLCGP}. \tag{41}$$

The total life cycle cost includes all directly or indirectly linked cost categories, according to the followings:

$$TLCC = C_D + C_P + C_{OI} + C_{OII} + C_R + C_E + C_S + C_H + C_{EN} + C_{PE} \tag{42}$$

where the cost indexes refer to the following cost categories:

D - development: all actions starting from the concept generation until the detailed design that includes the technology development, their testing in general form (at academia and technology transfer institutions), conceptual and preliminary design including the simulation studies, laboratory tests, and real environment tests;

P – production: all basic element production (as vehicles for transportation system, cooking in restaurant), construction of required infrastructure, service environment (as road system, building for production plants, shops) and monitoring, management subsystem (like centre for transport management, traffic management system including the info technology sub-systems, as Internet of Things);

OI – operation I. usage: all costs related to the use / application of the given item, product or service (as car, mass transportation vehicle usage, production machine operation);

OII – operation II: technical / technological operation: cost of maintenance, repair, modernization (including for example the repair of the car, renewal of the infrastructure, modernization of the info-communication system as shifting from 4G to 5G, application of the parts, items, materials in repair, or even the procurement of the new instruments);

R – recycling: all costs generated at the end of the operation of the system including the recycle of the infrastructure or the application of circular economy;

E – economy: all costs caused by the changes in the economy that might be classified into five groups: a.) changes in the economy and its development (as inflation, renting conditions, bank interest, wages), b.) costs of "losses", disadvantages (users' value of time, delay in logistic supports, use of land) c.) advantages, profit, d.) effect of natural disasters and e.) security or generally the un-lawful events;

S – society: costs linked to the changes in the social habits, expectation (as demand related to the given item, product, service, personal income, mobility);

H – health including the safety and partly the security: costs caused by the direct, indirect and external effects of using / operating the system on human health / life (accidents, injure, fatality, long term effects of emissions);

EN – environment: short and long term effects of using / operating the given system on the environment (e.g. greenhouse emission, climate change);

PE – penalty: is a new cost element taking into account the interest of the next / future generation (for example extensive use of oil, lithium mining), partly subsidiaries or priority list of development supporting this category.

The first five cost elements are generated directly by the usage of the given product, item or service, including the preparation, operation and recycle. The other five cost elements are secondary (indirect) effects, or impacts caused by the use of the investigated product, item or service. The impacts can be classified into benefits (composed by a positive impact on the economy and society, like enhanced mobility, access to higher education), and negative effects / impact (as costs caused by accidents, impact on the environment). The costs related to benefits and extra costs appeared at third parties (not directly using the product, item or service) are called as externalities. The estimation of the externalities are highly addressed in the literature (Buchanan, 2001), (Essen *et al.*, 2008, 2019). On the other hand, penalty as an externality is a new element, which is a virtual cost considering the interests of the future generation.

Regarding the equation (39), all costs of the life-cycle should be covered, including the (i) use of the given item, product, service, in (ii) the required and supporting infrastructure, (iii) under the applied monitoring / management system and (iv) under the given regulatory / policy environment. This translates to four separable parts, (j = 1, 2, 3, 4). In addition, all cost elements are determined by the "k" system that contains "l" sub-systems and "p" items or elements. The cost related to the "p – th" item can be estimated by the "r" indicators (D), being multiplied with the coefficient (C) that transfers the driver value into the caused cost and by rate of changes in price, interest and discounts (d_v). Altogether, the total life cycle cost can be determined by the following:

$$TLCC = \sum_{i}^{10}\sum_{j}^{4}\sum_{k}^{l_{i,j}}\sum_{n}^{m_{i,j,k}}\sum_{p}^{q_{i,j,k,n}}\sum_{r}^{s_{i,j,k,n,p}}\sum_{t}^{v} C_{i,j,k,n,p,r} D_{i,j,k,n,p,r} d_{i,j,k,n,p,r,t}\,, \tag{43}$$

where $t = 1,2,\ldots,v$ – timeframe in years; $C_{i,j,k,n,p,r}$ - cost transfer coefficient, $D_{i,j,k,n,p,r}$ - driver, indicator, parameter, $d_{i,j,k,n,p,r,t}$ - rate of changes in price, rate of interest, discount

Applicability - testing the proposed indexes

The author of this thesis addressed the implementation of new and pioneering systems, concepts along his entire professional, scientific career, and more particularly in his (i) MSc (Rohacs, 2004a) and early papers (Rohacs, 2004b, 2006a, 2007c), (Rohacs, et al., 2005), focusing on small aircraft, (ii) PhD (Rohács, 2007a) and following EU project publications (Laplace , et al.,2011), (Ghijs & Rohacs, 2012, 2013) on demand, accessibility and affordability of personal aircraft transportation systems, and (iii) habilitation thesis (Rohacs, 2020) investigating TPI index and defining TSPI.

The developed total impact performance index and its determining methodology was applied in numerous projects, e.g. in the conceptual design of a 4-seater small aircraft and in a small cargo UAV (Gal, et al., 2018), (Rohacs & Rohacs, 2019). For the 4-seater aircraft, the methodology was used to compare the total life-cycle impact of a conventional, electric, and hybrid configuration. The performed investigations are part of the Hungarian National EFOP-3.6.1-16-2016-00014 project titled “Investigation and development of disruptive technologies for e-mobility and their integration into the engineering education” (IDEA-E, 2017 - 2020), which is being coordinated by the author of this thesis. The problem was generated by the fact that due to the rapid development of the new technologies, solutions – especially in the electric / hybrid – electric propulsion area – the conceptual aircraft design methodologies (Raymer, 1992), (Roskam, 2017), (Torenbeek, 2013), (Gundlach, 2014) were found to be powerless and a new approach to aircraft design considering the total performance index was required.

Examples

The result of the developed new approach to the conceptual design of a small aircraft based on the total performance index is given in the Figure 41. below:

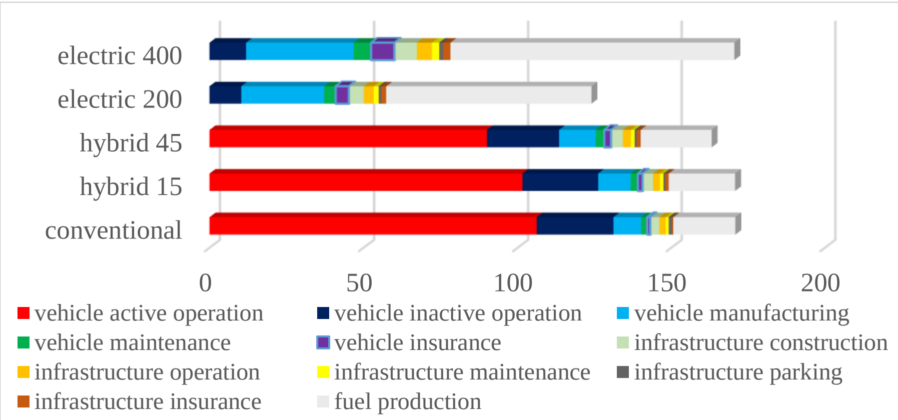


Figure 41. The total life cycle CO_{2e} emission of the investigated small 4-seater aircraft

(conventional – like Cessna 172, hybrid 15 and 45 – hybrid electric aircraft with possible use of full electric flight mode for 15 or 45 minutes, electric 200, 400 – full electric aircraft with battery capacity 200 and 3400 kWh) (Wangai, et al., 2017)

The index and the developed methodology was published in several papers (Rohacs, 2011, 2013), (Voskuijl, 2013), (Rohacs, et al., 2013), Wangai, et al., 2017), (Gal, eta al., 2017, 2018), (Venczel, et al., 2017), (Wangai, 2019 a), (Rohacs & Rohacs, 2019, 2020a, 2020b, 2020c).

The total sustainable performance index (TSPI) was investigated in several fields of application. For example, Figure 42. demonstrates the applicability of the concept for the analysis of different aircraft propulsion systems.

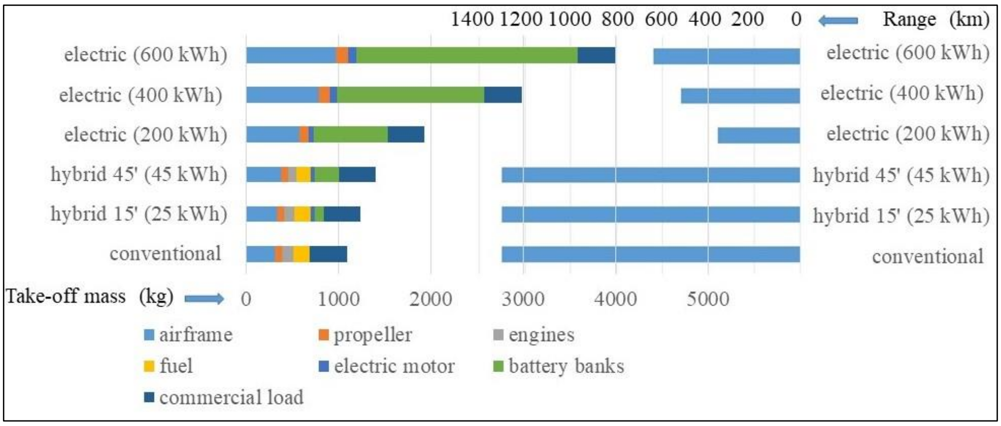


Figure 42. Comparison of the fully electric, hybrid and conventional small aircraft configurations

Full electric (with battery capacity 200, 400, and 600 kWh), hybrid (with 15 or 45 minutes of electric mode) solutions and conventional well-applicable aircraft (analogic to Cessna 172) with hybrid or fully electric propulsion systems. (IDEA-E, 2017 – 2020), (Sziroczak *et al.*, 2020), (Rohacs, 2022a)

Alternatively, Figure 43. shows the collection of records permitting further performance calculations related to the lithium electric batteries.

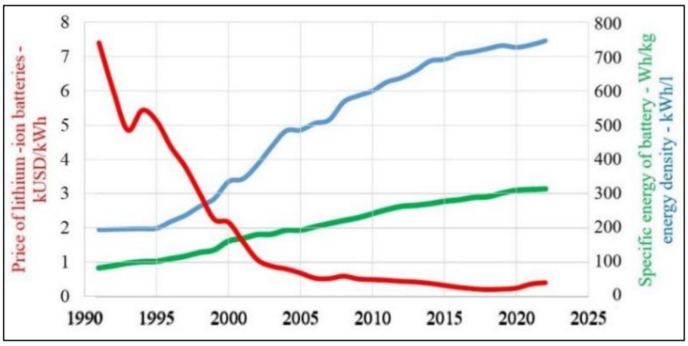


Figure 43. Price and specific energy of lithium-ion batteries (Rohacs, 2022a) (based on (Vereecken, 2020), (*The Economist*, 2021), (Ziegler and Trancik, 2021))

Finally, another field of application is the study of greener aircraft fuelling. Unfortunately, even the most promising method – the use of greener or alternative fuels, energy support – has severe problems that delay the targeted deadline for the introduction of zero-emission or net-zero carbon emission configurations. Some of the most important difficulties are the followings:

- Technologies of new and alternative fuel production and practical application are in development, or early "grows" states (e.g. the specific energy requirement of electric propulsion might only be available in 15 – 20 years later (IATA, 2019)), while numerous efforts addressing new fuels or advanced propulsion systems, including the traditional fossil kerosene, biofuel, e-kerosene, liquid (green) hydrogen, electric hybrid aircraft, fuel cell (hydrogen + electric motors), and electric energy (de Jong *et al.*, 2017), (Doliente *et al.*, 2020), (Shahabuddin *et al.*, 2020), (Bauen *et al.*, 2020), (Zhou *et al.*, 2022), (Yusaf *et al.*, 2022), (Hoelzen *et al.*, 2018), (Baroutaji *et al.*, 2019), (Wheeler, 2016), (Schäfer *et al.*, 2019),

- Aviation also emits the so-called non-CO_2 emissions, which contains oxides of nitrogen (NO_x), soot particles, oxidized sulfur species, and water vapour (Lee *et al.*, 2021). The impact of non-CO_2 impact can be taken into account as CO_2 equivalent (CO_{2e}) or can be measured by the radiation forcing index (RFI) (Jungbluth and Meili, 2019).
- Aircraft fuel or energy consumption – in a simplified approximation – is directly proportional to the aircraft weight, which is increasing with the liquid hydrogen reservoirs' insulations, fuel/hydrogen cells, electric batteries, and inversely proportional to aircraft lift – drag ratio and total efficiency of the propulsion system (namely advanced aerodynamics and complete solution of the propulsion system from energy storage to propellers/trust generation) (National, 2016), (Rohacs and Rohacs, 2020a).

The comparison of the some key aspects of the various greener and alternative fuels is summarized in the Figure 44. For the assessment, 110 g/pkm CO_2 emissions of the fossil jet medium-haul turbofan aircraft is considered as a basis (100%). The fuel price is given in %, as of spring of 2022, since then the kerosene price changes chaotically (in 2019 it was about 50 % less than nowadays, which reduced to another 25 % in 2020, before returning to 50 % in 2021). As one might observe, CO_2 emissions of full electric configurations on a total life-cycle basis are even higher than the fossil fuel based reference, which clearly shows the evidence of life-cycle cost and emission assessments. In addition, the costs associated to the sustainable concepts are in same cases several times higher than the reference (Barke et al., 2022).

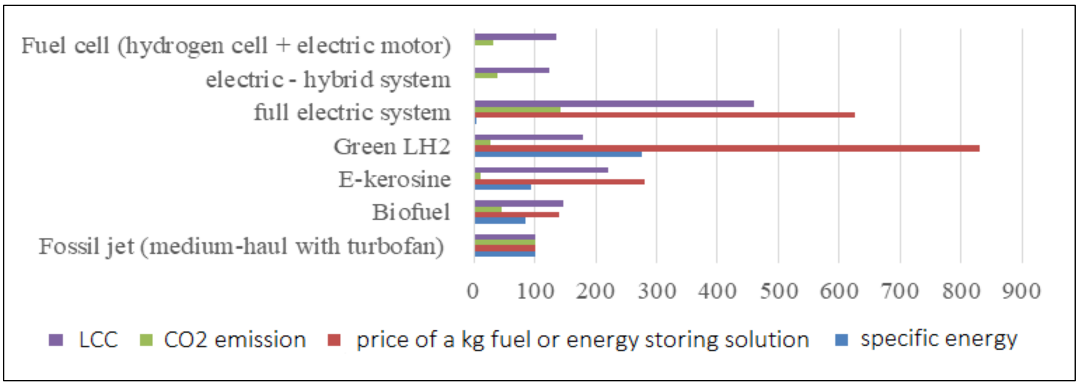


Figure 44. Comparison of the key indicators of different fuels and propulsion systems of mid-size aircraft (in % relative to fossil jet configurations)

One might consider that the electricity price must be defined by the amount that 1 kg batteries might store. In case of batteries with excellent available specific power (400 – 500 kWh/kg), the electricity price is about 60 - 75 Eur /kg plus another 550 Eur per kg of battery. Naturally, the price of electricity is very different from the market price of other fuels because of the subsidy of renewable energy generation and the absence of taxation. An additional problem is caused by the fact that electric batteries' weight does not change during the flight; batteries must be held on the board during the entire duration of the flight. The full-electric aircraft have a considerable reduction in CO2 (determined for the life cycle) depending on the energy mix of the supplying energy. However, this result can be reached with a severe decline in range. In another case, the increased aircraft weight (in order to have the extended range) results in more significant emissions and even impossible solutions using the available and emerging technologies). Finally, some critical aspects of the most promising fuel, the hydrogen reservoirs need rigid insulations, the price is high (where for example only the transportation of the liquid hydrogen equals to 2 - 3 USD / kg (McKinsey, 2021)). Nevertheless, it has an excellent specific power, which might be comparable with carbon based fossil fuels.

Conclusions

Due to the powerless of the generally used techniques linked to sustainability evaluations, two general indexes were developed: Total Performance Index (TPI) and Total Sustainable Performance Index (TPI), based on total life cycle assessment. The calculation methodologies were described for both indexes, which might be seen relatively simple, but their calculation require extensive amount of preliminary studies to identify, evaluate and select the required inputs.

The defined indexes and methodologies were tested in several EU and national research projects, in the development of improved conceptual design methodologies (in aircraft development).

The performed investigations suggest to employ the introduced indexes and their calculation methodology in the evaluation of the radically new technologies, concepts, such as small and electric / hybrid aircraft.

Summary

I defined, developed and applied new total impact assessment factors as Total Performance Index and Total Sustainable Performance Index, given as total life cycle costs related to the governing parameters.

- The costs induced by all life cycle effects of transportation system are related to the unit of transport work (pkm, or tkm) or flight time (flight hours).
- It could be applied for various areas (e.g. safety, efficiency, greening), and different systems or to life cycle phases of aircraft.
- The application of the proposed approach was demonstrated approach in the conceptual design of numerous innovative aircraft concepts, for example for a 4-seater aircraft with electric and hybrid electric propulsion systems. Here, I defined the applicable methodology, introduced a new method to determine the required range prediction equations and demonstrated the applicability of the developed methodology. The concept of index formulations was applied to the investigation of several new concepts, sub-solutions of aircraft, as well as the examination of new fueling possibilities.
- The proposed indexes – with a more mature comparison than the generally used techniques – highly support the development of future aviation, especially in the pioneering and disruptive domains.

4.2. Energetic evaluation of the new aircraft developments

Problem

The possible development and operation of fully electric aircraft configurations in the near future is often considered to be rather optimistic, since numerous SRAs not fully considering the conceptual limitations (e.g. prime material availability) and not assessing the evaluation criteria for the entire life-cycle, including the indirectly linked elements. In addition, methods evaluating the energetic effects (e.g. energy consumption and energy reduction) of such new technologies and solutions are not clearly defined. As a result, there is a ***clear need to define and develop the energy coefficients to compare various future aircraft developments***.

There are needs in definition and developing the energy coefficients for comparison of future aircraft developments.

Basic principles

Electric and hybrid-electric propulsions systems (Pornet *et al.*, 2015), (Antcliff *et al.*, 2016), (Jansen *et al.*, 2017), (Schäfer *et al.*, 2019), (Sziroczak *et al.*, 2020), (Xie *et al.*, 2021) might be the most promising emerging technologies and solutions to support the ambitious goals of policy makers, and more particularly in the reduction of the aviation related environmental impact. According to ACARE, these are generally translated to a 65% reduction in the noise and chemical emissions, a 75% decrease in the CO_2 and a 90% decline in the NOx emissions (while also reducing the risk of accidents by 90%) (ACARE, 2011). These targets are considered with top priority, which leads to the development of rigorous standards and more complex regulatory environment. For example, because climate change is affected considerably by the CO_2 emissions at high altitude, the ICAO Committee on Aviation Environmental Protection (CAEP) developed a special CO_2 standard, and introduced it in the aircraft certification process in 2020 (ICAO, 2017b).

One of the core element of electric propulsion systems is the battery package. Unfortunately, it has several identified challenges and barriers, such as the low specific energy or the thermal instability (Hepperle, 2012), (Kvasha *et al.*, 2018), (Gál *et al.*, 2018). Due to the low specific energy of the available battery technologies, fully electric aircraft configurations have unacceptably high take-off weight and / or dramatically reduced range. Another interesting problematic fact is that with full electric propulsion systems the aircraft weight does not change over the flight, unlike to conventional configurations, where fossil fuel is burned and thus the weight is continuously decreasing.

The use of energy factors, like energy intensity (energy efficiency defined as energy related to passenger travel distance, kWh/pkm, or fuel consumption per pkm) and energy use (fuel energy consumption per seat km) has a long history (Schäfer *et al.*, 2019), (Baharozu *et al.*, 2017), (Skowron *et al.*, 2021). The energy factors can be adapted to electric and hybrid-electric aircraft configurations at three levels: (i) energy intensity of the cruise mode, (ii) energy use for the total flight (flight mission) and (iii) total energy use including all the energy consumption associated to the transportation of goods or people. The energy factors can be defined as the energy related to a unit passenger km or, perhaps a better choice, a unit payload km. The energetic coefficients can be developed by the methods determining flight performance, flight mechanics (Anderson, 1998), (Sadraey, 2017).

Solutions

The energy efficient of the aircraft is often characterized by the range (R) introduced by Breguet (Raymer, 2012) based on the aircraft weight loss due to fuel consumption:

$$R = \int_{W_{final}}^{W_{start}} \frac{V}{g \cdot TSFC} \frac{C_L}{C_D} \frac{1}{W} dW \quad \text{or} \quad R = \int_{W_{final}}^{W_{start}} \frac{1}{g \cdot PSFC} \frac{C_L}{C_D} \frac{1}{W} dW \,, \tag{44}$$

where: W – is the weight of aircraft (*start*, *final* – specify the start and final condition of investigated flight), V – speed, g – gravitational acceleration, *TSFC* – Thrust Specific Fuel Consumption (kg fuel required to generate the unit of thrust during the unit of time, i.e. kg/N/s), *PSFC* – Power Specific Fuel Consumption, and C_L, C_D are the aerodynamic lift and drag coefficients.

For a propeller aircraft, instead of thrust, power (P) should be taken into account, being equal to $P_p = \eta_p P_e$, where indexes p and e depict the propeller and engine, η_p is the propeller efficiency coefficient. Since power equals to thrust (T) multiplied by velocity, $P = TV$, the equation (44) have two forms for jet and propeller driven aircraft.

The real range depends on the flight mission, or flight strategies (e.g. gradual steady climb, applied cruise condition, descent strategy, fuelling strategy). Since it is based on the weight reduction (fuel burn), it cannot be directly applied to the electric and hybrid-electric aircraft configurations, which fully or partly store their energy in batteries with constant weight over the entire flight. This problem could be solved with a new range formula developed by the author, introduced in a research paper (Rohacs & Rohacs, 2020a), as shortly discussed below.

Accordingly, range might be determined by the time depending velocity (V) of the aircraft, from the start (t_{start}) to the final $\left(t_{final}\right)$ time of the flight

$$R = \int_{t_{start}}^{t_{final}} V dt \,. \tag{45}$$

Knowing that the energy reduction during an elementary time frame can be specified from the total energy (E) reduction:

$$\frac{dE}{dt} = -\frac{dE_{fuel}}{dt} - \frac{dE_{bat}}{dt} \tag{46}$$

$$R = \int_{E_{final}}^{E_{start}} \frac{V}{\frac{dE_{fuel}}{dt} + \frac{dE_{bat}}{dt}} dE \tag{47}$$

where indexes fuel and bat define the source of energy as from fuel or batteries.

Let us introduce the hybridization factor (Voskuijl *et al.*, 2018) (energy degree of hybridisation), ψ, as the ratio of the energy (E) stored in the batteries and the total energy stored in fuel and batteries:

$$HF = \psi = \frac{E_{bat}}{E_{total}} = \frac{E_{bat}}{E_{fuel} + E_{bat}} \tag{48}$$

and also power split, PS (power degree of hybridisation), that is defined at all the different flight phases,

$$PS = \frac{P_{em}}{P_{total}} = \frac{P_{em}}{P_{em} + P_{ce}} \tag{49}$$

and the supply power ratio as the ratio of powers integrated over the full block flight mission,

$$SPR = \frac{\int_0^{t_{bt}} P_{em}(t)dt}{\int_0^{t_{bt}} P_{total}(t)dt} \tag{50}$$

where *P* is the power and indexes *em, ce, total* stand for electric motor, conventional engines and total respectively (as the whole system including electric motor and conventional engine) that generate the propulsive power. Finally, the index *bt* defines the block time, ie time from t=0 as propulsive system (engine) start-up to shut down after taxiing.

By using the power split factor and the determined required power, the components of energy reduction (equation (47)) can be defined as

$$\frac{dE_{fuel}}{dt} = -\frac{PSFC}{\eta_{pst_{ce}}}\frac{H_{fuel}}{g}(1 - PS)P_r \tag{51}$$

$$\frac{dE_{bat}}{dt} = -\frac{PS\ P_r}{\eta_{pst_e}} \tag{52}$$

where *H* is the specific energy, the specific heat of consumable fuels, H_{fuel} is the specific energy stored in batteries, H_{bat}. $\eta_{pst_{ce}}$, η_{pst_e} are the total efficiency coefficients of the conventional and electric propulsion sub-systems, while subscript *r* defines the required value (here required power).

Using the *PSFC*, H_{fuel} g, and $\eta_{pst_{ce}}$ (specific power fuel consumption, specific heat of fuel, gravity acceleration and total efficiency coefficient of conventional engine) may cause some problems if there is a mistake in the harmonisation of their dimensions and values.

Firstly, the *PSFC* can be defined as mass per unit of power per second or weight per unit of power per second. Usually technical documents provide reference values in weight per power per time forms, therefore the *SPFC* must be divided by *g*. (Such approach is used by most books and papers dealing with aircraft flight performance.) Usually the specific heat, according to its definitions is given in J/kg $=m^2/s^2$.

Secondly, $\eta_{pst_{ce}}$ can be defined as total system efficiency including the engine, transmission and the propeller efficiencies. This means that this efficiency coefficient equals to the ratio of energy propelling the aircraft related to the energy of fuel burned. This coefficient ranging between 20 – 26 % might be increased to even 36 %, in case of highly effective systems. Unfortunately, the operational manuals of most engines provide fuel consumption as fuel used to generate the unit of break horse power (BHP). This power is measured at the shaft of the engine, before the losses in power caused for example by the gearbox, auxiliary components, and the driving the propellers. Therefore, in such case $\eta_{pst_{ce}}$ must be calculated or measured accordingly. Sometimes, this coefficient is referred to as propeller efficiency coefficient and it is equal to about 76 – 82 %.

The required power can be determined by assuming flights in quasi-steady, quasi-rectilinear modes, like in cruise flight when thrust must be equal to weight over the *k* ratio of lift and drag coefficient:

$$P_r = TV = \frac{W}{k}V \tag{53}$$

With the substitution of (51), (52) and (54) in (47)

$$R = \int_{E_{final}}^{E_{start}} \frac{\eta_{pst_{ce}} \eta_{pst_e}}{\left(PSFC \frac{H_{fuel}}{g} (1 - PS) \eta_{pst_e} + PS \eta_{pst_{ce}} \right)} k \frac{1}{W} dE \quad (54)$$

and assuming that the power split, aerodynamic lift to drag ratio ($k = C_L / C_D$; defining the aerodynamic goodness of the aircraft), the propulsion efficient coefficients and the engine *PSFC* are all constant in cruise flight, the following equation can be achieved:

$$R = \frac{\eta_{pst_{ce}} \eta_{pst_e}}{\left(PSFC \frac{H_{fuel}}{g} (1 - PS) \eta_{pst_e} + PS \eta_{pst_{ce}} \right)} k \int_{E_{final}}^{E_{start}} \frac{dE}{W} \quad (55)$$

The *PSFC* is highly dependent on the cruise speed, effectively the position of the throttle, or rotation speed of the engine. Specifically, combustion engines may have very different *PSFC* depending on the operational mode. As usual, in case of lower rotational speeds, a lean fuelling mode might be applied and fuel consumption can be considerably reduced. However, engine operational modes could be harmonised with different aircraft cruise speeds at nearly the same fuel consumption.

For direct propulsive gas turbines, such as turbojets or turbofans, the required power must be determined as required thrust (equal to the actual drag) multiplied by the flight velocity. In case of considerably reduced velocity, the lift coefficient, and with it the angle of attack and finally the drag coefficient must be increased. So, as the final results, the fuel consumption near the optimal conditions must be nearly the same.

To solve the integral, the simplified mass (weight) breakdown, the weight balance equation could be used as follows:

$$W = W_e + W_{pl} + W_f + W_b + \Delta W_e \quad (56)$$

Here the W, W_e, W_{pl}, W_f, and W_b are the take-off (or total), empty, payload, fuel and battery weights. In this approach, the empty weight is the sum of weights of the airframe and systems, including e.g. the engines, transmissions, ΔW_e defines the changes in empty weight from a baseline configuration caused by the changes in propulsion system elements including the batteries. In a simplified case, this might be determined as $\Delta W_e = C_e W_b$. Of course, the C_e coefficient depends on e.g. the type of the propulsion systems; hybridisation and power split factors, battery energy density (weight of batteries), or structural solutions of the airframe. As a first approximation C_e can be defined as a constant.

The weight components, most often related to the maximum take-off weight, are called weight fractions $\overline{W_i} = \frac{W_i}{W_{TO}}$ $(i = e, pl, f, b)$. They can be usually determined using semi-empirical formulas defined by well-known industry standard aircraft design books and methods. In practice, these weight fraction formulas cannot be applied to the investigation and preliminary design of aircraft with hybrid-electric propulsion systems. This is because, the relative aircraft weight components are changing significantly in case of using electric or hybrid-electric propulsion systems. In addition, there are no universally accepted and available new theoretical or semi-empirical formulas to determine the weight fractions for the electric and hybrid-electric aircraft components.

As first order simplified calculations, the weight of fuel and batteries can be defined as a function of the energy stored:

$$W_b + W_f = \left(\frac{E_{bat}}{H_{bat}} + \frac{E_{fuel}}{H_{fuel}} \right) g = \frac{E_{bat} H_{fuel} + E_{fuel} H_{bat}}{H_{bat} H_{fuel}} g \, . \quad (57)$$

Introducing the predefined total energy, E_{total} required for the realisation of the planned cruise flight and using the hybridisation factor, ψ, the weight of fuel, battery packs and changes in empty weight can be determined as

$$W_{bat} + W_{fuel} + \Delta W_e = (1 + C_e) W_{bat} + W_{fuel} = \frac{(1 + C_e)\psi H_{fuel} + (1 - \psi) H_{bat}}{H_{bat} H_{fuel}} g E_{total} . \quad (58)$$

Combining this equation with equation (54), the range of aircraft using hybrid propulsion systems (after solving the integration) can be predicted as:

$$R_{hybrid} = \frac{\eta_{pst_{ce}}\eta_{pst_e}}{\left(PSFC\frac{H_{fuel}}{g}(1-PS)\eta_{pst_e}+PS\eta_{pst_{ce}}\right)} k \frac{H_{bat}H_{fuel}}{g\left((1+C_e)\psi H_{fuel}+(1-\psi)H_{bat}\right)} \ln\left(\frac{\frac{(1+C_e)\psi H_{fuel}+(1-\psi)H_{bat}}{H_{bat}H_{fuel}}gE_{total}+W_e+W_{pl}}{W_e+W_{pl}}\right). \quad (59)$$

This equation (59) can be used for hybrid aircraft the same way as the Breguet range equation can be applied to conventionally powered configurations. It is a more advanced calculation technique, compared to the published available references, which takes into account the changes in empty weight of the aircraft.

If ψ equals to zero, Equation (59) reduces to the initial Breguet range equations defining the range of conventional aircraft burning fossil fuel equation (44).

Figure 45. demonstrates the applicability of the range equation (59) investigating hybrid-electric aircraft. These curves describe examples of changes in aircraft range (of the cruise part) depending on the hybridisation factor, ψ, battery energy density, H_{bat}, lift to drag ratio, k and coefficient of changes in aircraft empty weight, C_e. The calculation (IDEA-E, 2017), (Rohacs and Rohacs, 2020b) is performed for a small 4-seater aircraft. The power split (PS) is changing with the hybridisation factor $PS = \psi$. Other variables are assumed to be constants. It is clear that in reality most of the variables are changing considerably depending on for example on the chosen cruise speed, engine characteristics, flight operational modes. The total range of aircraft is calculated by the horizontal, climb and descent phases, while the maximum achievable range can include the additional flight distance achieved by the reserve fuel.

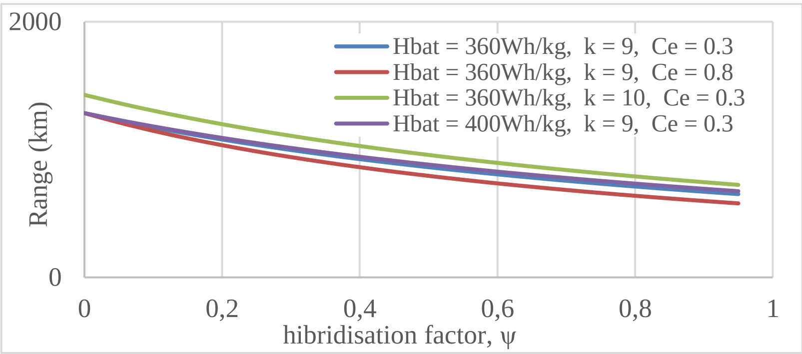


Figure 45. Range depending on the hybridization factor and cruise speed.

The important novelties of the equation (59) is that it (i) includes the usage of the available energy (stored in fuel and batteries), (ii) considers the energy available for the flight, and (iii) covers the changes in the weight fractions (comprising the changes in the empty and payload weights).

Due to the more complex weight assessments over the flight and the low specific energy of the available batteries, the role of energetic analysis is essential for the electric and hybrid configurations. Energetic problems could be solved either by (i) new energetic coefficients, or by (ii) developing new conceptual design methodologies (see point 4.1.).

For the first approach – the development of new coefficients for the evaluation of electric or hybrid aircraft energetic efficiency – the following simple energetic factors are recommended (see Figure 46. and subsequent paragraphs).

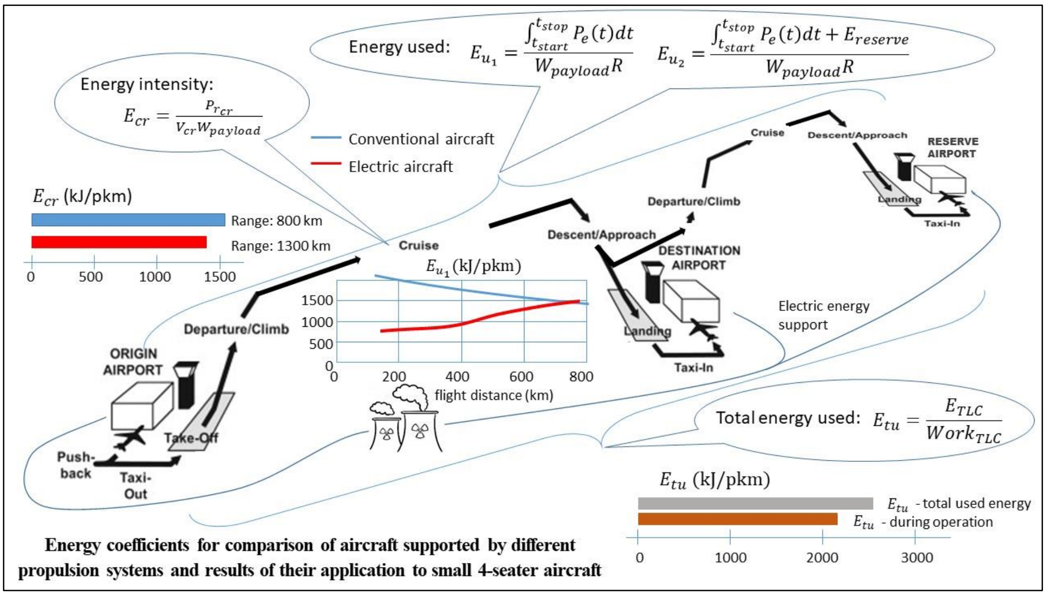


Figure 46. Introduced new energy coefficients for advanced energetic efficiency evaluation (Rohacs & Rohacs, 2020a),

Energy intensity, E_{cr}

It defines the energy used for a unit of transportation work in the cruise (*cr*) stage of a given flight:

$$E_{cr} = \frac{E_{cr}}{w_T} = \frac{E_{cr}}{sM_{payload}} = \frac{E_{cr}}{sM_{payload}}\frac{\Delta t}{\Delta t} = \frac{P_{cr}}{v_{cr}M_{payload}} \rightarrow \frac{P_{rcr}}{V_{cr}W_{payload}}. \tag{60}$$

This energy factor, as others, can be defined as energy per unit of work. Here work is not a physical, rather a transportation work, being equal to moving a mass, $M_{payload}$ for a given distance, *s*.

This factor can be interpreted as a general definition of energy use for a unit of distance by an aircraft in cruise flight mode (kJ/km). This is the inverse of the specific air range (*SAR*) given in km/kJ instead of km/kg. While the specific air range is used when the efficiency is in focus, the energy intensity is rather powerful for the development and selection of alternative or mixed energy sources, propulsion systems.

Energy used, E_u

This energy factor calculates the total energy used (energy consumption) over the planned flight mission (from start, through taxi until engine stop, even comprising the reserve energy) of a given aircraft related to the unit of transportation work:

$$E_{u_1} = \frac{\int_{t_{start}}^{t_{stop}} P_e(t)dt}{W_{payload}R} \qquad E_{u_2} = \frac{\int_{t_{start}}^{t_{stop}} P_e(t)dt + E_{reserve}}{W_{payload}R} \tag{61}$$

where P_e is the engine power depending on the flight altitude and the engine rotation speed (or throttle position).

This energy efficiency factor seems similar to the block fuel per range (BF/R – kg/km), which is determined for the block time (from start of engine, taxi out until stopping the engines or from closing until opening the aircraft doors). The block fuel is used by the operators to evaluate the effective service of given destinations by a given aircraft or to select the appropriate aircraft for the destinations.

The energy used factor is an essential indicator, as it characterises the entire energy, being required to transport a unit mass to a unit distance, which could be translated to the efficiency of the entire propulsion system including the batteries, and other electric/hybrid aircraft features or design characteristics.

Total energy used, E_{tu}

In addition, a third energetic factor can be also used to define the total life cycle (TLC) use of the energy (total life cycle energy consumption) that is related to the entire life cycle of an electric / hybrid aircraft:

$$E_{tu} = \frac{E_{TLC}}{Work_{TLC}} \tag{62}$$

In this case, the energy used is determined upon the entire life cycle of the aircraft, comprising thus the design, development, production, operation, recycle phases, and even including the energy of other related systems, such as the production and operation of special supporting infrastructures, or the production of the electric engines, batteries. This last is also significant, seeing that the battery life is limited and they must be replaced several times during the lifecycle of the aircraft.

Applicability

The use of the recommended energy factors are crucial for sound comparisons, however their calculation is a complex duty. For example, the energy used factor is highly dependent on the exact implementation of the flight mission. To cope with this problem, supporting software like Piano 5 and Piano X (Marco *et al.*, 2020) could be used, which covers more than 250 aircraft datasets for various flight missions and flight simulations.

During the investigation of the applicability of the proposed energy factors, numerous other calculation techniques were also discovered and assessed.

For example, the energy used (E_u) factor could be derived from the instantaneous required power, upon the following formula:

$$P_r = T_r V / \eta_{pst} \ . \tag{63}$$

The change in the total energy of the aircraft (as sum of the potential and kinetic energies) might be defined with the first following approximation:

$$(T - \mathrm{D})V = W \frac{d}{dt}\left(h + \frac{v^2}{2g}\right) \tag{64}$$

where *h* is the flight altitude. Using equation (63) in (64) leads to:

$$P(t) = \frac{T(t)V(t)}{\eta_{pst}(t)} = \frac{1}{\eta_{pst}(t)}\left(D(t)V(t) + W(t)\frac{d}{dt}\left(h(t) + \frac{v^2(t)}{2g}\right)\right) \tag{65}$$

where the total propulsion system efficiency depends on the power split *PS*:

$$\eta_{pst}(t) = PS\,(t)\eta_{e.pst}(t) + \big(1 - PS(t)\big)\eta_{ce,pst}(t) \tag{66}$$

where superscripts *e,pst* and *ce,pst* represent the total efficiencies of the electric and the conventional engine propulsion systems.

The drag could be approximated with the following:

$$D(t) = C_D(t)q(t)S = \left(C_{D_0}(t) + K_1 C_L(t) + K_2 C_L^2(t) + \Delta C_D(t)\right) q(t)S$$

$$D(t) = C_D q(t)S = \left(C_{D_0}(t) + K_1 \frac{n(t)W(t)}{q(t)S} + K_2 \left(\frac{n(t)W(t)}{q(t)S}\right)^2 + \Delta C_D(t)\right) q(t)S \qquad (67)$$

where C_{D_0} is the drag coefficient at zero lift, K_1 and K_2 are the approximation coefficients, ΔC_D is the extra drag generated by elements and devices of the aircraft, q is the dynamic pressure, S is the aircraft wing surface and n is the instantaneous load coefficient.

Seeing that it is rather problematic to calculate the time dependent functions of the required aerodynamic coefficients, aircraft and engine characteristics, instead of integrating the energy usage as a function of time, the flight mission can be divided into smaller, well defined $i = 1, 2, \ldots m$ segments (such as taxiing, take-off, climb) and the used energy for each segment can be determined with the averaged characteristics such as the followings:

$$P_{ref_i} = \alpha_i P_0 \frac{1}{(PS)_i \, \eta_{e.pst_i} + [1-(PS)_i]\eta_{ce,pst_i}} \left\{ \left[C_{D_0} + K_1 \left(\frac{n_i \beta_i}{q_i} \frac{W_{TO}}{S}\right) + K_1 \left(\frac{n_i \beta_i}{q_i} \frac{W_{TO}}{S}\right)^2 + \Delta C_{D_0} \right] q_i S V_i + \beta_i W_{TO} \left(\Delta h_i + \frac{V_{i_{end}}^2 - V_{i_{begin}}^2}{2g}\right) \right\}. \qquad (68)$$

where α_i and β_i are the power lapse ratio and weight ratio coefficients. α is the ratio of power, relative to the take-off reference power in the given flight condition, and β is the ratio of the weight at the given flight segment to the take-off weight.

Altogether, the energy used factor can be estimated with the following equations:

$$E_{u_1} = \frac{\sum_{i=1}^{m} P_{ref_i} t_i}{W_{payload} R}, \qquad E_{u_2} = \frac{\sum_{i=1}^{m} P_{ref_i} t_i + E_{reserve}}{W_{payload} R} \qquad (69)$$

where t_i is the flight time in the i-th flight mode or the i-th flight mission segment.

The performed investigations also showed how much the mission related details, or the covered elements of the assessment could modify the energy factors. This is clearly illustrated by the thought-provoking results (see Figures 47, 48) of one of the authors' related electric aircraft focused project, titled IDEA-E (IDEA-E, 2017). This initiative showed that the energy intensity of the cruise flight mode, E_{cr} (Figure 47.) for an electric aircraft (using batteries with 400 Wh/kg specific energy) may require less total energy (stored either in fuel or batteries) during the cruise phase than a conventional aircraft. However, once the cruise speeds of the various configurations are equal (electric 800 Vcr), or the ratio of the energy stored in the batteries is higher, then the energy efficiency of electric aircraft is lost.

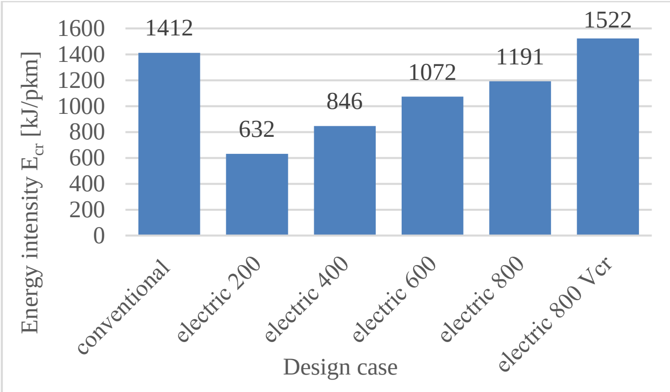


Figure 47. Energy intensity comparison over cruise phase of a conventional 4-seater aircraft (similar to Cessna 172), its electrified versions with 200, 400, 600 and 800 kWh energy storage at reduced and normal (Electric 800 Vcr) cruising speed.

Here energy is determined as the total energy that must be stored in either the batteries or in the fuel. If the applied and not the stored energy is in focus, then the energy intensity should be multiplied by the efficiency coefficient of the total propulsion systems; around 0.28 for conventional aircraft and 0.8 in case of full electric aircraft.

Another example from the project illustrates the ratio of aircraft operation and total energy use. As illustrated in the Figure 48, the total energy is approximately 15–20% higher than the operation alone, which suggests that sound energy comparisons of disruptive solutions should consider all directly and indirectly linked energy related components (e.g. manufacturing of batteries). Figures 47. and 48 are thus demonstrate the applicability of the adapted energy factors, and a more mature evaluation of novel aircraft configurations with different propulsion systems.

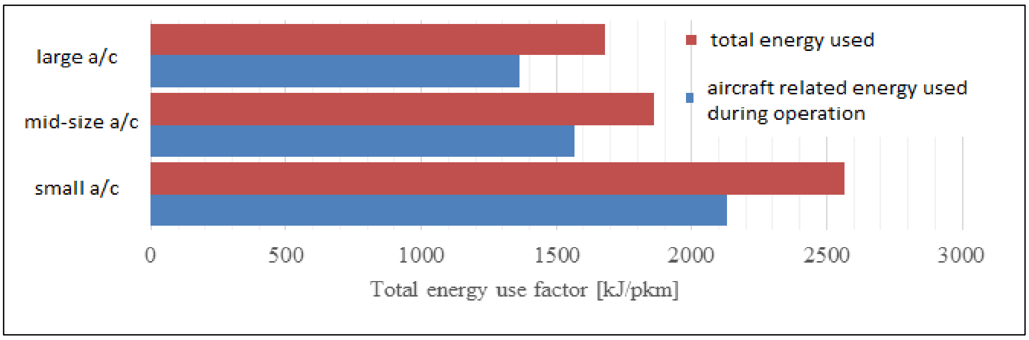


Figure 48. Total energy used factors of various passenger aircraft.

It should be noted however, that the future sustainable air transport depends on various other factors. For example, while the price of Li/kWh has steadily decreased (from 800 EUR/kWh in 2010 to just over 200 EUR/kWh in 2018) (Kavanagh *et al.*, 2018), the battery industry used 35 % of the global lithium production (in 2016), 65 % of which was applied by electric vehicles. If the number of electric vehicles increases in the same accelerated form as for observed in the last decades, then the known global lithium reserves will be used within the 100 years (seeing that the present recycling rate of the lithium is less than 1 %.

Examples

The proposed approach and the introduced energy coefficient were also applied in the new conceptual design framework for electric and hybrid electric aircraft configurations (Gál *et al.*, 2017b), (Rohacs and Rohacs, 2019), (Sziroczak *et al.*, 2020), and in the conceptual development of a smart map showing the locally available energy sources (Rohacs, 2022b, 2023a).

Conclusions

The overall objective of the stakeholders in the development of future aviation is to have a more effective, cleaner, safer and secure transportation. Seeing that energy consumption is a key element of these aviation KPIs, energy related adequate evaluations are of top priority. The proposed coefficients or indicators are to help this duty, and permitting even complex comparison studies of the various concurrent alternative solutions and concepts, and facilitation the most promising technology identifications accordingly.

Energy intensity, E_{cr}. It defines the energy used per a unit of transportation work over the cruise (hence subscript *cr*) phase of a given flight. Seeing that the cruise phase accounts for about 70-90% of the total flight time, the energy intensity evaluates the aircraft's aerodynamic goodness. This factor illustrates that small full electric aircraft may have 10 - 60 % lower (here it means better) energy intensity (thus it requires about 10 – 60 % less energy than the aircraft with burning fossil fuel). However, this great advantage is also considered as major disadvantage, seeing that such full electric small aircraft will have 50 – 80 % less range and / or 40 – 230 % greater take-off mass.

Energy used, E_u. This energy factor calculates the total energy used (energy consumption) to perform the planned mission (from start to final stop). It evaluates the energy used for a given flight destination (flight distance). As such, it combines the aircraft usage with the air transport operation (e.g. airline, airport operation and the air traffic management). This energy factor shows that a full electric small 4-seater aircraft might use less energy for a flight up to 750 km of range. In cases of a larger aircraft and a larger flight distance, hybrid-electric propulsion systems are more reasonable, which could help to reduce the environmental impact at the airport vicinities.

Total energy used, E_{tu}. The third energetic factor evaluates all the energy required (contributed directly and indirectly to the transport of a given good or people). From a sustainability point of view, this is the most useful energy factor for the comparison of the different types of aircraft and their operations. This factor can be determined by using a rather complex approach based on total life cycle assessments. The estimation of this energy factor showed that the total energy used per unit of work done is 15 – 20 % higher than the total used energy during the aircraft operation.

All these factors can be used to determine the required performance related to new propulsion systems, and thus could support the successful development of disruptive and sustainable air transport systems.

Summary

I developed complex energy related indicators to perform complex comparison studies of the various concurrent alternative solutions / concepts, which could support the successful development of disruptive and sustainable air transportation system.

- The proposed indicators permit to assess the energy intensity, the energy used, and the total energy related to the new technologies, or concepts.
- It was found that for the comparison of various competing alternatives from a sustainability point of view, the use of the total energy used indicator that comprises all directly and indirectly related energy components is the most complex, but adequate indicator.
- The use of the indicators was demonstrated in numerous projects, which clearly indicated that the findings of the author could highly support the successful development of sustainable air transportation.

4.3. Developing safety and security philosophies for personal aircraft transportation systems

Problem

The available technologies already permit to develop small personal aircraft, which could be operated by less-skilled pilots (owners or plane renters) at small airport (built close to the city centres), together with the existing civil air transportation. However, ***seeing the experience of the targeted pilots, the operation of such aircraft must be supported by dedicated new safety and security philosophies***.

The possible solution must cover the reconsideration of the safety philosophy related to larger civilian aircraft, the development of the requirements to design / operate small personal aircraft configurations, and the creation of a security philosophy.

Basic principles (related to the development of personal aircraft)

Small and personal air transportation is in focus of various (i) large national projects (NASA Advanced General Aviation Transport Experiments (AGATE), General Aviation Propulsion (GAP), Small Aircraft Transportation Systems (SATS), Personal Air Vehicles (PAV)), (ii) international European projects (European Personal Air transportation System (EPATS) (EPATS, 2007), Small aircraft Transport Roadmap (SAT-Rdmp) (SAT-Rdmp, 2010 - 2012), Personal Plane Transportation System (PPLANE) (Pplane, 2009 - 2012), Efficient Systems and Propulsion for Small Aircraft (Esposa, 2011 - 2014), Enabling Technologies for Personal Aerial Transportation Systems (mycopter, 2011 - 2015) and (iii) Hungarian national projects, as the development of 4-seater composite aircraft (SafeFly, 2007 - 2010), the development of the Corvus Racer 540 acrobatic aircraft (Corvus, 2008 - 2010). The author of this theses was involved in each of the above listed initiatives, beside the NASA and mycopter projects.

The NASA SATS project developed an extremely good vision on the future development of small aircraft and introduced numerous new and original solutions (Holmes, 2004), (Moore, 2018). However, the personal air transportation system requires a new special safety philosophy as it might be based on new design philosophy using new advanced materials, piloted by less-skilled pilots, and operated at small airports close to the city centers, or even in the urban areas.

Solution - Development of safety & security philosophies

The author of this thesis was firstly investigating personal aircraft transportation in his MSc thesis (Rohacs, 2004a). This came with the radically new idea of connecting various control channels to facilitate the pilotage of the aircraft. Its applicability was demonstrated by a simple linearized time variant state space representation of the connected models of the engine and elevator control channels (Figure 49. and 50.).

Before the definition of the aircraft safety philosophy, the small aircraft related accident statistics were analysed, covering 48 safety aspects (related to the aircraft, airport, airspace, ATM, safety features), and summarised in a large scientific report „Deliverable 2.2 report on aircraft system improvement" of the Esposa project (Rohacs, et al., 2011).

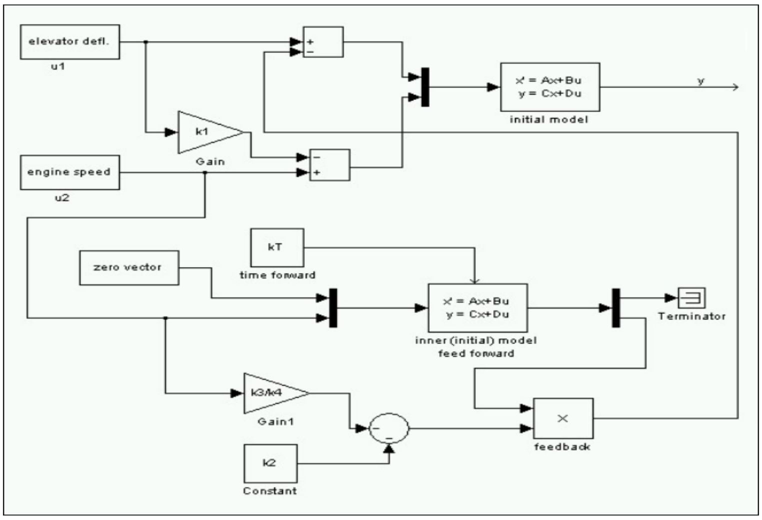


Figure 49. Connecting the engine control and the elevator to facilitate the control of a small aircraft (Rohacs, 2004a), (Rohacs, et al., 2010b).

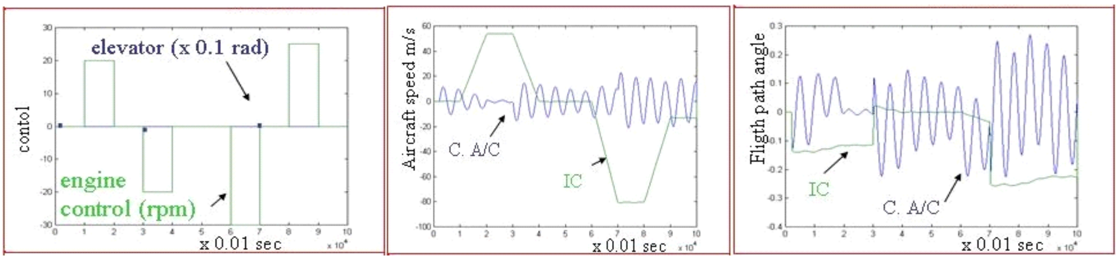


Figure 50. Automation to handle the engine and longitudinal control

(C. A/C: conventional aircraft control, IC: integrated control)

Motivated by the first promising results, the author continued to develop the new safety and security philosophies and the supporting systems. The new operational quality – as safety – factor was defined as the probability of deviation in the operational quality, $\delta\mathbf{Q}_r$ the flight safety threshold, δ_{fs}:

$$P\left(|\delta\boldsymbol{Q}_r(t)| \geq \delta_{fs}\right) \ , \qquad (70)$$

where $\delta\boldsymbol{Q}_r(t) = \boldsymbol{Q}_r(t) - \boldsymbol{Q}_r^n(t)$, i.e. difference in the real quality merit and the designed (nominal) quality. This merit might be determined for each flight situations.

This merit can be also applied as an overall merit, since the deviations in the operational quality might be caused by numerous different reasons, as error in the design, or faults in flight operations.

While flight situations could be modelled in simulations, in flight simulators, or even in real flight tests, the security aspect of the radically new solutions can only be partially evaluated. The physical or even cyber-attacks might be assessed in physics based simulations, but the “interest” of actors using unlawful actions cannot be realistically or meaningfully simulated. Therefore, a special method was developed (Rohacs, et al., 2014c) and applied that is based on the following approach:

$$R(t) = \sum_{i=1}^{n} R_i \prod_{j=1}^{m} R_{i,j}(t) \qquad (71)$$

where R – is the overall security risk, namely R_i is the risk of the identified $i = 1, 2, \dots, n$ security aspects (as event per 1 million flight hours), as initial risk of given event and $R_{i,j}$ is the ratio of the i-th risk respectively to the j-th major aspect of security risks. The last one takes into account the assets, vulnerability, outcomes, threat, violence, „success”.

Less-skilled pilot support

In the personal aircraft vision, a safety critical problem occurred related to the lack of flight experience of the less-skilled pilots. According to the personal aircraft concepts, these pilots will have their license, however the pilot training will be significantly easier, to overcome the constraining cost and time factors related to the actual practice. Therefore, such pilots will have less skills (Pplane, 2009 - 2012), (Rohacs, et al., 2011) and thus should be supported with *enhanced on-board automation and control*. Investigation of the work conditions, situation awareness – evaluation – decision – action process of the less-skilled pilots led to deeply study the pilot decision making methods and load management (Kasyanov, 2007), (Rohacs, et al., 2016b, 2019). Operators' load might be classified as task, work, information and mental loads. Their measurements might support the operators' load management, to increase the operational quality and safety. Seeing this, a complex research on the *operators' decision support and load management* was initiated by the author. The existing operator models required to be updated or adapted to the new requirements (for example on safety, cost-efficiency) and the system framework as defined by personal aircraft vision and strategic research agendas. According to human factors, several areas called for further attention and investigation, such as (i) the situation awareness, (ii) the workload (iii) the vigilance and monotony, (iv) the motivation and stress, or (v) the trust, complacency, and over-reliance (SESAR, 2015), (Metzger & Parasuraman, 2001), (Langan-Fox, et al., 2009), (Merwe, et al., 2010). The major results of this research are the followings:

- identify the role of operators in the future aviation context (shifting the role from active control to passive monitoring),
- adapt and improve the existing (well-known and applied model of Endsley (Endsley, 1995)) to model the situation awareness – decision process in the future air transportation environment (Figure 51.) (Rohacs, et al., 2016b),
- describe the situation awareness – evaluation – decision – action process,
- model the decision making procedures of the human mind by known chaotic attractor (Kasyanov, 2007), (Rohacs, et al., 2016b), (Kale, 2020),
- use the methods of subjective analysis to model the decision making processes,
- apply the models in various situations (like decision on go-around before landing, or decision on deconflicting methods in air traffic) Rohacs, et al., 2011),

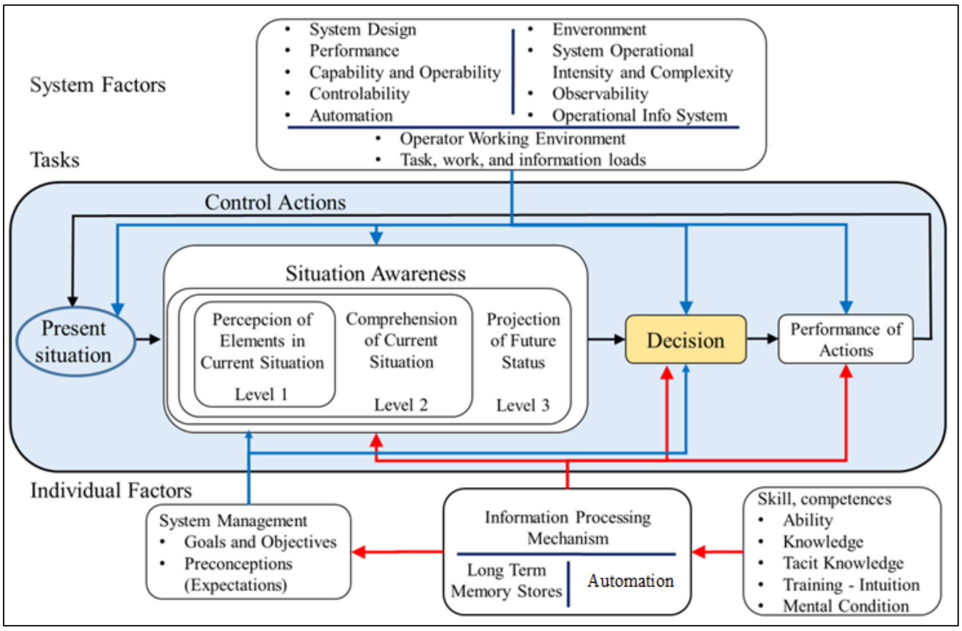


Figure 51. Model of situation awareness in the future air transportation environment (as the basis of subjective decision model)

- develop a new operator model as complex system including the task, work, informatics and mental (physico – psychological) loads,
- develop new methods to measure and evaluate the information overload and mental condition of the operators,
- develop a series of small MEMS (micro-electro-mechanical systems) based sensors and actuators to measure the operators' load conditions (Rohacs, et al., 2016b),
- design the possible integration of the sensors in the working environment (cockpit),
- develop methods to evaluation of the mental condition measurement evaluating the mental condition (Kale, 2020),
- define and develop the load management concept (Kale, et al., 2018a, 2018b), (Kling, et al., 2018),
- develop the supporting screens to adequately present the operator loads (Figure 52.),

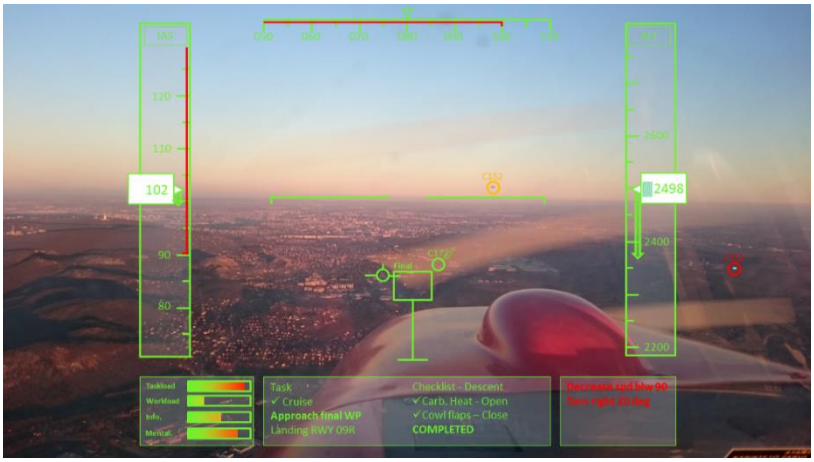


Figure 52. Display of the developed pilot support system (Rohacs, et al., 2019)

- develop the system for operator decision support (including ground and on-board parts and cooperative system with agents – other aircraft).

The investigation of less-skilled pilot situation awareness also comprised numerous research activities in the *subjective decision making processes* (Rohacs *et al.*, 2019), (Jankovics & Kale, 2018), (Kale, 2018, 2019, 2020), (Kale &Tekbas, 2017), (Kale, et al., 2017, 2018a, 2018b, 2020, 2021a, 2022). Along the decision making process, the pilot as subject (Σ) must firstly identify and understand the problem or the situation (S_i,), then the set of accessible or possible devices, methods and factors (S_p) should be selected from the disposable resources (R^{disp}), to finally decide and apply the required resources (R^{req}). For this task, the pilot applies its active and passive resources. The active resources will define how the passive resources are used:

$$R_{\mathrm{a}}^{\mathrm{req}} = f\left(R_{\mathrm{p}}^{\mathrm{req}}\right). \tag{72}$$

Instead of the function between the resources of the equation (74), the literature often uses the velocity of transferring the passive resources into the actives:

$$v_{\mathrm{a}}^{\mathrm{req}} = f_v\left(v_{\mathrm{p}}^{\mathrm{req}}\right), \tag{73}$$

where

$$v_{\mathrm{a}}^{\mathrm{req}} = \frac{dR_{\mathrm{a}}^{\mathrm{req}}}{dt}, \qquad v_{\mathrm{p}}^{\mathrm{req}} = \frac{dR_{\mathrm{p}}^{\mathrm{req}}}{dt}, \tag{74}$$

and in simple cases

$$f_v = \frac{\partial R_{\mathrm{a}}^{\mathrm{req}}}{\partial R_{\mathrm{p}}^{\mathrm{req}}}. \tag{75}$$

Alternatively, the pilot decision process could be also model by subjective analysis. For example, during final approach, the pilot must decide to land or to go around. This decision require time, which is the sum of (i) the time to understand and evaluate the given situation, σ_k, (ii) the time for decision making and (iii) the time to react (covering also the reaction time of the aircraft for the applied decision). This could be mathematically given as

$$t^{req} = t_{ue}^{req}(\sigma_k) + t_{dec}^{req}(S_a) + t_{react}^{req}(\sigma_k, S_a). \tag{76}$$

where σ_k defines all possible situations (e.g. σ_1 might be the situation of landing at first approach without any problems, σ_2 could be related to the situation when the under carriage system could not be opened, σ_3 might stand for a landing on the fuselage, σ_4 for go-around, or σ_5 for a successful landing after second approach).

While other techniques might be also available for the subjective decision making analysis, investigations clearly showed the evidence for the importance of the domain for the disruptive concepts as personal air transportation with less-skilled pilots, and generally applicable to all less-skilled operators (Tekbas & kale, 2017).

Ride control

With the developed new safety and security philosophies, the author investigated other supporting systems and tools that facilitate the development of personal aircraft transportation. Seeing the level of flight automation and the fact that small aircraft are expected to fly at low altitude, which is the most turbulence intensive region, the research focus turned to ride control to enhance passenger comfort. Generally, ride control can be assessed upon the aircraft motion, its reaction on air turbulence and the value added parameters (VAP) or value factors (VF) defining the comfort of passengers (Roskam, 1999). In addition, a special ride discomfort index (J_{RD}) was introduced for small aircraft controlled by less-skilled pilots (Rohacs, et al., 2011), (Rohacs & Rohacs, 2012b).

$$J_{RD} = a_0 + a_1\bar{a}_{z_g} + a_2\bar{a}_{z_c} + a_3\dot{q} + b_1(VF - b_2) + b_3(VAP - b_4) \qquad (77)$$

where the first part deals with the physical disturbance (dividing the vertical acceleration into the elements initiated by the gusts ($\bar{a}_{z_g}$), air turbulence ($\bar{a}_{z_c}$) and by pilot controlling the aircraft motion ($\dot{q}$ – pitch rate)) and the second part takes into account the human sensitivity to the comfort. $a_1, a_2, \dots, b_1, b_2, \dots$ are respective system coefficients.

Applicability - contribution to small aircraft development

The developed methods, evaluation index and safety, security risk calculation models, as well as the other results related to the less-skilled pilot support or total impact analysis were used in several international and national projects like Pplane (Rohacs, et al., 2011) , Gabriel (Vozella, et al., 2012), (Rohacs, et al., 2014), SafeFly (SafeFly, 2007 - 2010), and the Corvus racer development (Corvus, 2008 - 2010), (Wu, 2019), (Wu, et al., 2015).

One example showing the applicability of the risk evaluation can be demonstrated by the determination of the theft probability of small personal aircraft from a small airport during parking. Based on the equations (73), the risk (abstraction) could be defined such as summarized in the Table 3.

Table 3. An example of using the security calculation method to small personal aircraft theft

No.	Sub-system	Risk	initial risk	ratio of the risk model elements						risk
			(event per billion flight hours)	assets	vulner-ability	out-comes, conse-quences	threat	violenc e	success	(event per flight hours)
1.	Aircraft (staying/ parking at airport)	Theft	1	0.36	0.08	0,64	0.22	0.37	0.04	$6 * 10^{-14}$

where

- initial risk: up to now (while small aircraft are used by marginal amount of people with a complex licensing process), the initial theft risk might reach the level of $1 * 10^{-9}$ and about 95 – 98 % from these events belong to simple criminal acts and not terror actions; in the near future with the increasing number of aircraft being used by less-skilled pilots, this risk might increase by 10 – 100 times;

- assets: the value of the aircraft compared to the conventional aircraft might be decreased by 40 – 70 %,
- vulnerability: according to the terror actions, the vulnerability of a possible theft of small aircraft is small and will be reduced by the development of defence systems against small UAVs;
- outcomes: in normal criminal act, the outcomes might be high, while the risk of using small aircraft in terror action is reduced and their outcomes might be cut by 40 – 80 % compared to the existing aircraft,
- threat: because the vulnerability it should decrease by 40 – 70 %,
- violence: should be reduced – as the threat – by 40 – 70 %,
- success: the success of such actions according to the conventional aircraft on the conventional airport must drop by 90 – 95 %, at least due to introduced new security laws.

Another example of security risk analysis relates to the Gabriel project, as shown in the table 4.

Table 4. Using the developed security calculation method to evaluate the risk of the Gabriel Concept (part of the original table from (Rohacs, et al., 2014c))

No.	Sub-system	Risk	initial risk	ratio of the risk model element						risk
			(event per billion flight hours)	assets	vulner-ability	out-comes (conse-quences)	threat	violence	success	(event per billion flight hours)
1.	Aircraft (parking at the airport)	Theft	1	0.97	0.08	1.07	0.44	0.48	0.07	0.0012
2.		Armed attack	3	0.97	0.96	1.12	1	1	1	3.1288
3.		Sabotage	0.5	0.97	0.96	1.1	1	1.1	1	0.5634
4.		Attack by UAVs. UGVs	5	0.97	0.96	1.14	0.96	1.1	0.97	5.4369
5.	Aircraft (in flight)	Hijacking	12	0.98	0.95	1.2	0.96	1.32	0.96	16.3090
6.		Bomb on the board	1	0.97	0.94	1.14	1	1.1	0.97	1.1091
7.		Armed attack	4	0.97	0.96	1.12	1	1.1	0.95	4.3595

The subjective decision making was used in the investigation of the personal / small 4-seater aircraft development projects Pplane (Rohacs, et al., 2011), SafeFly (SafeFly, 2007 - 2010), and investigated by a PhD thesis (Kale, 2020). Results were published by several papers as (Rohacs *et al.*, 2019), (Kale *et al.*, 2020, 2022). The concept was applied to the analysis of the landing processes of small aircraft, driven by pilots with different skills and experience. Figure 53. shows a simplified decision making situation at an approach about the go-around (Kasyanov, 2007). At t_0, x_0, $S_a : (\sigma_1, \sigma_2)$ indicates the set of alternative situations with the distribution of preferences $p(\sigma_1)$ and $p(\sigma_2)$ (where σ_1 indicates the landing and σ_2 defines the go-around).

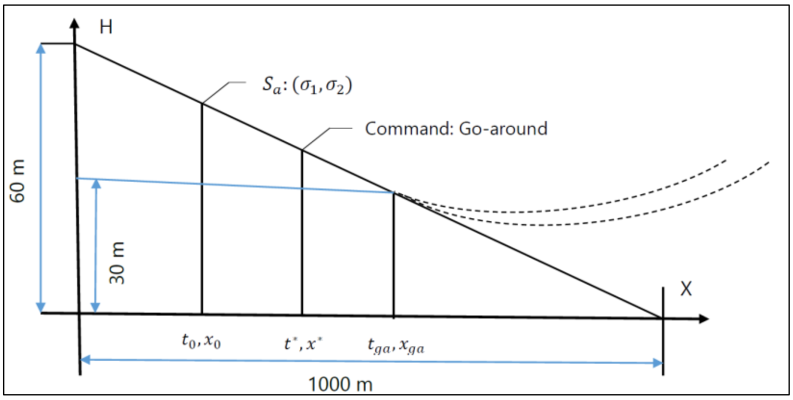


Figure 53. Final phase of aircraft approach

The preferences are oscillating, because of the exogenous fluctuation (while decision altitude is getting closer) and the endogenous processes (depending on the uncertainties in the situation awareness and operators (pilots) incapacity to make decisions. Professor Kasyanov introduced a special chaotic model (Kasyanov, 2007) based on the modified Lorenz attractor (Stogatz, 1994) for modeling the endogenous dynamics of the described process.

$$\begin{aligned} \frac{dX}{dt} &= aY - bZ - hX^2 + f(t); \\ \frac{dY}{dt} &= -Y - XZ + cX - mY^2; \\ \frac{dZ}{dt} &= XY - dZ - nZ^2. \end{aligned} \tag{78}$$

where *a, b, c, d, h, m, n* are the constants while *f* takes into account the disturbance. (In case of $h=m=n=0$ and $f(t)=0$ the model turns into the classic form of Lorenz attractor.) In this model, the coordinates of the attractors can be defined as X - is an inner endogenous parameter, $Y = \beta$ and $Z = \alpha$.

After assessing the subjective probabilities to perform a landing or a go-around ($p(\sigma_1)$ and $p(\sigma_2)$) in a flight simulation environment, a simulation model was created in Matlab environment. Figure 54 shows the results achieved (Kale, 2020). As one might observe, student pilots are thinking “slowly” and they might make a decision after 6 – 10 sec. On the other hand, less-skilled pilots are thinking faster, and change their mind between the possible decisions with higher frequency, but require almost the same time for a final decision. Experienced and well experienced pilots reach the fastest, and generally need 3-to 4 sec for decision making.

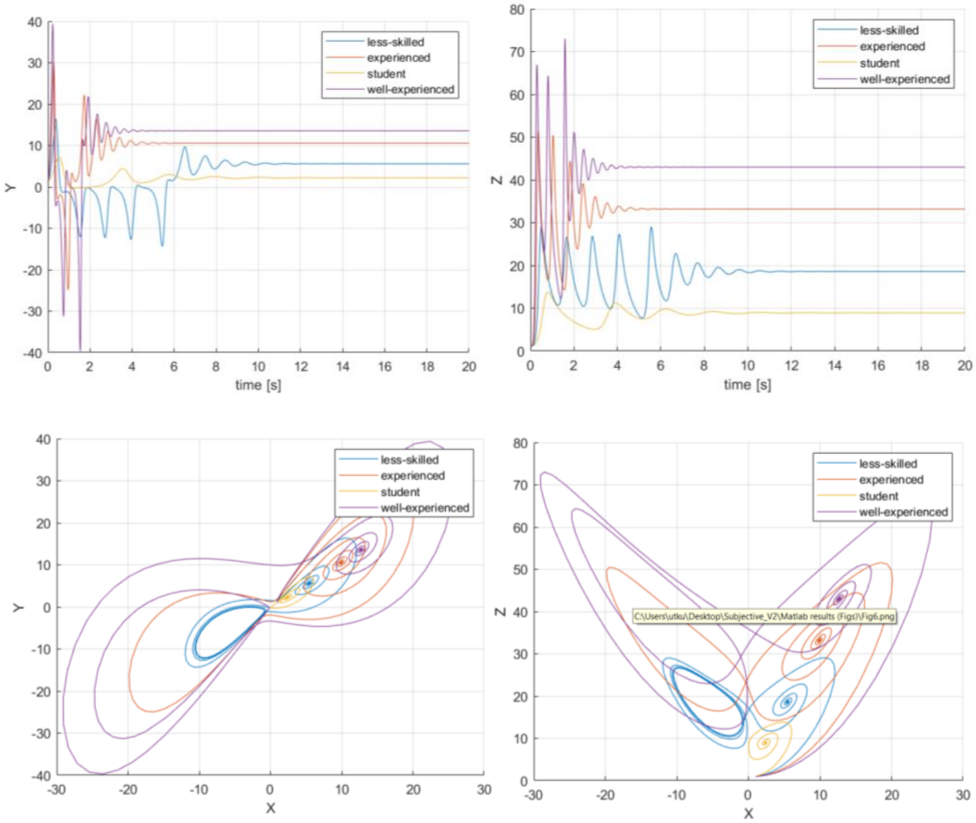


Figure 54. Results of simulation of way of pilots situation awareness, evaluation – reaction (X, Y, Z are the internal variables of the introduced chaotic attractor of the equation (85))

The investigations performed help to have a more complex overview of the pilot decision making processes, which could be used to better define, design, develop various pilot support systems.

Examples

The developed safety and security philosophies are also applicable in other fields of interest, and could highly support the definition of a supportive environment for disruptive technologies. Findings were used for example (i) in the enhancement of operators' workload monitoring and management system (Kale, et al., 2020, 2021a, 2022), (ii) in the development of pilots' working environment and air traffic controllers' workstation at HungaroControl (Rohacs, *et al.*, 2016a, 2016b), (Bos, et al., 2016), (Kale *et al.*, 2021a), but also (iii) in the evaluation of pilot training. The investigations were usually perform in national and international research projects, (PPLANE, 2009 – 2012), (GABRIEL, 2011 – 2014), (IDEA-E, 2017 – 2020), (SAFEMODE, 2019 – 2022)

Conclusions

The development of the safety and security philosophies created the following most important scientific solutions:

- Development of complex situation awareness – decision making processes
- Definition of less-skilled pilot support systems (such as ride comfort)
- Introduction of the philosophy on the integrated control, by cross connecting various control channels (between the engine and elevator control and coordinating the control of the ailerons and the rudder),
- introduce a new operational quality merit,
- Development of a new model for advanced safety risk assessment,
- Development of a new security prediction and assessment techniques for radically new technologies and concepts,

Summary

I (i) defined an advanced situation awareness – decision making process, (ii) investigated and created several new methods, models for safety and security risk evaluation (e.g. subjective decision model), and (iii) developed a series of supporting systems (e.g. cross-control, ride control, operators' new working environment).

- It was found that the advanced situation awareness – decision making process, and other supportive systems (e.g. mental condition monitoring) could permit the operation of pilots with less experience in the novel personal aircraft operations,
- The modelled subjective decision making process provided significantly deeper adequate information on the human factors related to less-skilled pilots, which could highly support the selection or definition of supportive technologies (e.g. cross-control, synthetic vision)
- The use of the proposed new subjective decision making process, supporting systems and the advanced safety and security philosophies were demonstrated in numerous research projects.

4.4. Thesis V

I developed new **total impact assessment indexes** and **supporting frameworks** to perform sound comparison studies of the various concurrent alternative solutions / concepts and provide a supportive environment for the deployment of disruptive air transportation concepts.

- I defined a **total impact assessment index** in terms of all costs generated by the system related to the unit of work performed (like pkm), along the entire life cycle, and comprising the core externalities (such as economy or social benefits, health and environmental impacts, or the interest of the future generation).

$$TPI = \frac{TLCC}{TLCW} = \frac{TOLCC}{TLCW} + \frac{TILCC}{TLCW} = TOPI + TIPI$$

where *TPI* is the total performance index, *TOPI* is the total operation performance index, *TIPI* total impact performance index, *TLCC/TOLCC/TILCC* are the total / total operational / total impact *LCC* (life cycle cost) and the *TLCW* is the total life cycle work. The *TOPI* as the operational cost of the given vehicle, given transportation mode is well known and applied by the owners, operators, service providers. It plays a determining role in the users' selection of the vehicle, transportation mode and transportation chain. On the other hand, *TIPI* deals with the externality.

By covering numerous externalities, the proposed indexes provides significantly more precise results relative to simple life-cycle cost assessment, and thus a more realistic evaluation of various alternatives. The proposed technique was used in numerous national and international projects, for example for (i) the comparison analysis of various 4 seater small aircraft and radically new maglev aircraft configurations, and (ii) the possible optimization of small energetic systems.

- I improved the **small aircraft safety philosophy** and safety by created several **supporting systems** (e.g. ride control, advanced cockpit instruments) for small aircraft pilots, aiming to reduce workload, and rise safety.
- I (i) adapted the known Endsley **situation awareness model** to the future aircraft and air transport environment by including the operators' skill, performance and knowledge into the model, and (ii) defined the operators' situation awareness – evaluation – decision process by the required time (to understand, evaluate, decide, react to the given duty / situation upon subjective decisions based on their knowledge / practice). Relative to the generally used situation awareness models, this approach provides significantly deeper and adequate information on the human factors related to less-skilled pilots, which could highly support the definition of advanced pilot supportive technologies and concepts. The model was tested in flight simulator, and results were validated with airline pilots with alternative competence and experience.
- I have introduced a special formula for **complex security risk assessment** related to radically new technologies:

$$R(t) = \sum_{i=1}^{n} R_i \prod_{j=1}^{m} R_{i,j}(t)$$

where *R* – is the overall security risk, namely R_i is the risk of the identified *i* = 1, 2, … , *n* security aspects (as event per 1 million flight hours), as initial risk of the given event and $R_{i,j}$ is the ratio of the *i*-th risk respectively to the *j*-th major aspect of security risks. The last one takes into account the assets, vulnerability, outcomes, threat, violence, „success".

Most important publications related to Thesis V:

- Rohacs, D.: “Analysis and optimization of potential energy sources for residential building application”. *ENERGY 275* Paper: 127508, 2023.
- Kale, U., Alharasees, O., Rohacs, J. and Rohacs, D.: “Aviation operators (pilots, ATCOs) decision-making process”, *Aircraft Engineering and Aerospace Technology*, Emerald Publishing Limited, Vol. 95 No. 3, pp. 442–451, doi: 10.1108/AEAT-02-2022-0053, 2023.
- Alharasees, O.; Jazzar, A.; Kale, U.; Rohacs, D.: “Aviation communication: the effect of critical factors on the rate of misunderstandings”. *Aircraft engineering and Aerospace Technology* 1748-8842 1758-4213 95 (3) pp. 379-388, 2023
- Balli, O.; Kale, U.; Rohács, D.; Hikmet, K.T.: “Environmental damage cost and exergoenvironmental evaluations of piston prop aviation engines for the landing and take-off flight phases”. *ENERGY 261* : Part B Paper: 125356 , 2022.
- Balli, O.; Kale, U.; Rohács, D.; Karakoc, T. H.: “Exergoenvironmental, environmental impact and damage cost analyses of a micro turbojet engine (m-TJE)”. *Energy Report* 8 pp. 9828-9845. , 18 p., 2022.
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5. Conclusions

As introduced, the *research problem* was that the aviation related strategic research agendas and visions defined challenging targets, which might only be met with the development and implementation of radically new, so-called disruptive technologies. Seeing the nature and complexity of such initiatives, more mature techniques are required for the entire development process, starting from the demand assessment to supporting framework development. As a consequence, the *overall objective* of this thesis was to develop advanced modelling techniques, supporting practices and philosophies for disruptive and sustainable technologies, systems, concepts, covering the following core development segments:

- the modelling of disruptive technology: to assess at first the preliminary demand,
- the technology development and deployment: to identify, select, preliminary evaluate, and develop the targeted technology,
- the evaluation and supporting framework definition: to assess in detail the impact of the developed technology and propose a supporting framework to facilitate the market and public acceptance (e.g. with energetic evaluation, or advanced safety and security philosophies).

The *overall result* of the author is the contribution to the creation, investigation, test and implementation of future disruptive technologies and solutions helping to reach the ambitious targets of the aviation industry. The developed techniques and models were *validated and demonstrated* in numerous national and international research projects (e.g. the use of maglev in commercial air transportation), which clearly showed that the proposed techniques provide an outstanding support for the development of disruptive technologies, systems and concepts.

The findings of the investigations are summarized in the following 5 thesis (see last point of each chapter).

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