A HOLISTIC APPROACH TO EVALUATE THE AIR TRANSPORTATION SYSTEM

Stephan Langhans*, Volker Gollnick*, Eike Stumpf*
***Air Transportation System and Technology Assessment, DLR, Germany**

Keywords: *Evaluation of Technology, Air Transportation System, Systems Engineering*

Abstract

The German Aerospace Center's (DLR) newly founded institute of air transportation and technology evaluation has been given the mission to integrate disciplinary DLR activities on an ATS level. To accomplish this, a systems engineering approach is presented, adapted to the conditions of DLR and the ATS as the system of interest.

In order to capture required disciplinary knowledge on a technology in question, the analysis phase allows for methods like scenario-process and Delphi surveys. Based on this outcome, requirements and a functional description are derived. Methods of different fidelity are applied to find a design synthesis, which is to be evaluated against the requirements or a benchmark. Based on this, a decision is taken.

Special effort is required to integrate high fidelity methods and tools in the overall evaluation process, managing the trade-off between abstraction and computational speed on the one side and on the other significance of results.

1 Introduction

Passenger volume growth will, after peaking in the last few years, remain strong. Global air traffic will be boosted by the emerging of new markets especially in Asia and stay at a high annual growth rate of 5.1% until 2011 and beyond [11]. At the same time, aviation emits gases and particles directly into the upper troposphere and lower stratosphere where they have an impact on atmospheric composition [1]. These emissions, multiplied by constant high air-traffic growth, have a considerable impact on the climate, expressed e.g. by the concept of global warming potential.

Further aspects pose a threat on the efficiency of the air transportation system (ATS): State-of-the-art ATC procedures will not be able to cope with the increasing amount of workload due to constant and high traffic growth while ensuring and increasing further safety standards; airport and airspace capacity is limited and already a bottleneck in certain parts of the ATS; oil price increase and fluctuations pose a threat on airline economic performance; small profit margins in airline business increase competition on the market which makes niches more and more attractive.

Challenging projects and goals have been established around the globe to anticipate and direct the future development of the ATS on a sustainable path (VISION 2020, SESAR, NGATS, JTI Clean Sky, and more [1;20;18;14]).

What all holistic aviation-related R&D efforts have in common is the need to solve a technical and organizational problem-set with often contrary objectives. One reason for this is the necessity for involving various disciplines in the problem-solving in order to cover all its aspects and to manage its complexity.

Under these conditions, a multidisciplinary and integrative approach is required to assess the global potential of new technologies in terms of feasibility, functionality and economic and ecologic effectiveness.

Within the continuum of knowledge, technology is understood to be located between know-how and science [15]. Especially in high-technology related disciplines like aeronautics, these transitions on the continuum are wide, with technology having a strong decline towards science.

In order to cope with these challenges, an integrative institute at the German Aerospace Center (DLR) was established in 2007 following the mission to integrate the various disciplinary R&D efforts undertaken in the aeronautics domain of DLR into the a holistic ATS context. A function is created to both bridge the gaps between the specialized disciplines and integrate disciplinary achievements in meta-systems such as aircraft, ATC, airport or the ATS as a whole. By pointing out potentials of new technologies, industry should be stimulated to facilitate research and integrate rising technologies within their product-development.

In order to achieve these ambitious goals, a tailored process is required. A systems engineering (SE) approach will serve as the foundation of the design and development activities, facilitating a holistic air transportation system evaluation methodology.

2 Systems Engineering (SE) Theory

SE is a widely spread school of thoughts for solving complex technical problems in a structured approach. Giving examples, NASA [17] and the Department of Defense [7], have a long tradition in SE. Numerous publications give both theoretical and practical guidance to systems engineering [22; 6; 10]. For this reason, the introduction to SE in this paper is limited to only those SE elements which later play a major role in this approach of evaluating new aviation-related technologies.

2.1 Reasons for Complexity in Systems

A system can be described as an ensemble or combination of elements or parts forming a complex or unitary whole, such as (…) a transportation system [3]. Engineering sciences usually focus on technical systems which include all types of human-made artifacts. Going further into detail, each system consists of components, which are the operating parts of the system, attributes describing the components and relationships linking components to each other [6] in order to achieve one common objective. In addition a system is also defined by its boundaries, which result in interfaces to link the system to the outside world.

The objective complexity of a system increases with an increasing amount of components, the cross-linking and the dynamics of the system, caused by a change of these elements over time.

For technical systems, the time of existing is covered by the product life-cycle, segmented in the phases of

- Conceptual / preliminary design,
- Detailed design and development,
- Construction / production,
- Operational use and system support, and
- Phase-out, retirement, disposal and recycling.

In general, long life-cycles increase complexity as the predictability of future system states decreases and risk increases. Also the number of stakeholders in the system, e.g. manufacturer and users, increases while their expectations on the system will alter during time. The involvement of multiple stakeholders increases the number of design considerations reaching from technical aspects like *functionality* to aspects like *reliability and maintainability*, *human factors*, *environmental compatibility*, *economic feasibility* and *disposability*. These dynamics enhance system complexity further.

2.2 SE Problem Solving Approach

A fundamental problem-solving approach was identified by Dewey [13] in the early last century, and many later processes are based on his thoughts. The approach contains the sequenced elements of problem identification, problem analysis and the suggestion of solutions. An iteration of these steps will lead to the best possible solution of the problem.

The problem solving approach in SE also founds on this sequence and is shown in Fig. 1. The launch of the shown cycle is triggered by at least the awareness of the existence of a problem. For defining the target area, the current situation has to be understood as a basis for the goal setting. The customer's requirements are expressed in terms of functional requirements, performance requirements and design requirements [7]. This step also includes a functional analysis and allocation which are derived from the requirements. The synthesis of solutions converts the functional system definition into a physical concept and design. The evaluation goal is to compare the solutions against the requirements. Methods must be applied to verify each requirement in a quantitative way. Finally, a decision has to be made to choose a solution or using a new technology. This leads to a result, which in some cases means another trigger for a new process.

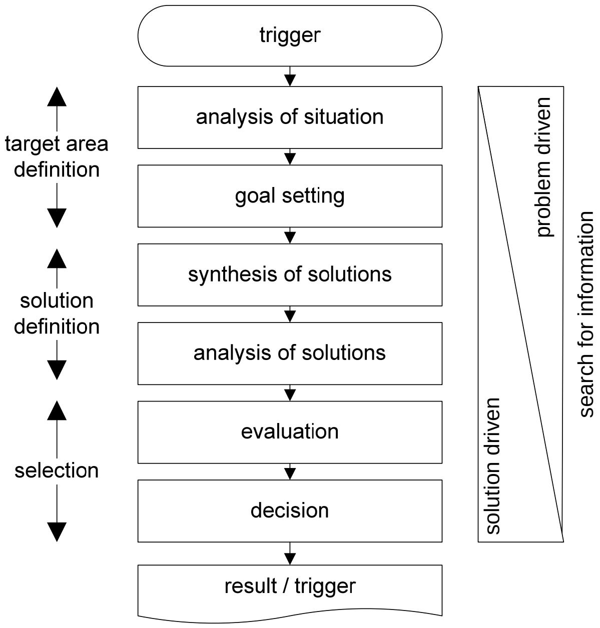

Fig. 1. Problem Solving in Systems Engineering [1]

2.3 Further SE principles

Apart from the above mentioned problem-solving cycle, SE provides further ideas to e.g. facilitate complexity reduction.

Abstraction meets the fact that every system is part of a higher order system [22]. This is sometimes referred to as system-of-systems (SoS). A system of interest (SOI) comprises of sub-systems representing the scope of each system stakeholder. Each sub-system is further broken down into sub-systems in a hierarchical way. The lowest level hierarchy may be treated as black-boxes. The opposite way of this breakdown is called abstraction. Here, a more global relation-oriented view is enabled by widening the angle of observation on the system. Complex subsystems are treated as black-box while parallel systems and their relations to each other are taken into account. This approach is a prerequisite for thinking 'out of the box'.

In this work, a level-definition is introduced which relates to certain level of abstraction and subsequently to complexity. Depending on the problem, simulation and evaluation models will be selected according to these levels.

Life-cycle considerations are necessary to consider all life-time dependent stages of a system. The system itself, its boundary conditions and, as part of these, the stakeholder change are not constant during life-time.

These aspects of SE will be applied to aviation systems and technologies in the subsequently described process.

3 Characteristics of the Air Transportation System (ATS)

The ATS is treated as a complex system of interest (SOI) [22] in the sense of SE. The SOI is embedded in its operating environment consisting of the physical environment and higher order systems such as general transportation, legislation, society, weather and climate to mention just a few. The SOI itself consists of the mission system performing the actual primary function of transporting people and goods between and origin and a destination (OD). The mission segment is embedded and interweaved into a complex supporting system. Depending on the nature of the ATS-related technology and the point of view it is investigated under, any element of the ATS can become a mission system. Looking at a single flight of an aircraft from gate to gate for example, the aircraft and its route are in the main focus, whereas the surrounding systems airport, air-traffic control (ATC) or maintenance service provider (MRO) contribute in a supporting way. The system of interest comprises of the following systems, including their stakeholders:

Tab. 2. ATS elements and stakeholders

Sub-system	*Prime stakeholder*
Aircraft	Airline, OEM, MRO
Airport	Passenger, airport operator, airline
ATC	society (safety), air navigation service provider (ANSP)
Mission	Passenger, Airline
Airport Vicinity	Neighbors, airport operators
Legal Framework	Policy makers
Etc.	

Each system itself again consists of an accumulation of sub-systems, increasing the complexity of the system-of-systems.

The air transportation system covers all ground- and air-operations at the airport and in its vicinity, the aircraft as a highly complex system, the airlines operating the aircraft and air traffic service providers like air traffic control and related instances.

4 DLR Structure & Institutes

DLR is the national center for aeronautics and astronautics. The primary research focus is in these two fields is at DLR. Additional branches for ground transportation research and energy research exist giving DLR the unique competence to cover the complete air transportation system, including non-aeronautic aspects such as inter-modal transport connection of airports and satellite navigation and communication to mention just a few..

Within the field of aeronautics, 18 institutes are conducting disciplinary, fundamental and inter-disciplinary application-oriented research in the fields of aircraft technology (e.g. aerodynamics, aeroelasticity, structures, flight mechanics, materials, design & construction, flight systems, propulsion and more), air-traffic management, airport operations, human factors, human physiology and meteorology. In order to integrate the disciplinary DLR activities on an ATS level the institute of air transportation and technology evaluation has been newly founded acting as a complement.

5 SE influenced ATS Technology Evaluation

Although DLR's activities addresses the definition phase of the system only, nearly all further steps have to be considered when defining a new system. Of special importance is the consideration of the operations and support phase with the operator being the key customer to a product.

Technology is defined on the basis of [4] as the knowledge on an approach for solving a problem or improving the characteristics of system within the aviation SOI. This knowledge is either owned by a human or is manifested in a physical object. Another useful distinction is given in [19] between 'hard' and 'soft' technology. The first is usually associated with engineering or science product the latter on the other hand is describing processes or organizational structures. In this paper, both aspects are addresses when using the expression technology.

5.1 Description of Methodology

A technology evaluation process is outlined, based on the SE approach given in Fig. 1. Different methods are presented as well as they way they are inter-linked. The knowledge of DLR is located in the disciplinary institutes and connected to people, methods or processes there. By applying an iterative, staged approach which makes use of decompositions and abstractions, this knowledge is integrated. A graphical description of the process can be found in Fig. 3 on page 9.

5.1.1 Trigger

As a starting point of the technology evaluation process, one can think of different reasons. Generally speaking, the process can be triggered either problem driven or solution driven. The first is known from a typical SE problem solving approach whereas the latter one would be the start of a somewhat modified SE approach.

One such a solution driven may be the request from a DLR disciplinary institute to assess a technology currently under detailed, investigation under a broader scope. This request could be triggered by the need to reveal the overall potential of this technology under question to potential investors.

5.1.2 Analysis of Situation

The triggering problem-description can be a scrappy, blurry, controversial description of a problem or a desired situation. In general this description is outlining the expectations of the customer, being located in any of the systems life-cycle phases. Possible customers are all stakeholders in the ATS as described in chapter 3.

The goal of this step is to understand the problem and its manifestation, the reasons for the problem and interdependencies.

One essential step is to understand the current situation, and even more, possible future situations. As development cycles in aviation are in the order of decades, correctly predicting the future is not possible. One established way to cope with the uncertainty in future planning is the use of scenario analysis. Originally being developed for military applications, Royal Dutch Shell used this method later on for strategic planning purposes [9]. Aviation has always been a global business and with the establishment of global markets, this scope was even intensified. Not only this, but also the rise of environmental challenges with all its consequences in the last decades fostered the need for a clear perception of the future for a more solid strategic planning.

Depending on the level of detail of the scenario statements, macro-, meso- and micro-scenarios are distinguished [16]. A macro environment describes socio-economic and global ecologic development. Suitable macro-level scenarios are for example:

- SRES [12]: Special Report on Emissions Scenarios (SRES)
- ACARE [5]
- CONSAVE [8]: Based on the IPCC SRES global scenarios

More detailed scenarios give a better insight in aviation related future developments and are at the same time consistent with the top-level macros views. The more detailed scenarios are tailored the certain problem areas and will be established within the problem solving process while the macros scenarios are kept constant.

In order to fully understand the problem as well as possible new technologies to solve the problem, expert knowledge is required. To a great extent, ATS-related expert-knowledge is widely provided within DLR. However, effort has to be undertaken to define, locate, capture and document the problem-specific knowledge. In order to tackle this task, a methodology is established to gather the right knowledge. This methodology consists of processes to find the experts, bring them together and share their knowledge as well as of methods to capture, structure, display and store the found information and knowledge. Expert interviews and surveys, graph theory and design structure matrices (DSM) are applied in this context.

As an output of the step 1, a clear, life-cycle oriented picture of the relevant stakeholders is available. The expectations are captured in a standardized way and aligned to the overall vision of the system. The problem area is well outlined and system elements are designated for potential changes. Functional and performance requirements are documented and so are technology constraints.

Measures of effectiveness and suitability (MOE/MOS) have been defined in order to quantify the achievement of the requirements in later stages. On aircraft level, such measures could be performance related ones like mission block-fuel or noise during approach and departure. For a “design to life-cycle” problem, suitable measures are for example availability and utilization or net present value (NPV). In a more global context, airport capacity or cumulated airspace delay are MOE for ATS effectiveness.

5.1.3 Goal Setting

The goal of any technical system is to perform a certain main function under certain performance requirements and constraints. Therefore, a functional analysis is a key component in this phase. A decomposition of higher-level functions into lower level functions will guide the subsequent design activities.

Enablers of the functional analysis are interdisciplinary teams using tools and models like quality function deployment (QFD), functional flow block diagrams, IDEF and more. A functional breakdown for an aircraft may look like the following:

Primary function

- *Transport people and goods*

Supporting functions

- *Accommodate passenger, crew and cargo*
- *Fly from departure to arrival*
- *Ensure safety and security*
- *Support maintainability*
- *Support operability*
- *Ensure aircraft compatibility with environment*

Also, the key indicators of system performance have to be defined in order to be tracked during the design process. The actual goals which have to be fulfilled by functions are defined as requirements in a quantitative way but without implying any possible solution. Based on the functional system breakdown described above, aircraft requirements comprise of design range, seating and payload capacity and an array of further limits on geometry, noise and emission characteristics, operating cost, and other issues.

5.1.4 Synthesis of Solutions

Based on the functional descriptions on step 3 ‘goal setting’, a computational, physical design of the system is developed. Depending on the identified problem area within the ATS and the MOE/MOS, systems within the ATS are designed at a level of detail resulting from a trade-off between fidelity and effectiveness. The different levels of detail range from handbook-methods over advanced MDO design methods to disciplinary tools.

Also, concepts for aircraft operations and ATC are developed in this phase. For each problem, a set of systems of the ATS is integrated. Depending on the problem-set, these systems are created new, or existing, previously modeled systems are used.

5.1.5 Analysis of solution

The aim of engineering analysis is to provide objective, fact-based data to support informed decision making [22]. Analysis methods will be applied based on the SOI and the level of systems-synthesis chosen. These methods must be able to capture the previously defined MOE/MOS and are related to aircraft design, mission or in a more global sense to the ATS.

On aircraft level, methods for aerodynamic and structural analysis are coupled and applied to analyze the design in an MDO way.

The aircraft mission performance is analyzed in flight simulations. Those are extended by methods to compute noise, local and global emissions. Standard tools for this purpose are for example EDMS and INM, for more detailed analysis, DLR internal, custom built tools are integrated. Those are for example able to model different noise-sources and -characteristics of an aircraft design.

On ATS level, analysis on capacity, delay, climate impact and cumulative noise measures are necessary. Therefore, air-traffic simulations give evidence on TMA traffic, airport capacity and noise impact on airport vicinity. To achieve also more detailed analysis results, methods with higher fidelity have to be integrated in the ATS-level simulation in order to e.g. model an aircraft’s 4D trajectory.

5.1.6 Evaluation

The evaluation step processes the information generated in the analysis phase in order to prepare the decision on a technology. Evaluation is considered as a validation in terms of SE [22] where a work product is assessed on its design and requirements to assure that it will meet the user’s operational needs. Although in this process the evaluation is the last step, validation and verification tasks are performed throughout the whole process.

The evaluation phase also provides objective functions for an optimization process, evaluation results are therefore provided to the design phase. Evaluation will monitor the fulfillment of requirements and the compliance with boundary conditions. Also, comparisons of design to benchmark design give evidence on achieved improvements for different MOEs.

Areas of validation can be of technical nature, consider environmental aspects and be quantified economically.

The technical evaluation comprises of the check for feasibility, functionality, safety and reliability of the new technology integrated into the air transportation system.

Local and global impacts of aviation are considered in the environmental evaluation. Emissions and noise are of primary interest in this context. Aviation's contribution to climate change is more and more influencing the technologic and operational development technologies. An evaluation of aviation emission takes into account the global future fleet as it develops according to different scenarios. Models are then applied to assess e.g. the global warming contribution of aviation emissions. Local emissions are also assessed in this way, but furthermore the local effects on the airport vicinity, including emissions from secondary traffic to and from the airport are under consideration. For noise assessment methods to assess the affected population at specific or generic airports for e.g. different approach procedures are applied.

Economic evaluation provides a way comparison between physically non comparable parameters. By translating these into a monetary value, a single unit for comparison is found. From an airline perspective, a cost-benefit analysis (CBA) for one aircraft or an entire fleet combines direct and indirect operating cost with the income of revenues at a certain rate of utilization. Manufacturers' cash flows define a required production rate to break even in a project, considering recurring and non-recurring cost such as expenses for R&D of new technologies. It is worth mentioning that economic evaluation is only done for reasons of comparability, it does not provide the information which is required for a full business-case calculation.

5.1.7 Decision

A decision for one of the designed system synthesis is required in this step. The decision itself is based on the outcomes of the system analysis and system evaluations.

As the evaluation creates an array of more than one parameter describing system performance, a way to compare those parameters is to make use of multi-attribute decision making. By weighting different MOEs to each other, one overall measure of performance can be derived and used for decision making. Depending on the boundary conditions and the scenario assumed, the weighting factors might put emphasis e.g. on ecologic performance such as noise and emission generation.

Also a risk analysis will provide a level of confidence for certain evaluation, which is also taken into account for the decision.

5.2 Organizational Aspects

In order to summarize all the technology research activities into a holistic ATS evaluation approach an integrated conceptual design and assessment organization was established in DLR.

This institute aims at combining and evaluating all efforts undertaken in DLR research and further more in academia and industry and hence provides a bridging function between all relevant activities.

Within DLR, aeronautics research in all areas relevant to the ATS is performed. High fidelity methods and tools are developed and used. In Fig. 2, those are located in the lower part and described with 'B' and 'C'. In horizontal axis, different 'fields of interest' or disciplines are given which provide tools of different level of detail. This is varying on vertical direction. In order to model the behavior on ATS level, usually several of the different fields of interest are part of the system. This is depending on the problem set and so is the level of detail that is required for every disciplinary field. For fields or sub-systems not in the primary scope, lower level methods and tools ('A') may be sufficient, whereas other more important aspects need modeling at higher level of detail. Questions on compatibility and interfaces as well as usability for people not familiar with the method and intellectual property issues arise in this context and need to be solved.

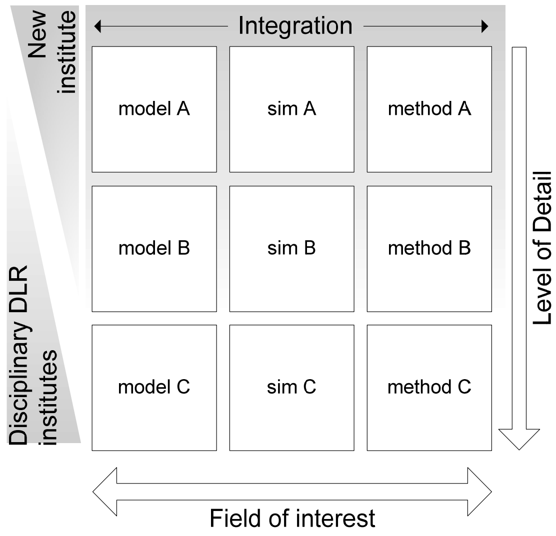

Fig. 2 Integrative function of the new DLR institute

5.3 Compatibility with IPPD Tenets

Integrated product and process development (IPPD) is a process aiming for integrated and concurrent development and manufacturing process planning tailored to the customer's needs. It constitutes of a set of tenets underlying every IPPD management phase from product concept to product use [21]. DLR's prime focus is the involvement in technology and product research and development in the first product life-cycle phases.

The technology evaluation process outlined in this paper is for this reason also aligned to the fundamental IPPD principles. The following principles are considered in the SE approach presented here: Customer focus, concurrent development if products and processes, early and continuous life-cycle planning, multidisciplinary teamwork, proactive identification and management of risk.

5.4 Integrated Product Teams (IPT)

The IPPD process is realized by setting up integrated product teams, namely teams of experts from relevant fields allowing for inter-disciplinary work in the early stages of research and development (R&D). The set-up of the research teams to be formed in the assessment process described in this paper, which are mainly engaged in the fuzzy front end of assessment (situation analysis and goal setting) and the final synthesis, follows an identical philosophy: all relevant research disciplines have to be involved in order to enable significant, relevant and transparent assessment results.

6 Conclusion and Outlook

To integrate the disciplinary R&D efforts at DLR, an integrated conceptual design organization is established, which follows the mission to integrate detailed research activities into the context of the entire ATS. With aeronautics facing tremendous challenges within the upcoming decades, this institute will extend DLR's capability to develop technologies for a sustainable air transportation system. In addition the identification of value of certain research will be of increasing importance.

This paper outlined a general systems-engineering approach which is in establishment at the institute. Low to medium level methods and tools are applied to conduct technical assessment. For more detailed analysis, the disciplinary DLR institutes are incorporated in the process. This poses a great piece of challenges on all researchers involved. When vertically integrating methods and tools upwards, special attention has to be paid to abstraction without disregarding essential feature of the more detailed model. Results of such a failed abstraction would be worthless. To prevent from this, the experts' and method owners' consultancy is essential.

Different DLR-internal, national and European projects are currently in progress or about to start. They provide enough opportunity to verify, consolidate and advance the process.

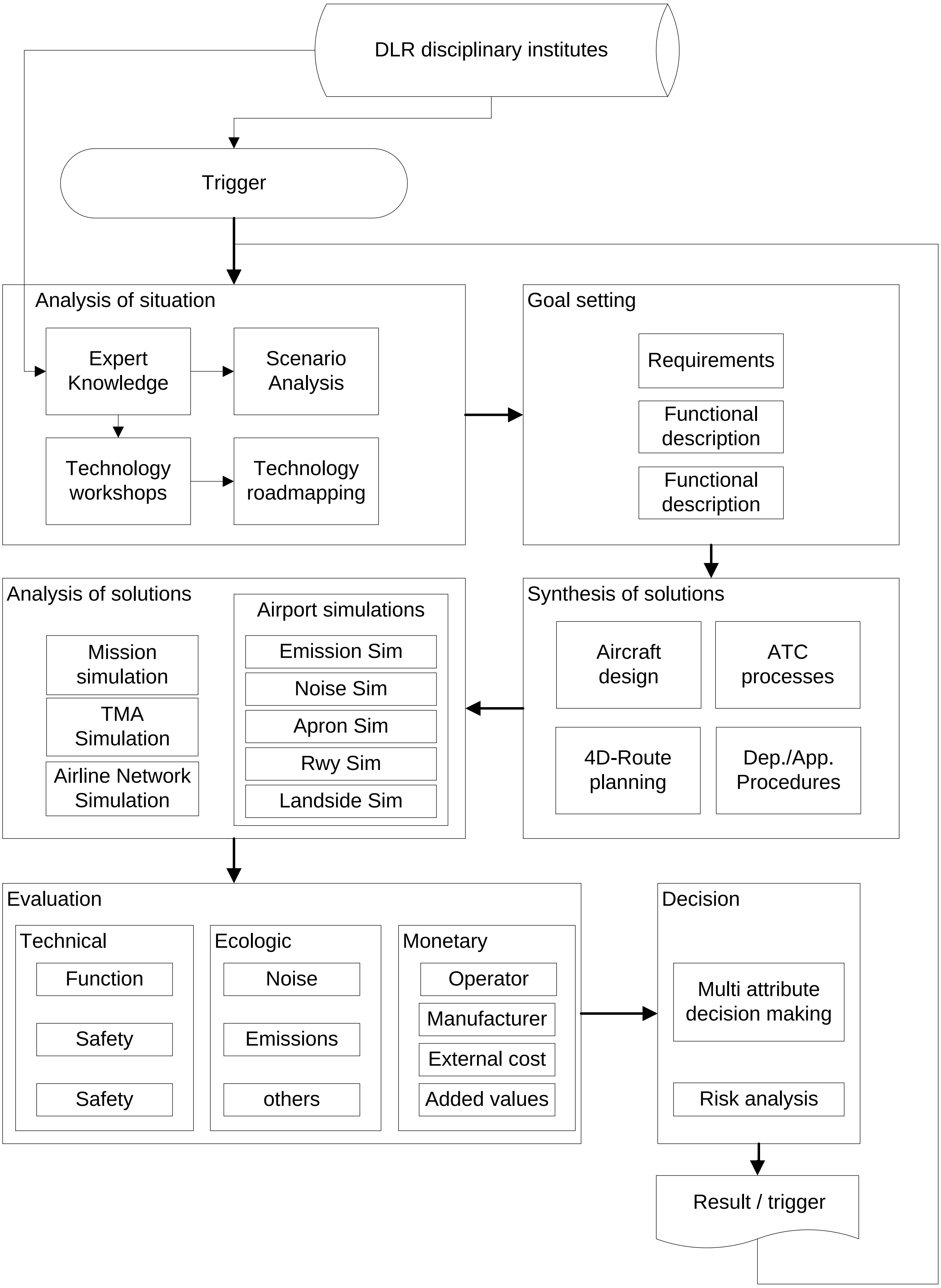

Fig 3. Systems engineering related plan of the DLR technology evaluation process

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