FRAUNHOFER-INSTITUT FÜR SYSTEM- UND INNOVATIONSFORSCHUNG ISI

WIND TUNNEL TECHNOLOGY ROADMAP AND ANALYSIS OF THE INNOVATION WITHIN THE FIELD

TECHNOLOGIE-ROADMAPPING AM FRAUNHOFER ISI: KONZEPTE – METHODEN – PRAXISBEISPIELE NR. 2

Wind tunnel technology roadmap and analysis of the innovation within the field

Project report to the
DNW German-Dutch Wind Tunnels, The Netherlands

Fraunhofer Institute for Systems and Innovation Research ISI

Karlsruhe (Germany), August 2010

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Executive summary

Objective and focus

The DNW German-Dutch Wind Tunnels, The Netherlands, commissioned the Fraunhofer Institute for Systems and Innovation Research ISI to carry out a project under the headline: “Wind tunnel technology roadmap and analysis of the innovation within the field”. The objective of the project was to identify future developments and analyze innovations in the field of wind tunnel technology in Europe.

Structure

The project is structured into three work packages:

- WP 1: Definition of a proper tool set for assessing wind tunnel technology within aeronautics (prerequisite);
- WP 2: Development of a wind tunnel technology roadmap including major applications in Europe till around 2030 (main part);
- WP 3: Analysis of the wind tunnel technology innovation system in Europe (additional part).

The project has run from April 2009 till April 2010.

Results and findings

Corresponding to the project structure, the results and findings of the project are arranged according to three work packages mentioned above:

- WP 1: Bibliometric analyses, technology roadmapping, and innovation system analysis are building a proper tool set for assessing wind tunnel technology within aeronautics and for charting the route of future developments;
- WP 2: A comprehensive European wind tunnel technology roadmap including applications and requirements offers a solid route of further developments in the field of wind tunnel technology in Europe, along the time line till 2030;
- WP 3: The wind tunnel technology innovation system in Europe provides an overview of leading agents which are a key for understanding the dynamics of innovations in wind tunnel technologies in Europe compared to other countries.

The results and findings of this project are based on a customised set of methods, including desktop research, document analyses, and bibliometric analyses, formal discussions, European expert workshops, and a series of personal and telephone interviews with both, technological experts of the wind tunnel community and different users of wind tunnel facilities in the aeronautics, automotive, logistics, transport, and defence industry.

As a result, the integrated wind tunnel technology roadmap that was created contains three parts. These are the technological part followed by the part that represents the market view, and finally the integration and connection of both parts.

On the first part of the **wind tunnel technology roadmap** that was created from technological experts several development paths could be identified. These paths not only contain technological aspects but also prerequisites. One of these paths concerns “pressure sensitive paint” and originates at the item of “good illumination” and even includes the question of “paint supply”. Most of the named prerequisites of the technology roadmap are external factors with regard to wind tunnel industry. As a consequence they need to be initiated explicitly by the wind tunnel community to be developed by their suppliers, which was supported during discussion. During the workshop three topics often were named, which are the topic of “miniaturization”, “turn-key systems”, and the issue of “automation”, which goes in line with the previous topic.

The **wind tunnel product roadmap** displays the other step on the way to generate a complete wind tunnel technology roadmap. In comparison to the technological part in the wind tunnel product roadmap a lot of aspects could be positioned over time and from then on exist as a continuous request once they appear on the agenda. Moreover numerous aspects that were listed affect cost situation. In the analysis it could be further identified that in the layer of “products & services” one half of all topics are related to model technology. Another noticeable fact is the large number of aspects that pick “trust in measured data” and “accessibility of data” as a central theme. The layer that comprises “challenges” one third of all aspects requires strategic decisions and hence, was sorted to “management issues”.

The **integration of the technological roadmap and the product roadmap** revealed three core aspects:

- First it could be identified, which topics are of highest technological complexity. Here the request from customer side that could be connected with the highest number of technological developments is the topic of “miniaturization”.
- Secondly also core technologies could be identified, which impact several customer requirements and products at the same time. Above all “model technology and manufacturing time” is the item earning highest attention since it has the largest leverage with eleven products and customer requirements that were identified to benefit from development progress in this field.
- The roadmap integration revealed also a third aspect. It could be identified which products and customer requirements are not connected to a single technological development on the technological roadmap. Here six white spots

could be identified, which equates to a tenth of the group of all requirements and products from the product roadmap part.

In a separate part the **wind tunnel technology innovation system** has been investigated with a regional focus on Europe but also some insights into other wind tunnel innovation systems. One focus of the investigation was laid on the incentive system present in different regions. For Europe it could be found that upon others also the research infrastructure of wind tunnels is of strategic relevance for the European Commission, which currently supports two activities (EWA, ESWIRP) of wind tunnel operators directly. Besides this regional perspective also the **technological innovation system** of wind tunnel industry has been described and investigated further. Twelve hindering factors could be identified that prevent ideal functioning of the technological innovation system and thus hinder the development of innovations. In order to make the innovation system of wind tunnels accessible and controllable a software-tool was designed that contains a large data base of members of the wind tunnel innovation system, which are either members of the national or of the technological innovation system. In addition also a list of all projects in aeronautics funded by the European Commission is appended. In order to manoeuvre through all data a graphical user interface has been integrated that allows to easily browsing through the data. Single members of the innovation system can be accessed directly via a hyperlink implemented in the data base.

1 Introduction

The overall objective of the project: “Wind tunnel technology road map and analysis of the innovation within the field” is to identify further developments and analyse innovations in the field of wind tunnel technology in Europe.

The project is structured in three work packages (WPs) (Figure 1):

- WP 1: Tool set for technology assessment;
- WP 2: Desk research on wind tunnel technology in Europe;
- WP 3: Analysis of the wind tunnel technology innovation system in Europe, with a more detailed study of its incentive system.

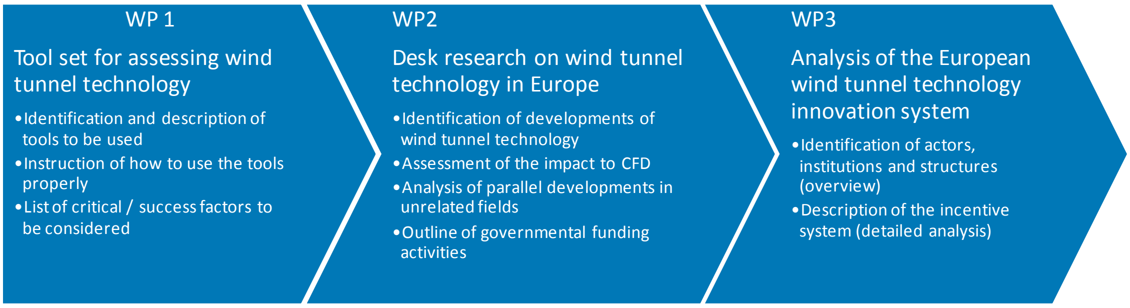

Figure 1 work packages of the project

The WPs are processed successively as preceding WPs are the basis for subsequent ones.

2 Methodology of the project

As a first WP and a prerequisite for the whole project, a tool set for assessing wind tunnel technology was defined which is applicable for the particular field of wind tunnel technology within aeronautics. This tool set is a further development of the foresight tools that are used by Fraunhofer ISI for assessing various other technologies and their position amongst the technologies that are supported by the society at large. The tool set provides a solid methodology of the project.

Within the pool of tools to be considered for technology assessment, the first choice was to avoid using interviews. Without doubt, on the one hand interviews could be a beneficial tool as they provide a fresh and straightforward look delivering personal views. On the other hand, however, interviews imply shortcomings, e.g. they are resource-intensive to carry out. Moreover, results derived from interviews are often biased and guided through underlying personal motivation and institutional interests. Particularly the phenomenon of over-optimism may affect a rather realistic perspective. Such effect typically do emerge in closed-shop communities and expert circles.

Despite possible shortcomings mentioned above, we have to make use of interviews during the project. The underlying reason was that the workshop format initially proposed could not be implemented. Hence, we had to find an alternative to include the knowledge of certain experts. We carried out a certain form of standardized and straightforward interviews, which in sum may emulate an atmosphere close to a workshop.

2.1 Objective and focus

The objective is to define a proper tool set for assessing wind tunnel technology within aeronautics. The focus is laid on three distinct tools:

- bibliometric analyses to get some quantitative data;
- technology roadmapping as the key tool to include (i) market view and technology perspective as well as to include (ii) internal expertise from the wind tunnel community and a fresh look outside the community;
- innovation system analysis to provide an overview of key agents like private and public institutions that are driving innovations in wind tunnel technology and to define the whole landscape of wind tunnel technology through framework conditions.

2.2 Methods applied

Two research methods have been applied: (i) Review of foresight methods used by Fraunhofer ISI for assessing various other technologies and their position amongst the technologies that are supported by the society at large, and (ii) kick-off workshop at DNW, Marknesse, The Netherlands, May 20, 2009, with detailed discussions which tools could be used to best meet requirements and fulfil expectations mentioned above.

2.3 Results and findings

The results and findings include a proper tool set for assessing wind tunnel technology applicable for the particular field within aeronautics. This tool set covers:

- bibliometric analyses;
- technology roadmapping;
- innovation system analysis.

The pool of foresight tools used by Fraunhofer ISI for assessing various technologies (Figure 2) formed the basis to define a proper tool set for assessing wind tunnel technology applicable within aeronautics.

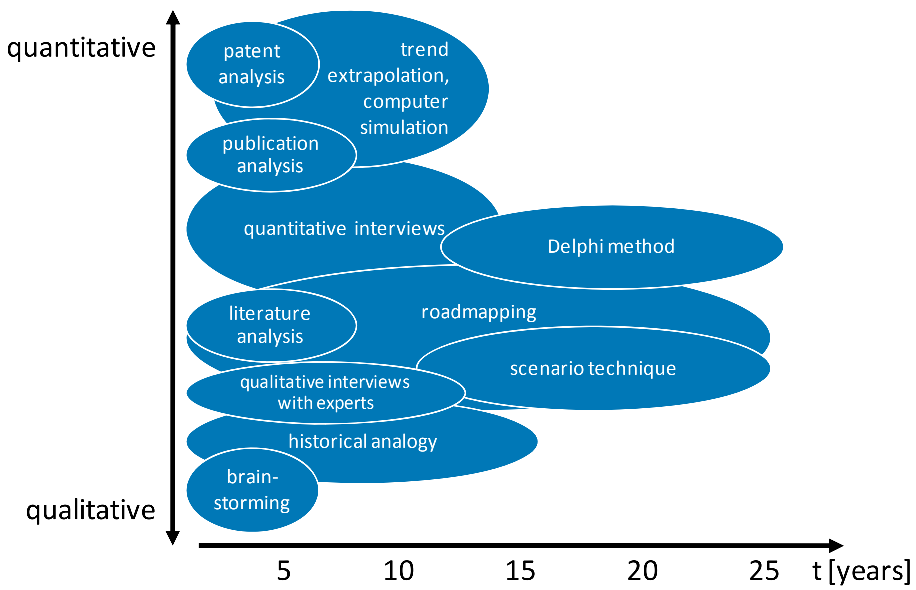

Figure 2 pool of foresight tools used by Fraunhofer ISI

While discussing the benefits and limitations of certain tools, a combination of three tools proved to be a suitable methodology for conducting the project (Figure 3): bibliometric analyses, technology roadmapping, and innovation system analysis.

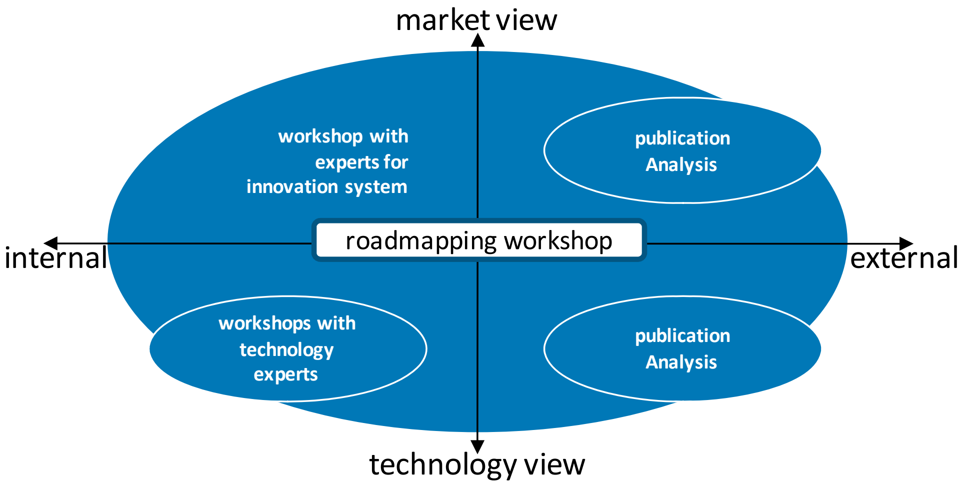

Figure 3 choice of tools used along the project

2.3.1 Bibliometric analyses

Bibliometric analyses are performed to study the communication in science through application of statistic methods on literature data which is drawn from literature databases. In this study the database SCOPUS™ has been used. Observed anomalies in data set usually display starting points for detailed investigations in order to shed light on underlying reasons. Bibliometric analyses are useful to identify research topics and to get information on research dynamics in different regions. In principle it is even possible to perform a network analysis of actors or institutions but which was not part of the present study.

2.3.2 Roadmapping

Roadmapping is increasingly used as a management technique for supporting innovation, strategy, and policy at firm, sector, and national levels. Motorola is widely accredited with the initial development of the technology roadmapping approach in the 1970s. Through its long history the roadmapping approach has evolved, as firms and other organisations have adapted the concept to address their particular needs and the changing business context. The longevity of the method is attributed to its ability to support strategic communication within and between organisations, and the inherent flexibility of the method, which can be readily customised. This flexibility is both an advantage and a challenge, as a standardised 'off-the-shelf' approach is rarely feasible.

A key benefit of the approach is the communication associated with the development and dissemination of roadmaps, particularly for aligning technology and commercial perspectives, balancing market 'pull' and technology 'push'. Roadmaps can take many forms, but the most general and flexible approach comprises a visual time-based, multi-layered chart, illustrated in Figure 4, enabling the various functions and perspectives within wind tunnel technology to be aligned, and providing a structured framework to address three key questions: Where do we want to go? Where are we now? How can we get there?

The form of roadmap (illustrated in Figure 4) is very flexible, and the structure of the roadmap, and the process used to develop it, can be adapted to suit many different strategic and innovation contexts. The roadmap framework can be considered as a dynamic business or systems framework for strategy and innovation, with the architecture of the roadmap providing a coherent and holistic structure (a common language) within which the evolution of the business system and its components can be explored, mapped, and communicated.

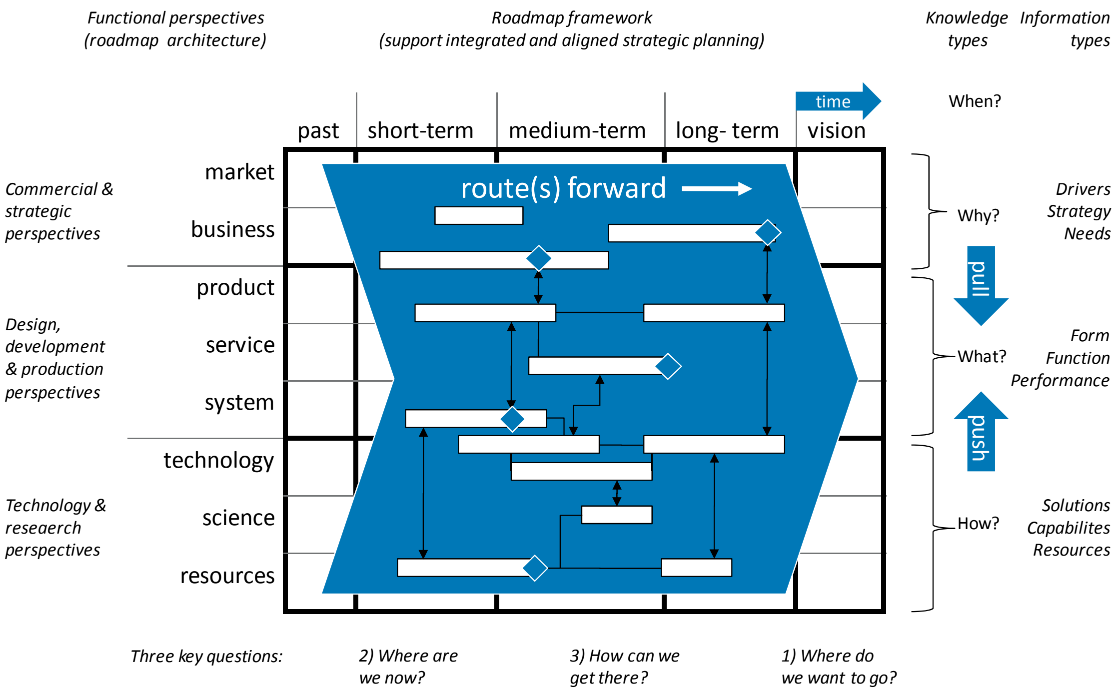

Figure 4 generic roadmap, illustration (Phaal et al. 2008)

2.3.3 Innovation system analysis

An innovation system analysis highlights a set of distinct key agents like institutions, which jointly and individually contribute to the development and diffusion of technologies and which provide a framework that allows governments forming and implementing policies to foster innovations (Figure 5). As such an innovation system analysis provides a system of interconnected institutions to create, to store and to transfer the knowledge, skills and artefacts, which drive innovations. A solid analysis grid is used for analysing the wind tunnel innovation system. This grid has proven to serve as a useful heuristic, not as a normative model.

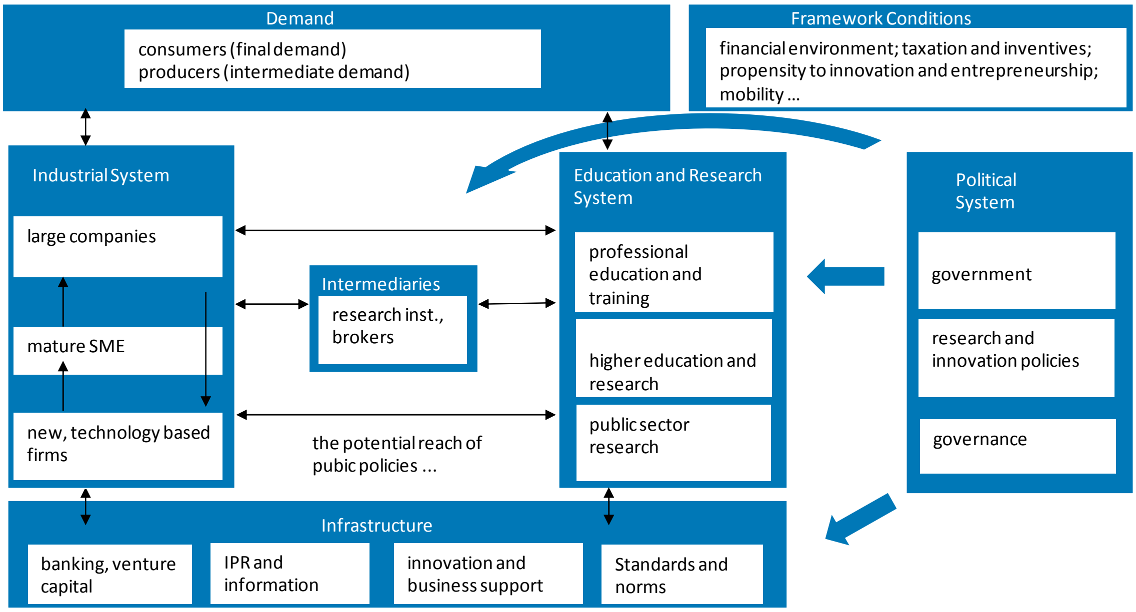

Figure 5 analysis grid for innovation systems (Smith and Kuhlmann 2004)

3 Wind tunnel technology roadmap

After the definition of and agreement on the tools to be used, a literature study based on publicly available documents has been performed, providing insights into the expected developments of wind tunnel technology in Europe and the impact of the development of numerical simulation capabilities (CFD) on it (WP 2).

As the main part of the project, a comprehensive wind tunnel technology roadmap has been developed, including major applications in Europe till around 2025-2030: The wind tunnel roadmap covers technological developments as well as future applications of wind tunnel users and their certain requirements.

3.1 Objective and focus

The objective is to develop a European wind tunnel technology roadmap charting the route of future developments in wind tunnel technology within aeronautics till 2025-2030. The focus is laid on technological developments (technology push) and on the market covering drivers, future applications, and their certain requirements (market pull), with specific attention to the impact of numerical simulation capabilities.

3.2 Methods applied

Three research methods have been applied:

(i) bibliometric analysis to identify trends in wind tunnel technology and to get quantitative data on these developments, roadmapping carried out

(ii) through a workshop format and

(iii) through a series of personal and telephone interviews.

3.3 Results and findings

The results and findings include a modular roadmapping approach. Three certain roadmaps have been developed:

- Wind tunnel technology roadmapping: bibliometric insights, wind tunnel technology roadmap;
- Wind tunnel product roadmapping: Sector specific insights, wind tunnel product roadmap;
- Integration of technology and product roadmap to an overall view.

3.3.1 Wind tunnel technology roadmap

The first step of the modular roadmapping approach applied is wind tunnel technology roadmapping. Wind tunnel technology roadmapping is focused on developments in wind tunnel technologies and in certain technology field. It covers the technology push perspective.

In order to generate the wind tunnel technology roadmap a workshop with eight outstanding experts in European wind tunnel technology was held at the Fraunhofer ISI in Karlsruhe, Germany, on September 30, 2009 (Table 1).

Table 1 participants of the wind tunnel technology roadmapping workshop, 2009

No.	Name	Organisation	Affiliation and Position
1	David Hurst	ARA	
2	Steve Roe	BAE Systems	Specialist Wind Tunnel Engineer
3	Jürgen Kompenhans	DLR	Department Head
4	Martin Bruse	German Dutch Wind Tunnels (DNW)	Head Measurement Techniques & Project Supervisor
5	Ulrich Jansen	European Transonic Wind Tunnel (ETW)	
6	Georg Eitelberg	German Dutch Wind Tunnels (DNW)	Director DNW
6	Sinus Hegen	National Aerospace Laboratory (NLR)	
7	Iwan Philipsen	German Dutch Wind Tunnels (DNW)	Department Head
8	Radek Ulman	Aeronautical Research and Test Institute CZ (VZLU)	
9	Elna Schirrmeister	Fraunhofer ISI	Researcher
10	Ralf Isenmann	Fraunhofer ISI	Researcher
11	Rolf Gausepohl	Fraunhofer ISI	Researcher

During introduction some research results of a bibliometric investigation were presented of which the most interesting findings are documented below (see 3.3.1.1).

This documentation is followed by a description of the roadmapping process and the discussion of the resulting roadmap itself.

In order to support the workshop activities an analytical grid was introduced as a first structure, which is referred to already in discussion of the bibliometric results (Figure 6).

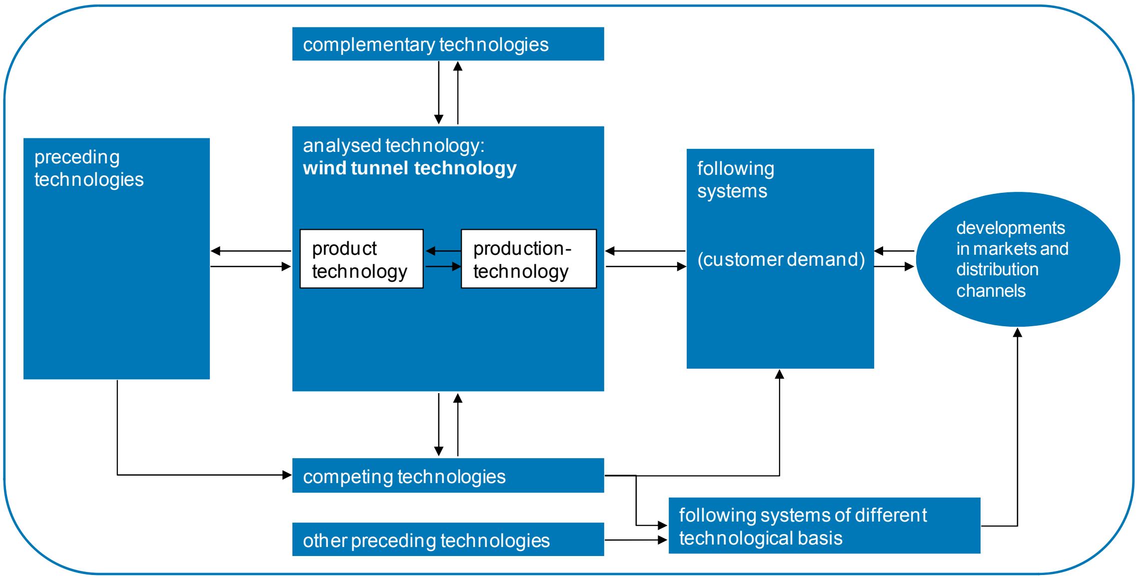

Figure 6 analytical grid for a systematic search of aspects for the technology roadmap

3.3.1.1 Bibliometric insights

Bibliometric analyses were conducted in order to investigate the intensity of research activities in the field of wind tunnel technology. As an indicator for intensity the number of publications for a specific scientific topic has been recorded and plotted over time.[1]

Bibliometric analyses were conducted for the following topics:

- wind tunnel technology
- computational fluid dynamics in general as well as for aerodynamic purposes
- data acquisition and processing
- pressure measurement techniques
- particle image velocimetry

In order to investigate scientific activity regarding wind tunnel technology, the field has been divided into different speed categories (Figure 7). The highest number of publications across all categories can be found for low speed wind tunnels with a speed up to 0.2 Mach. The smallest number of publications within the field was observed for high speed wind tunnels with a speed range from 0.2 Mach up to 0.9 Mach.

[1] Due to missing data base entries the three last years cannot fully be interpreted.

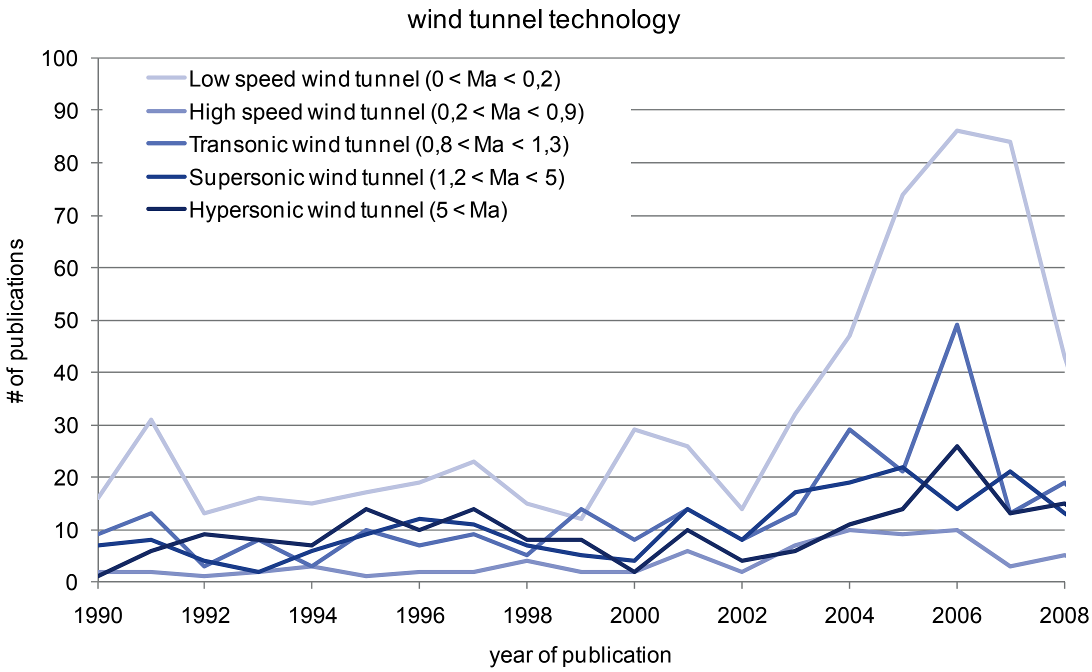

Figure 7 number of publications for different wind tunnel technologies

The research activity at low speed wind tunnels was investigated further analysing the activity in different regions. The result is displayed in Figure 8. Four regional categories were distinguished:

- Europe, including the European Union, Norway, Switzerland, and Ukraine
- United States of America and Canada
- Asia, including China, South Korea, Japan, India, Hong Kong, Taiwan, Singapore, Thailand
- others, meaning the rest of the world

From 2002 on Asia started to surpass USA in numbers of publication. For the following years a steep increase in Asia in publication activity can be observed. An overall increase of research activity concerning low speed wind tunnels can be observed starting 2002.

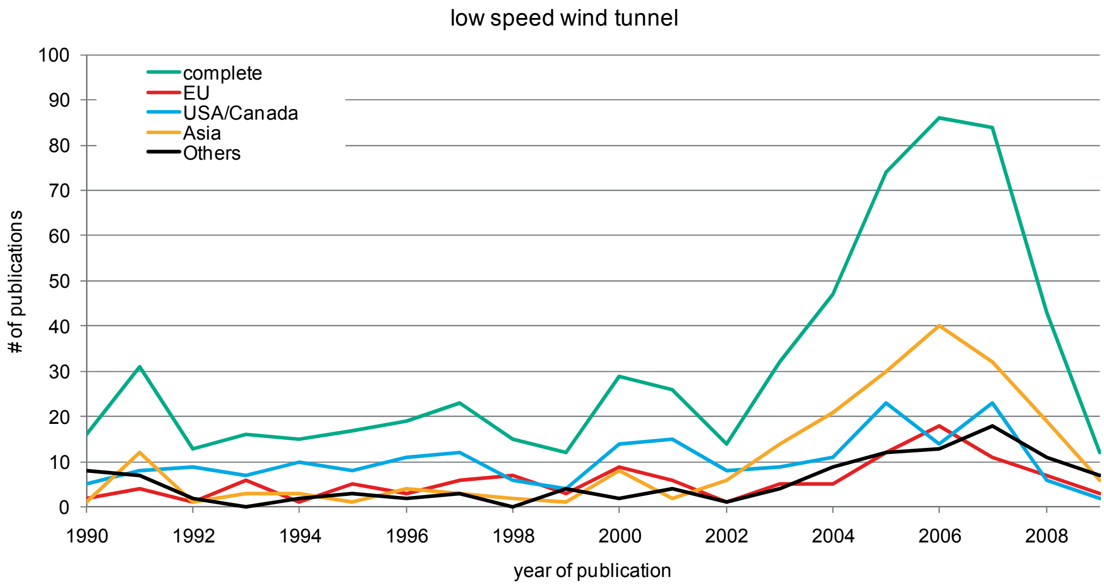

Figure 8 number of publications on “low speed wind tunnel technology” by region

In order to run wind tunnel tests many different technologies for data acquisition and data processing need to be available. The research intensity in this field in terms of number of publications is displayed in Figure 9. It can be observed that the research activity seems to start rising around year 2000 and peaks in 2004. This can be traced back to numerous conferences in this year:

- 22nd AIAA Applied Aerodynamics Conference,
- AIAA Atmospheric Flight Mechanics Conference,
- 10th AIAA Ceas Aeroacoustics Conference
- 5th Symposium on the Urban Environment
- ASEE Annual Conference Proceedings
- 13th Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association
- 9th Biennial ASCE Aerospace Division International Conference
- SPIE the International Society for Optical Engineering
- ASME Heat Transfer Fluids Engineering Summer Conference 2004

Secondly it can be interpreted that the USA during the last twenty years always had the highest number of publications in comparison with the other regions.

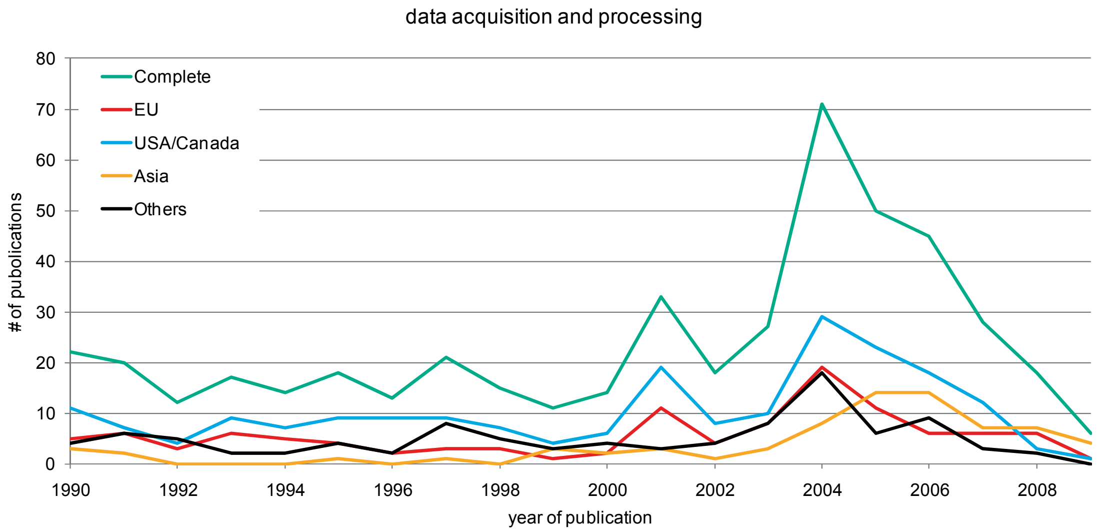

Figure 9 number of publications on “data acquisition and processing” by region

As a technological example for a data acquisition method and hence, for a preceding technology in regard to wind tunnel technology pressure measurement technologies were investigated in more detail (Figure 10). It clearly can be seen that the number of Asian publications has risen strongly around year 2002. Today this field seems even to be dominated by Asian research. Within the different research institutions the following Asian research organisations showed high publication activity:

- Japan Aerospace Exploration Agency
- China Aerodynamics Research and Development Center
- Beijing University of Aeronautics and Astronautics
- Tongji University
- Zhejiang University
- Shibaura Institute of Technology
- Peking University
- Harbin Institute of Technology

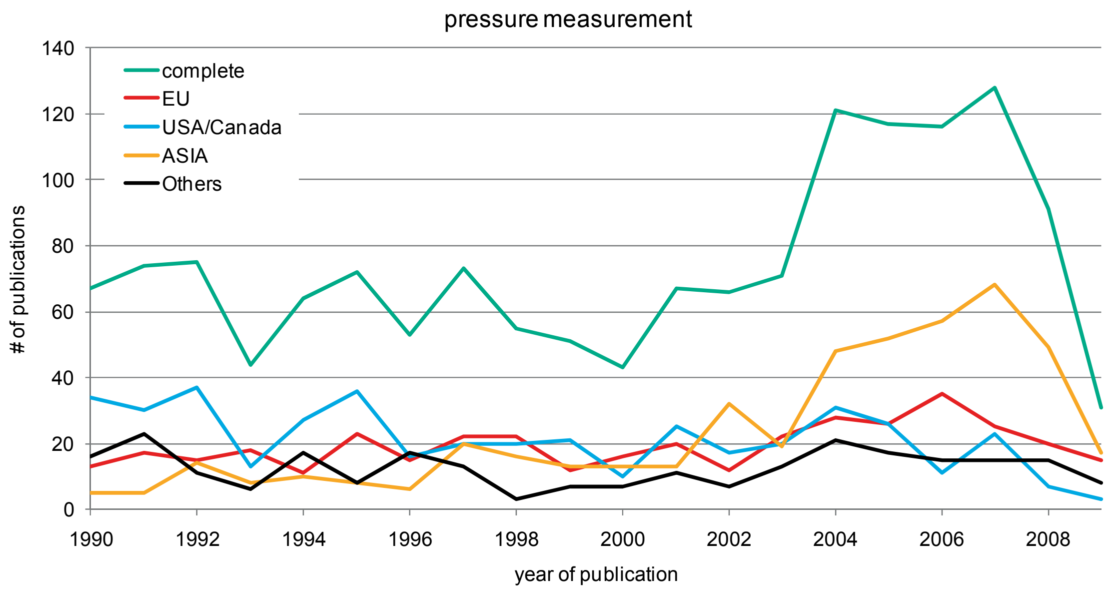

Figure 10 number of publications on “pressure measurement” by region

Complementary and competing technologies in respect to wind tunnel technology have been investigated as well. Therefore the field of “computational fluid dynamics (CFD)” was analysed. This technology on one hand complements research activities in wind tunnels. On the other hand certain tests can be replaced using CFD maybe even allowing advantage in respect to time consumption at comparable costs, thus competing with wind tunnels for the same customers.

In Figure 11 it clearly can be seen that “aeronautic CFD” displays only a small part of all publications within the whole field of research on CFD. The regional split seems to be rather homogeneously spread over the different regions, except for year 2004, which again can be traced back to numerous conferences in that year (Figure 12). Also here a steep increase in research activity across all regions can be observed starting 2002. Recently Asia showed tendency to surpass the other regions in number of published articles.

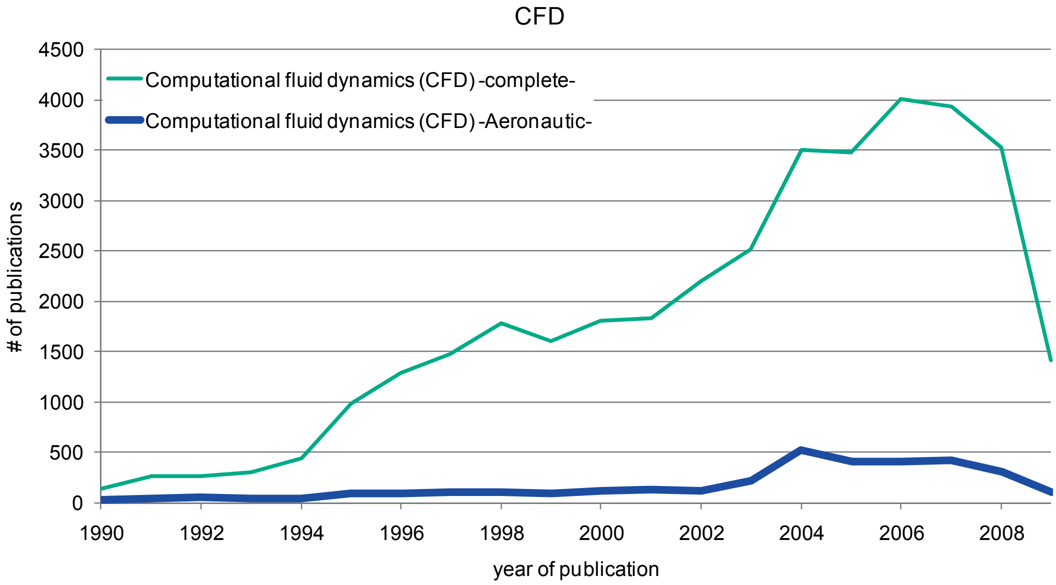

Figure 11 number of publications on CFD compared to CFD for aeronautic purposes

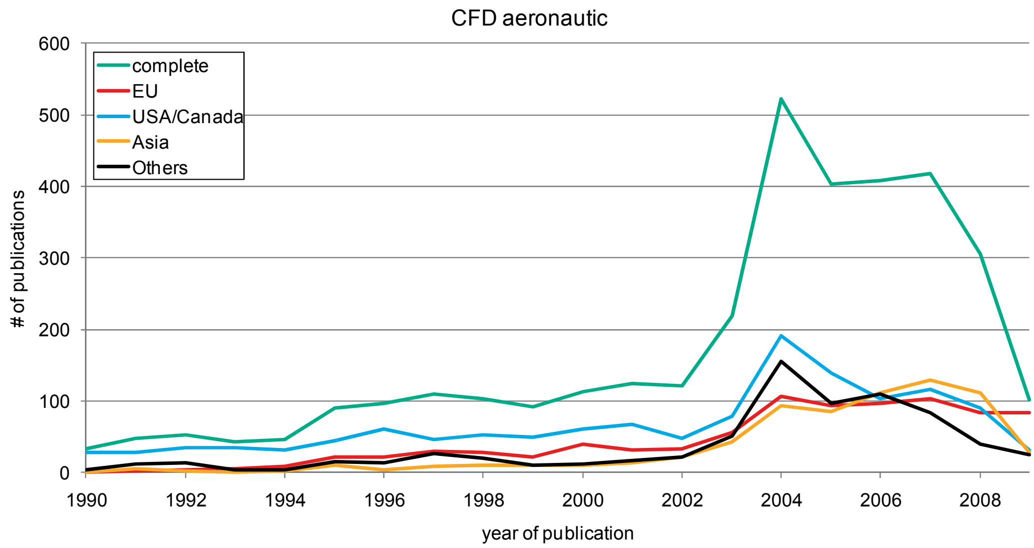

Figure 12 number of publications on aeronautic use of CFD divided by region

3.3.1.2 Wind tunnel technology roadmapping

As a first step towards a technology roadmap the participants were asked to collect individually any technology they would expect to be of relevance on a short-term basis (1-3 years), a medium-term (4-10 years) or a long term basis (>10 years). The entries were presented individually and sorted to one of the grid categories and clustered by the group.

At this point nine sublayers were defined and added to the initial roadmap structure:

- preceding technologies
  - acoustic testing
  - model technology
  - surface based imaging techniques
  - flow based imaging techniques
  - contact based techniques
- wind tunnel technologies
  - applications
  - infrastructure
- complementary technologies
  - computational fluid dynamics
- competing technologies
- management aspects

Each participant was asked to set priorities for single topics. This allowed focusing on the most relevant technologies of the initial large collection[2]. These technologies were subsequently used to create the technology roadmap.

In a following discussion the technologies identified as relevant and marked in green colour had to be positioned on the roadmap. During discussion some new aspects came up that were decided become part of the roadmap. These are marked in yellow colour and mainly cover prerequisites for certain technologies.

In a final step the dependence between single technologies on the roadmap was uncovered and fixed by arrows. The generated wind tunnel technology roadmap is displayed in

Figure 13.

[2] The entire collection is attached and can be found in the Annex.

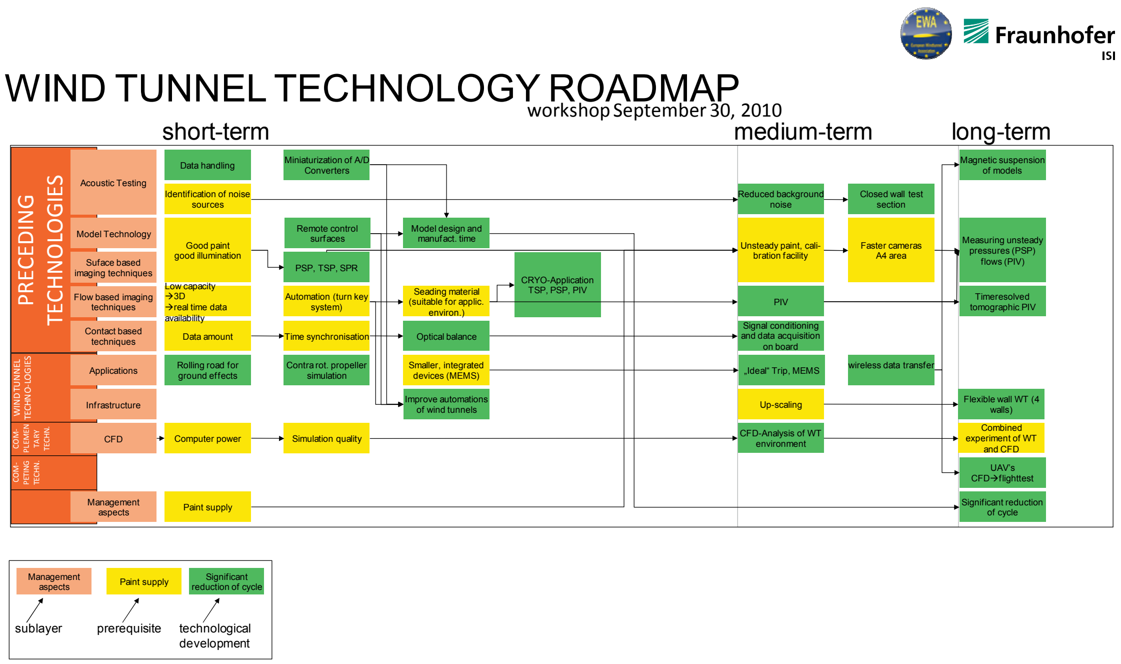

Figure 13 wind tunnel technology roadmap

The resulting roadmap is characterised by a significant amount of technologies that are expected to become relevant in 4 to 10 years from now, which was addressed by several speakers in a final discussion. In is unlikely that all of them will become available at the same time. It is rather to be expected that the development of some technologies will be postponed due to limited research capacities, maybe even postponed until reaching the long-term part of the roadmap.

For those technologies not being developed exclusively for wind tunnel applications (e.g. information technology, cameras) it has been suggested to keep in close contact with industries developing those technologies in order to ensure consideration of specific requirements of wind tunnels and to be able to influence the development path.

The layer of “preceding technologies” displayed in Figure 16 covers numerous examples of technologies that could serve more industry sectors than just wind tunnels. A few items like miniaturization or data handling can be assigned to two sublayers. “Cryo-applications” for instance covers both, surface based and flow based imaging techniques.

The dependence between prerequisites and technologies displayed in the roadmap as arrows shall be explained with the sublayer “Contact based techniques”. These techniques generate a large “data amount” that takes time to be recorded. The time delay between acquisition and recording of the data might become significant, especially when compared with other data sets acquired with a different technique. It is necessary to guarantee “time synchronization”, meaning that the recorded time belonging to a measured value should be the same time when the data had been measured. A possible solution represents the technology of “fibre optical balances”, which would increase the speed of data transfer. But this technology may be only an intermediate step on the way to an optimal solution. Such an optimal solution could be “Signal conditioning and data acquisition on board” (of the model), which would avoid and circumvent the above mentioned problems.

The aspect “Model design and manufacturing time” shall be explicitly named here since it displays a key to a “significant reduction of cycle” time and hence, is of high importance for customers (see 3.3.3.1).

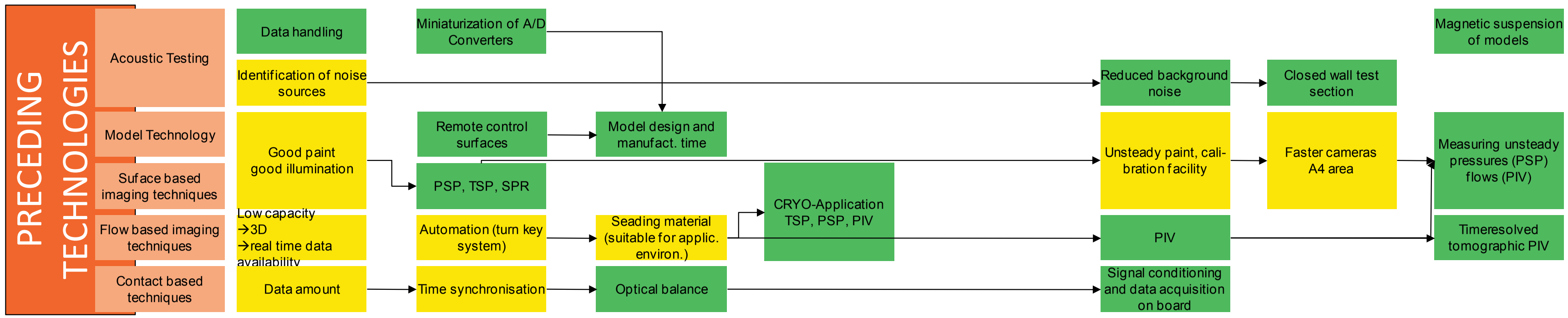

Figure 16 technologies wind tunnels rely on

Figure 15 core wind tunnel technologies

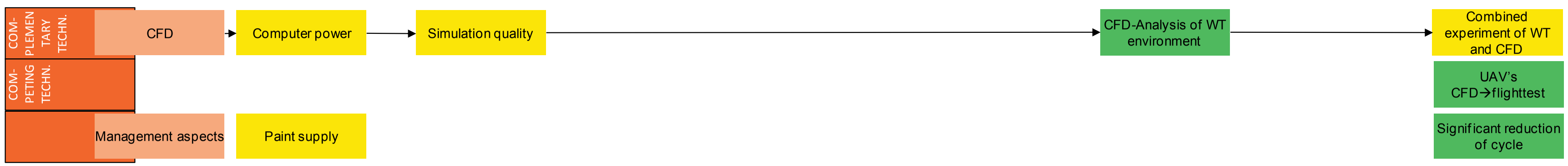

Figure 14 technologies competing or complementing core wind tunnel technologies, and management aspects

Concerning the whole wind tunnel technology roadmap the technologies that will become relevant on a long-term basis initiated a discussion during the workshop about the vision and long-term-perspective of the wind tunnel industry.

Three aspects have been discussed in more detail:

- magnetic suspension of models,
- unmanned aerial vehicles (UAVs), and
- a vision of the future for today existing wind tunnel facilities.

Even though the stingless magnetic support would ease the generation of data and would allow to record data that are closer linked to real flight conditions, several concerns were mentioned here regarding the possibility of a realization. Interference between a possible magnetic field and the electromagnetic waves of antennas transporting sensor data will disturb the current data acquisition process. Additionally the strength of magnetic fields necessary to carry adequate models (concerning size and weight) needs to be that strong that power supply and, hence, costs might become of significant importance. As a conclusion it was judged that this topic would take a long development time.

As a second point UAVs were discussed and were seen as a technique able to substitute some tests of wind tunnel testing. As an advantage it was seen that corrections due to walls of a test chamber or due to any kind of support of the model become obsolete and thus proximity of acquired data to reality can be increased. As an open question to this technology wireless data acquisition from the aerial vehicle was put into focus.

The third long-term aspect about the future of wind tunnel facilities has been discussed judging flexible walls as desirable parts of wind tunnels. The question was raised if in long-term the current facilities will become subject to a consolidation process with only a few, newly built facilities in the end. The objective and motivation of such a consolidation could be to focus activities in order to better compete with technologies like UAVs. In such a scenario this could be used to conceive wind tunnels including the concept of four flexible walls, drastically reduced background noise, and other up-to-date technology. As conclusion of the discussion the scenario of consolidation, which competes with the approach of an incremental improvement of facilities, was estimated to be rather unlikely.

3.3.2 Wind tunnel product roadmapping

Further to the wind tunnel technology roadmap charting developments in technologies, the next step in the modular roadmapping approach is wind tunnel product roadmapping. Wind tunnel product roadmapping is focused on applications of wind tunnel technologies. Hence, it covers developments in different fields of applications and assesses their – sector specific – requirements. A wind tunnel product roadmap displays the users' perspective and thus provides the market pull perspective.

A second workshop with key users of European wind tunnel technology – scheduled in January 2010 – was prepared. Due to organisational reasons, unfortunately the workshop could not be conducted. Hence, the format of wind tunnel product roadmapping has been adapted. In order to emulate a workshop, a series of personal and telephone interviews with key users has been carried out.[3]

Each personal or telephone interview resulted in a certain profile. The profile was structured rather close to the layout of the product roadmap architecture proposed. This procedure facilitates identification of developments, i.e. arrangement along time scale and assessment in terms of relevance.

Based on initial interview results one integrated profile has been established and expanded further in the course of the remaining interviews (Figure 17).

The overall profile after combining all individual profiles could be transferred into the architecture of the wind tunnel product roadmap: It includes layers, sublayers, and assessments according time scale and relevance of requirements to wind tunnel facilities from users' perspective.

3.3.2.1 Sector specific insights

In addition to the above mentioned advantages the structured roadmapping approach provides a surplus value: The generated profiles from all interviews of one single industrial sector could be regarded as characteristic for this sector. For example, users from logistics and transport industry have a certain view on wind tunnel facilities and their products. This view differs from the expectations that e.g. the helicopter industry has towards wind tunnels.

The interviewees (i.e. users) consider their profile as of strategic relevance. They do not wish to disclose their own specific view. Due to reasons of confidentiality, single profiles are attached in anonymous manner.

[3] See 6.1 (p.68) for a full list of interviews.

instruction:

1. please check the list of topics if it is correct (for elimination please use the "strike out"-function)
2. please complete the list if topics are missing
3. please verify the position of each topic concerning the layers (i.e. drivers, requirements, products, challenges); please indicate changes by number (1-4) in front of the topic
4. please mark the position of each topic on the time axis (short term-mid term-long term) with an **X** concerning its relevance

			short term			medium term			long term
layers of the roadmap ↓	relevance	time in years →	1	2	3	5	7	9	>9
drivers (no. 1)		A/C development (conventional)							
		costs							
		productivity							
		reduction of lead time							
		high quality results							
		differential technologies (unconventional)							
		new wind tunnel strategies (new corrections, special tests)							
		pure R&D							
		tool development for testing tools							
		CFD tool development							
		motorised testing (future engine: open rotor, propelled VHBR, noise contraints)							
		time constraints							
requirements and needs (no. 2)		productivity							
		cost control (reduction)							
		flexibility							
		remotely controlled moveables (mainly low speed)							
		flexibility of wind tunnel working time							
		acoustic testing: improvements in open test section, data handling, lead time)							
		TSP							
		PSP							
		PIV (vortex, interferences, high speed)							
		advanced measurement techniques (TSP, acoustics, PIV, PSP)							
		miniaturization (MEMS, balance crossings, telemetry)							
		acoustics (closed test sections, corrected aerodynamics)							
		data acquisition							
		high fidelity of data capture							
		accuracy of systems							
		measurement of forces and moments							
		measurement of pressures							
		cost reduction							
		cost structure of measuring methods							
		miniaturization of load models							
		certification concerning flight safety							
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)							
		static load							
		surface loads							
		strain-gauge measurements							
		model design							
		turn-key system for PIV							
		store loads configurations measurements							
		store loads							
		store release							
		end of rail, semi-release							
		end of stroke, semi-release, still attached							
		transition loads							
		acoustic analyses							
		drag pitching moments							
		full flutter expansion							
		conversion of pressures into loads, one integrated model							
		diagnostic testing							
		understand undesired flight behaviour							
		twin sting testing, low cost							
		rotary testing, low cost							
		rotary derivatives							
		powered mode testing							
		measuring propeller systems							
		testing under unsteady conditions (for pressures and flows)							
		unsteady pressures							
		turbulances							
		PSP for low speed wind tunnel testing, especially sensitive							
		PSP continuous load visualization							
		PIV for diagnostic testing							
		measuring duct behaviour							
		hinge moments measurement							
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping							
		"cultural" differences in between R&D, institutes and industry							
		finances							
		relation to CFD							
		large data storage, handling, post processing (e.g. acoustics)							
		model deformation measurement, model deflection							
		PIV for high speed wind tunnel testing							
		illumination for PSP							
		illumination for PIV							
		non-intrusive techniques							
		wireless data acquisition							
		self-trimming models							
		harmonizing both methods, CFD and wind tunnel testing							
		remote control surfaces in order to change configurations							
		advances in data capture							
		a levitating model to eliminate need for sting correction							

Figure 17 overall profile covering users' perspective on wind tunnel products, schematic illustration

3.3.2.2 Wind tunnel product roadmap

The result of transferring the user profiles into the roadmap architecture is the wind tunnel technology product roadmap (Figure 18). Only those items were picked out of the list of all items and transferred into the sketched roadmap, which were marked by the interviewees to be of high relevance.[4]

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[4] The complete list of mentioned items can be found in the annex.

Figure 18 wind tunnel product roadmap

3.3.2.2.1 Drivers

The interview partners were asked to give insight into their own constraints and motivations in order to pin down why they run tests at wind tunnel facilities. This separate layer is displayed in Figure 20.

The main layer is divided in two, one of which is called “socio-economic environment”, the other “market”. This represents the division between external influences and sector specific constraints.

One specific example for this distinction is “reduction of noise”. As a market requirement it has been positioned to be relevant at short-term, while environmental concerns from society on noise issues appear at medium-term. This topic is strongly anticipated by industry and can be interpreted as a result of the development time needed until realisation.

Two further aspects, which both are positioned at mid-term, shall be shortly explained.

The first is “non-recurring cost reduction”. This type of costs can be seen as one-time costs, which don’t result in learning and therefore cannot be saved when redoing the same. They are identified in industry as leverages in order to improve cost basis.

The other aspect is called “Differential technologies (unconventional)” and expresses the need of e.g. an aircraft manufacturer to provide products with features that differentiate the own products from competitors’ products.

3.3.2.2.2 Requirements & Needs

In this layer that is sketched in Figure 19 a new structural detail is added. Again two sublayers have been defined to categorize all aspects in either “application” or in “infrastructure”. The latter implies the necessity to change the infrastructural set-up of a facility in order to cover single needs. The structural detail added consists of four aspects that cover both, applications and infrastructure, and are therefore positioned in between the two sublayers.

One topic shall be explained in more detail. The topic of “productivity” is mentioned in this layer again and appeared already in the layer “drivers”. In “drivers” it is of importance since manufacturers need to increase their productivity and in this regard are depending on wind tunnels. In “requirements” it is stated again because they pass this duty on to wind tunnels to help them fulfilling it.

Besides new technological capabilities the layer of “requirements & needs” is characterized by another big group of requirements, which concerns trust in and accessibility of measured data:

- high fidelity of data capture
- determination of influence of test set-up on aero-data

- time and cost efficient measurement of a complete aerodynamic data set
- open access to previous data
- fast data handling and available to the customer
- improvement of on-line data evaluation
- accuracy of systems
- data acquisition

During the roadmap integration workshop one aspect has been added to this layer by the workshop participants, which is called “Experimental simulation capability for novel propulsion concepts“. In order to indicate its origin the colour of this item is orange.

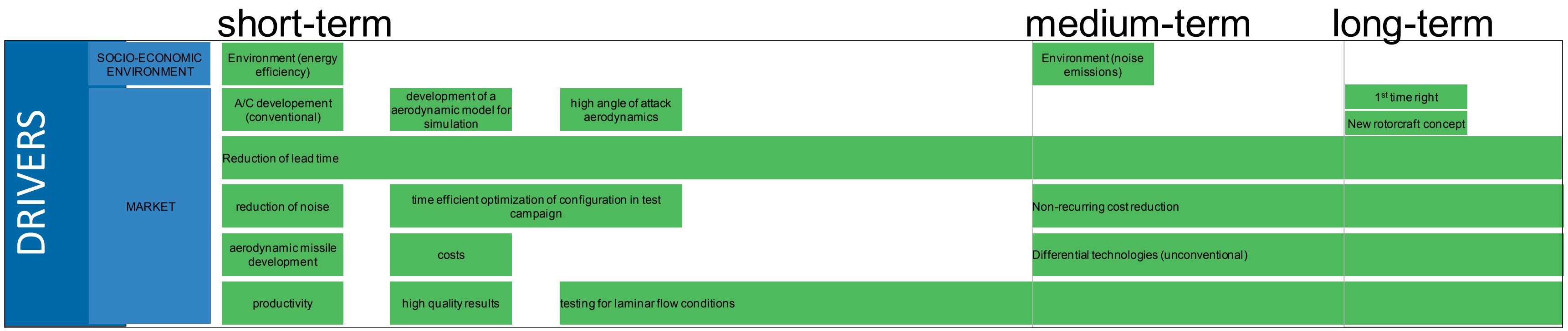

Figure 20 motivations of customers to run tests in wind tunnels

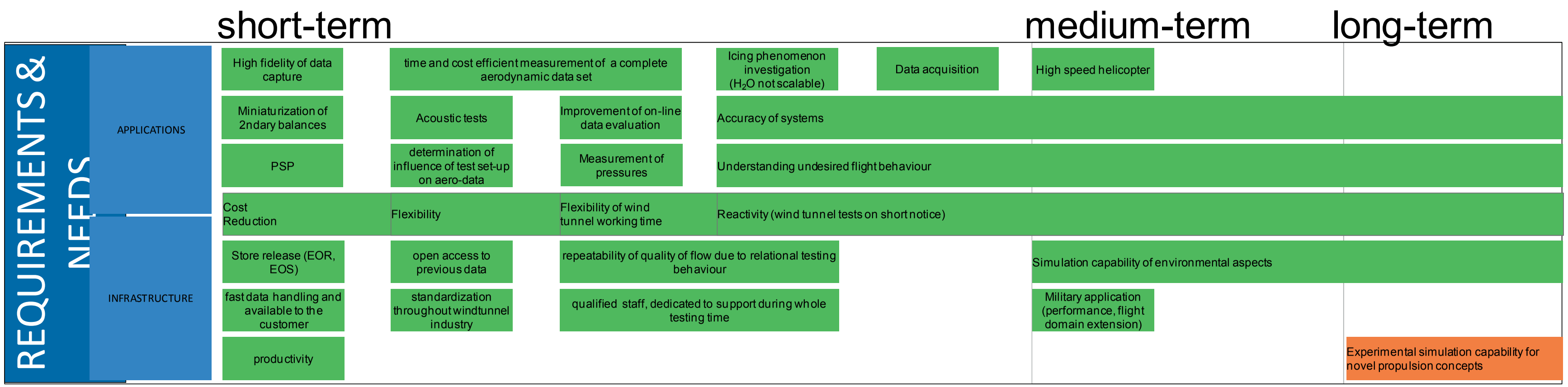

Figure 19 requirements and needs of customers towards wind tunnels

3.3.2.2.3 Products & Services

The subcategories of this layer (Figure 21) were chosen to be similar to the categories of the technology roadmap and extended by one new category called “services”. This structure afterwards facilitates the subsequent step of integrating both, the product and the technology roadmap (see 3.3.3).

In the layer “Products & Services” a few topics were positioned between two layers due to a double affiliation. “Testing under unsteady conditions (pressures & flows)” even was attributed to three sublayers, which are “model technology“, “imaging techniques“, and “contact-based techniques“

Two topics needed to be positioned across two different time categories (short-term and medium-term), indicating a customer request in 3 to 5 years time from today: “analysis of separation processes“ and “conversion of pressures into loads - one integrated model”. “Analysis of separation processes” was requested for the separation of e.g. a special aircraft from a kind of carrier aircraft or the separation of store loads.

In comparison with the technology roadmap in “Products & Services” one sublayer was of major interest: The sublayer “model technology” alone comprises 14 different aspects, which is one half of all aspects of “Products & Services”.

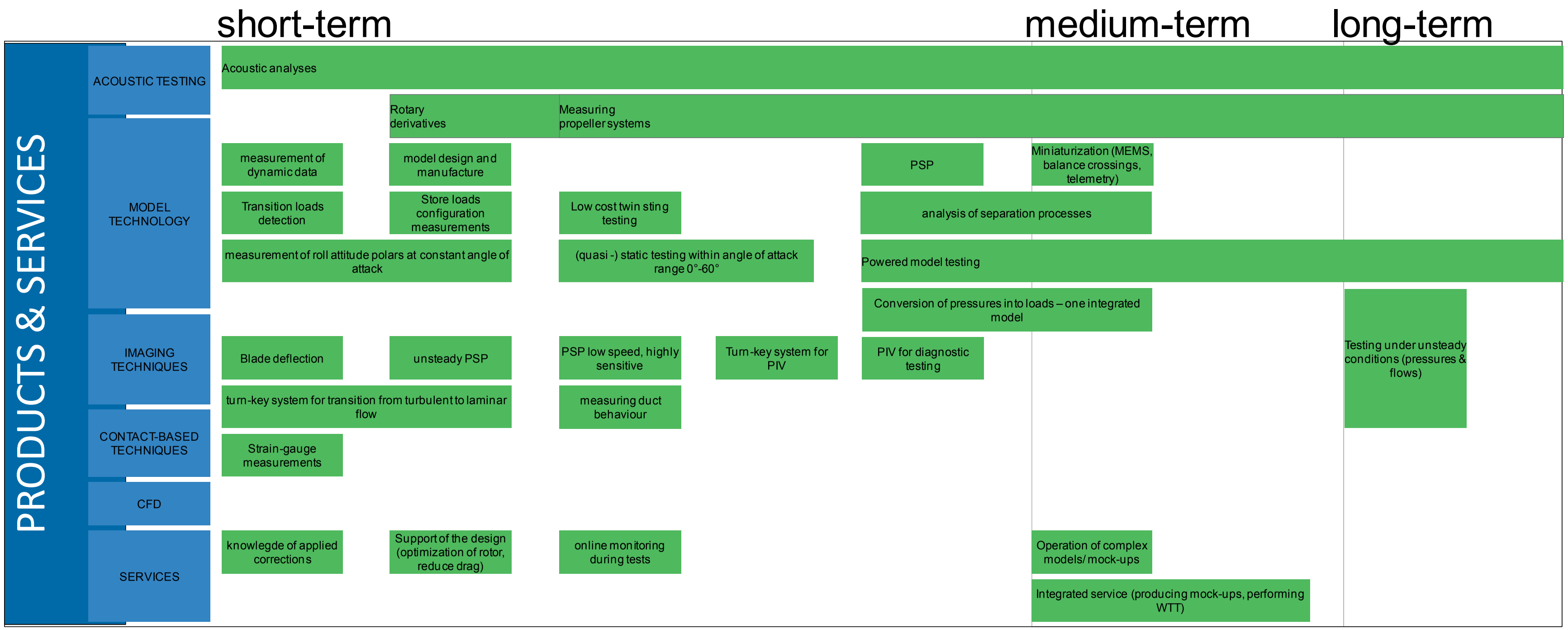

Figure 21 products and services expected from customers

3.3.2.2.4 Challenges

The layer called “Challenges” (Figure 22) collects items either from the layer “Requirements & Needs” or from the layer “Products & Services”, which were judged to be of challenging quality.

Aspects added to this layer were sorted in two sublayers called “Management” and “R&D, Complementary Technologies”. In the layer “Management” an item has been added here during the roadmap integration workshop, which is indicated in orange: “Increase of flexibility”.

The managerial challenge “revised model safety requirement” is motivated by the numerous types of new materials currently under investigation for aircraft manufacture. Due to strict rules based on traditional materials there is only little freedom for customers to introduce those new materials into their models for wind tunnel tests.

On a medium-term basis two challenges appear to be relevant, which are “wireless data acquisition” and “active laminar flow control”.

The first can be connected with the challenge to establish a “levitating model”, which can be thought of through an electromagnetic field carrying the model. This levitating model depends on technological progress for wireless data acquisition, which is tolerant to strong electromagnetic fields.

3.3.2.2.5 General

As known from previous projects, also here the interview partners could more easily name aspects to be fixed on the product roadmap that are of importance on a short-term basis (1-3 years). It was rather difficult to collect entries that will become relevant on a mid-term (4-9 years) or a long-term basis (>9 years).

Various aspects were named to be of relevance continuously beginning at a certain time horizon. In the integrated roadmap these items were indicated with a “C”.

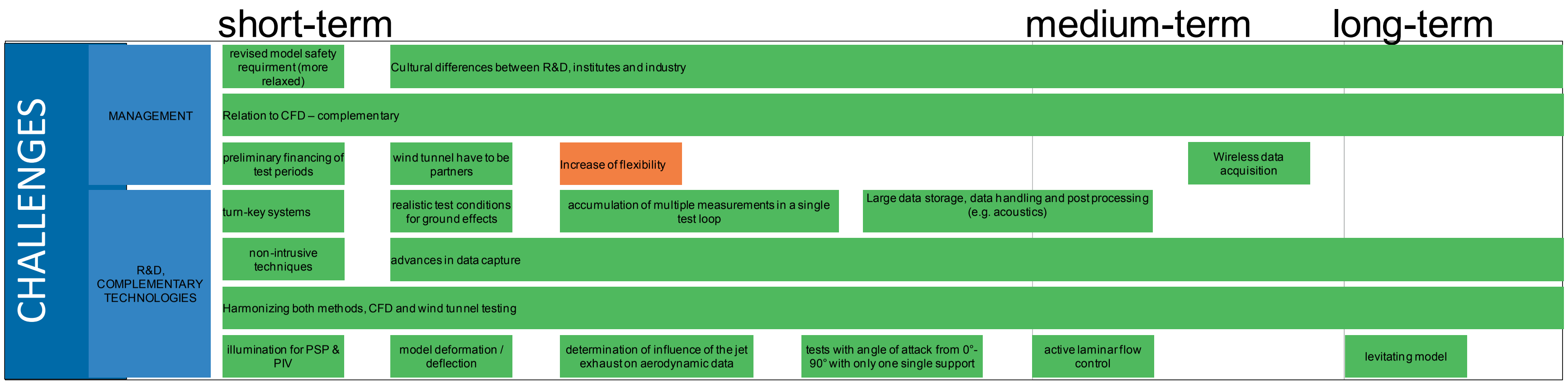

Figure 22 requirements and products identified as challenges

3.3.3 Integration of technology and product roadmap

On the basis of the wind tunnel technology roadmap on one hand and the wind tunnel product roadmap on the other, both roadmaps can be connected and thus allow integrating technology push and market pull (Figure 23). This also means linking the expertise of wind tunnel specialists with key users' requirements in certain fields of applications like aeronautics, logistics, transport, and defence.

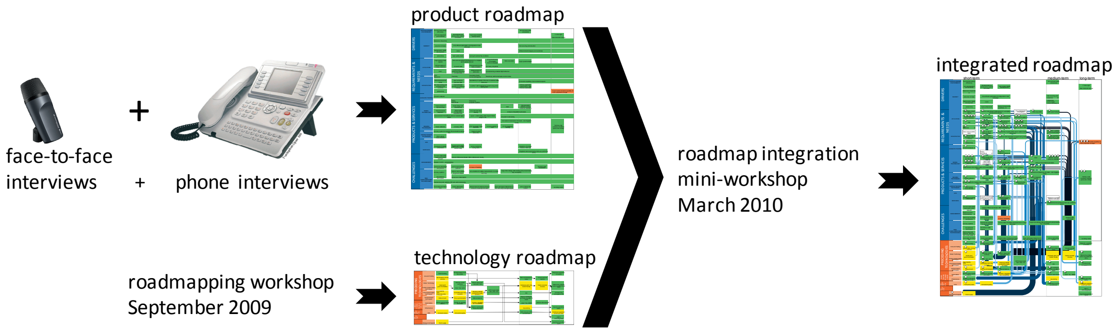

Figure 23 single steps on the way to the integrated wind tunnel roadmap

The wind tunnel technology roadmap and wind tunnel product roadmap have been connected during a mini-workshop at DNW, Marknesse, The Netherlands, March 25, 2010 (Table 2).

Table 2 participants of the mini-workshop at DNW 2010

No.	Name	Organisation	Affiliation and Position
1	Sinus Hegen	National Aerospace Laboratory (NLR)	
2	Georg Eitelberg	German Dutch Wind Tunnels (DNW)	Director DNW
3	Cor Joosen	German Dutch Wind Tunnels (DNW)	Deputy Director DNW

In principle, two approaches could be applied in order to integrate the wind tunnel technology roadmap and wind tunnel product roadmap: Top down approach (market driven, market pull) and/or bottom up approach (technology driven, technology push).

- For the top down approach the following questions are characteristic:

  (i) Is it possible to provide the products/services identified in the wind tunnel product roadmap based on technologies identified in the wind tunnel technology roadmap?
  (ii) Where are the gaps?
  (iii) Where is consistency along time missing?
  (iv) Which are technologies without links to products/services?
  (v) What is the value of unlinked technologies?

(vi) Are there opportunities for emerging business: new product/service development?

- Specific questions can also be found for the bottom up approach:

  (i) Is it possible to use technologies identified in the wind tunnel technology roadmap for the development of any new products/services as identified in the wind tunnel product roadmap?
  (ii) Where are the gaps?
  (iii) Where is consistency along time missing?
  (iv) Which are technologies without links to products/services?
  (v) Do emerging business opportunities exist?
  (vi) Are new products/services possible/necessary?

Here, the market driven top down approach has been applied.

The core task to be worked on in the workshop was the following question:

Does a technology exist within the technology roadmap in order to meet the customer requirements mentioned in the product roadmap?

The question had been applied on two of the four layers of the product roadmap:

- “Requirements & Needs“
- “Products & Services“

As a result of this workshop it was possible to deduce the following aspects:

- Importance of a technology

  Which technologies are referred to by many products and requirements?

- Development sequence

  Is a certain technology development finished at the time when a respective product is expected to be available?

- Importance of a product / requirement

  Which are the products and requirements that are met by more than one aspect of the technology roadmap?

- White spots on the product roadmap

  Which are the products and requirements that cannot be met by any technology mentioned in the technology roadmap?

3.3.3.1 Most important technologies

Key technologies with the largest leverage effect could be identified by integrating both, product roadmap and technology roadmap.

Those entries of the technology roadmap, to which many products and requirements could be linked, are the ones to be focused on for developing progress. Any advancement here has a broad effect since it impacts all of the linked customer requirements.

A list of identified key technologies, which at least have links to three aspects of the product roadmap, can be found in Table 3.

In Table 6 (page 40) all technologies are listed together with the respective products and requirements that were linked to the single technology. Each technology has been given a number, which is noted also in the illustrated roadmap.

The most impactful technology is called “model design and manufacturing time” (no.15) since six requirements and five products would benefit from improvements in this “preceding technology”.

Most of the requirements and products, which are connected with item no.15, are requested for short-term already. In this regard enhancements in “model design and manufacturing time” are slightly in backlog. For “high speed helicopter” and “experimental simulation capability for novel propulsion concepts”, of which the first is positioned at medium-term and the latter at long-term, the technology no.15 is available when needed and thus ideally positioned.

“Management aspects” could be identified as a second important key “technology” with eight links from the product roadmap. Most of the named entries are services. For the rest “Management aspects” means that a strategic decision needs to be taken first before the required action could be initiated. Here, a “development sequence” is difficult to determine since “Management aspects” is a sublayer and hence not positioned over time.

With in total seven connections from the product roadmap also the surface based imaging techniques “PSP, TSP, SPR”[5] are important technologies in order to satisfy the customer.

---

[5] PSP: Pressure Sensitive Paint, TSP: Temperature Sensitive Paint, SPR: Stereo Pattern Recognition

Table 3 hierarchy of key technologies

priority	name	number of links
1	Model design and manufacture time	11
2	Management aspects	8
3	PSP, TSP, SPR	7
4	Signal conditioning and data acquisition on board	6
5	Improve automations of wind tunnels	5
6	Data handling	4
	CFD Analysis of WT environment	4
7	Contra rotating propeller simulation	3
	Measuring unsteady pressures (PSP) / flows (PIV)	3

3.3.3.2 Most important products or requirements

Switching perspective after integrating both roadmaps within the product roadmap all those items can be identified that can be resolved and satisfied by more than one technology. This serves as a hint that wind tunnel providers already identified these issues as important, since they can be approached with a number of different technologies. This also indicated the technological complexity of a single product/requirement since several technologies are needed for its realisation.

In Table 4 all products and requirements are listed, which have connections to at least three aspects of the technology roadmap. One of the listed items from the top two items is listed as requirement / application, the other as product / model technology. It becomes obvious that on the importance of miniaturization (with in total eight (!) connections) wind tunnels and their customers seem to have a similar appraisal.

Table 4 hierarchy of products and requirements

priority	name	number of links
1	Miniaturization (MEMS, balance crossings, telemetry)	4
	Miniaturization of 2ndary balances	4
2	Experimental simulation capability for novel propulsion concepts	3
	Flexibility	3
	Flexibility of wind tunnel working time	3
	Measurement of dynamic data	3
	Reactivity (wind tunnel tests on short notice)	3
	Transition loads detection	3
	Understanding undesired flight behaviour	3

3.3.3.3 White spots on the product roadmap

As a last result from the roadmap integration workshop all those products and requirements remained that do not have any connectivity. These items can be found in Table 5.

Table 5 unconnected requirements and products in the product roadmap

name
Icing phenomenon investigation (H_2O not scalable)
Store release (End-Of-Release, End-Of-Stroke)
Rotary derivatives
Store loads configuration measurements
Support of the design (optimization of rotor, reduce drag)
Operation of complex models / mock-ups

3.3.3.4 Description of the Integrated Wind Tunnel Roadmap

In the following the roadmap illustrated in Figure 24 is explained in regard to its graphical elements.

The abscissa of the roadmap indicates progress in time. It is divided in three parts: short-term (1-3 years), medium-term (4-9 years), and long-term (>9 years).

On the ordinate all blue layers and sublayers, from “drivers“ to “challenges”, represent the product roadmap. Entries marked with “C“ are thought to be ongoing and continuously present. The orange layers and light-orange sublayers positioned below comprise all layers of the technology roadmap.

The arrows show how requirements and products can be fulfilled by a certain technology from the lower part. The more products and requirements refer to a single technological aspect the bigger and the darker the blue arrows get.[6]

In addition to the arrows the single technologies were given individual numbers, which are cited in the product roadmap in the upper part, if a link could be established.

All unconnected products or requirements were marked as a white field (instead of green). Orange fields within the product roadmap were added during the roadmap integration workshop. Yellow fields within the technology roadmap mark topics, which were added collectively during the workshop and which are mainly prerequisites in comparison to green entries, which represent technological developments.

[6] Roadmap that were illustrated for each class of arrows separately are displayed in Figure 25 to Figure 33.

INTEGRATED WIND TUNNEL ROADMAP

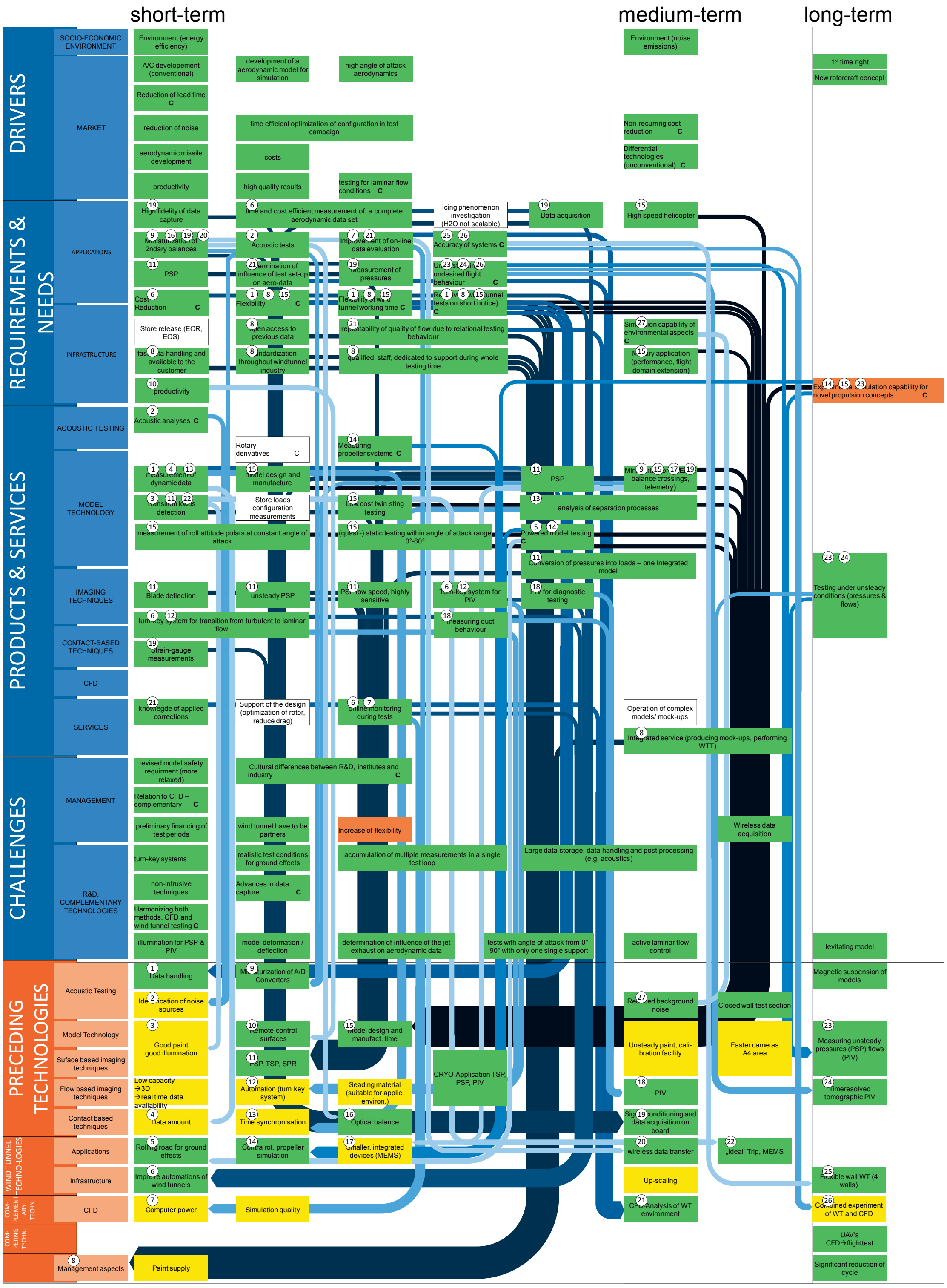

Figure 24 integrated wind tunnel roadmap

Table 6 linkage between products / requirements and technologies

No.	Technology-Roadmap: Technologies	Linked Requirements, Products of the Product Roadmap
1	Data handling	Flexibility
		Flexibility of wind tunnel working time
		Reactivity (wind tunnel tests on short notice)
		Measurement of dynamic data
2	Identification of noise source	Acoustic tests
		Acoustic analyses
3	Good paint, good illumination	Transition loads detection
4	Data amount	Measurement of dynamic data
5	Rolling road for ground effects	Powered model testing
6	Improve automations of wind tunnels	turn-key system for transition from turbulent to laminar flow
		Turn-key system for PIV
		Cost reduction
		time and cost efficient measurement of a complete aerodynamic data set
		online monitoring during tests
7	Computer power	online monitoring during tests
		improvement of online data evaluation
8	Management aspects	Flexibility
		Flexibility of wind tunnel working time
		Reactivity (wind tunnel tests on short notice)
		Open access to previous data
		fast data handling and available to the customer
		standardization throughout wind tunnel industry
		qualified staff, dedicated to support during whole testing time
		Integrated service (producing mock-ups, performing WTT)
9	Miniaturization of A/D converters	Miniaturization of 2ndary balances
		Miniaturization (MEMS, balance crossings, telemetry)
10	Remote control surfaces	productivity
11	PSP, TSP, SPR	Blade deflection
		unsteady PSP
		PSP low speed, highly sensitive
		Transition loads detection
		PSP *(as a requirement - application)*
		PSP *(as a product - model technology)*
12	Automation (turn-key system)	Turn-key system for PIV
		turn-key system for transition from turbulent to laminar flow
13	Time synchronisation	measurement of dynamic data
		analysis of separation processes
14	Contra rotating propeller simulation	Measuring propeller systems
		Powered model testing
		Experimental simulation capability for novel propulsion concepts
15	Model design and manufacture time	High speed helicopter
		Flexibility
		Flexibility of wind tunnel working time
		Reactivity (wind tunnel tests on short notice)
		Military application (performance, flight domain extension)
		Model design and manufacture
		Experimental simulation capability for novel propulsion concepts

		Miniaturization (MEMS, balance crossings, telemetry)
		Low cost twin sting testing
		measurement of roll attitude polars at constant angle of attack
		(quasi -) static testing within angle of attack range 0°-60°
16	Optical balance	Miniaturization of 2ndary balances
17	Smaller, integrated devices (MEMS)	Miniaturization (MEMS, balance crossings, telemetry)
18	PIV	measuring duct behaviour
		PIV for diagnostic testing
19	Signal conditioning and data acquisition on board	Strain-gauge measurements
		Miniaturization of 2ndary balances
		High fidelity of data capture
		Data acquisition
		Miniaturization (MEMS, balance crossings, telemetry)
		Measurement of pressures
20	wireless data transfer	Miniaturization of 2ndary balances
21	CFD Analysis of WT environment	knowledge of applied corrections
		repeatability of quality of flow due to relational testing behaviour
		Improvement of on-line data evaluation
		determination of influence of test set-up on aero-data
22	"Ideal" Trip, MEMS	Transition loads detection
23	Measuring unsteady pressures (PSP) / flows (PIV)	Understanding undesired flight behaviour
		Experimental simulation capability for novel propulsion concept
		Testing under unsteady conditions (pressures & flows)
24	Time resolved tomographic PIV	Understanding undesired flight behaviour
		Testing under unsteady conditions (pressures & flows)
25	Flexible wall WT (4 walls)	Accuracy of systems
26	Combined experiment of WT and CFD	Accuracy of systems
		Understanding undesired flight behaviour
27	Reduced background noise	Simulation capability of environmental aspects
-	Low capacity (3D, real time data availabil-ity)	-
-	Paint supply	-
-	Simulation quality	-
-	Seeding material (suitable for applic. environ.)	-
-	CRYO-Application TSP, PSP, PIV	-
-	Unsteady paint, calibration facility	-
-	Up-scaling	-
-	Closed wall test section	-
-	Faster cameras A4 area	-
-	Magnetic suspension of models	-
-	UAV’s CFD: flight-test	-
-	Significant reduction of cycle	-
-	-	Icing phenomenon investigation (H2O not scalable)
-	-	Store release (EOR, EOS)
-	-	Rotary derivatives
-	-	Store loads configuration measurements
-	-	Support of the design (optimization of rotor, reduce drag)
-	-	Operation of complex models/ mock-ups

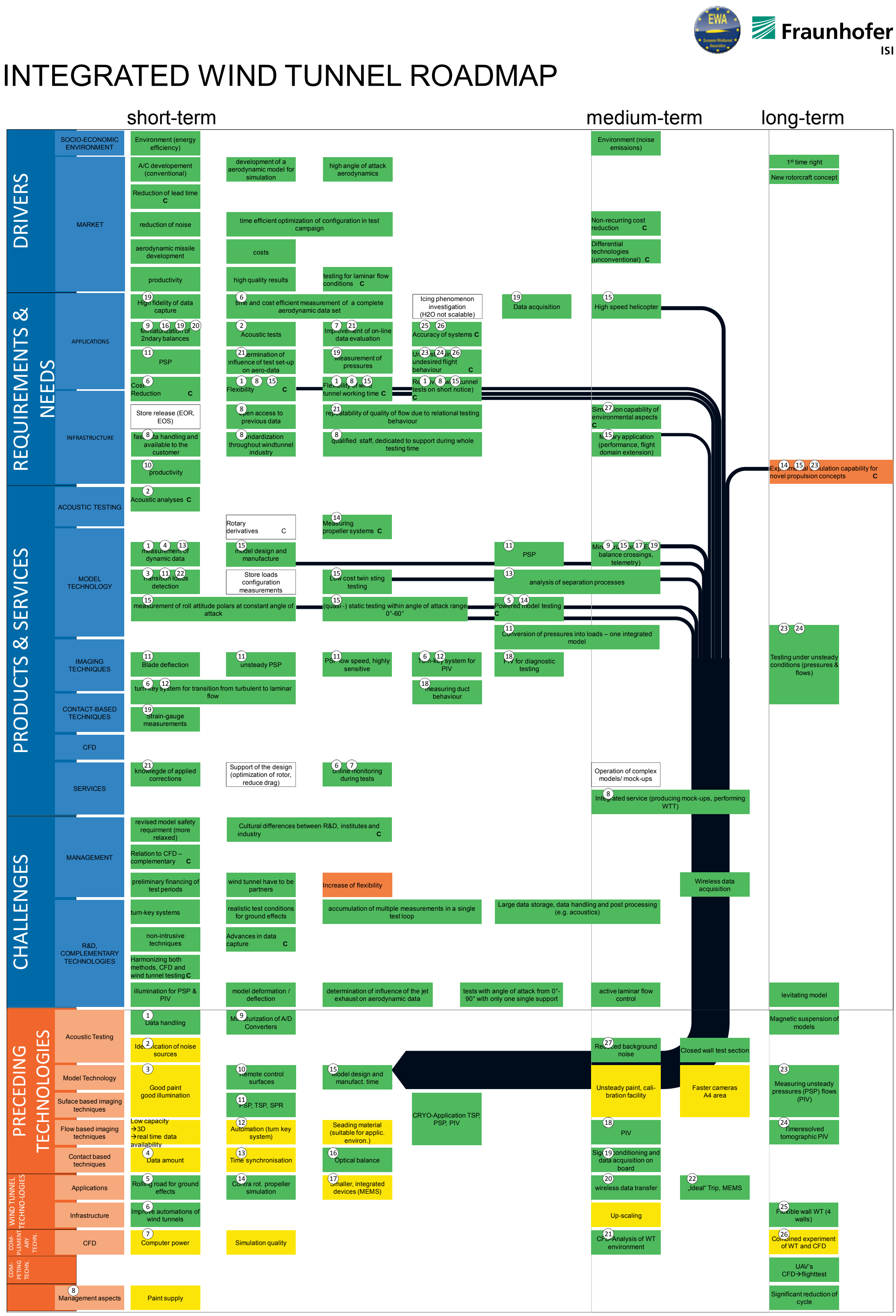

Figure 25 links from the product roadmap to “Model design and manufact. time”

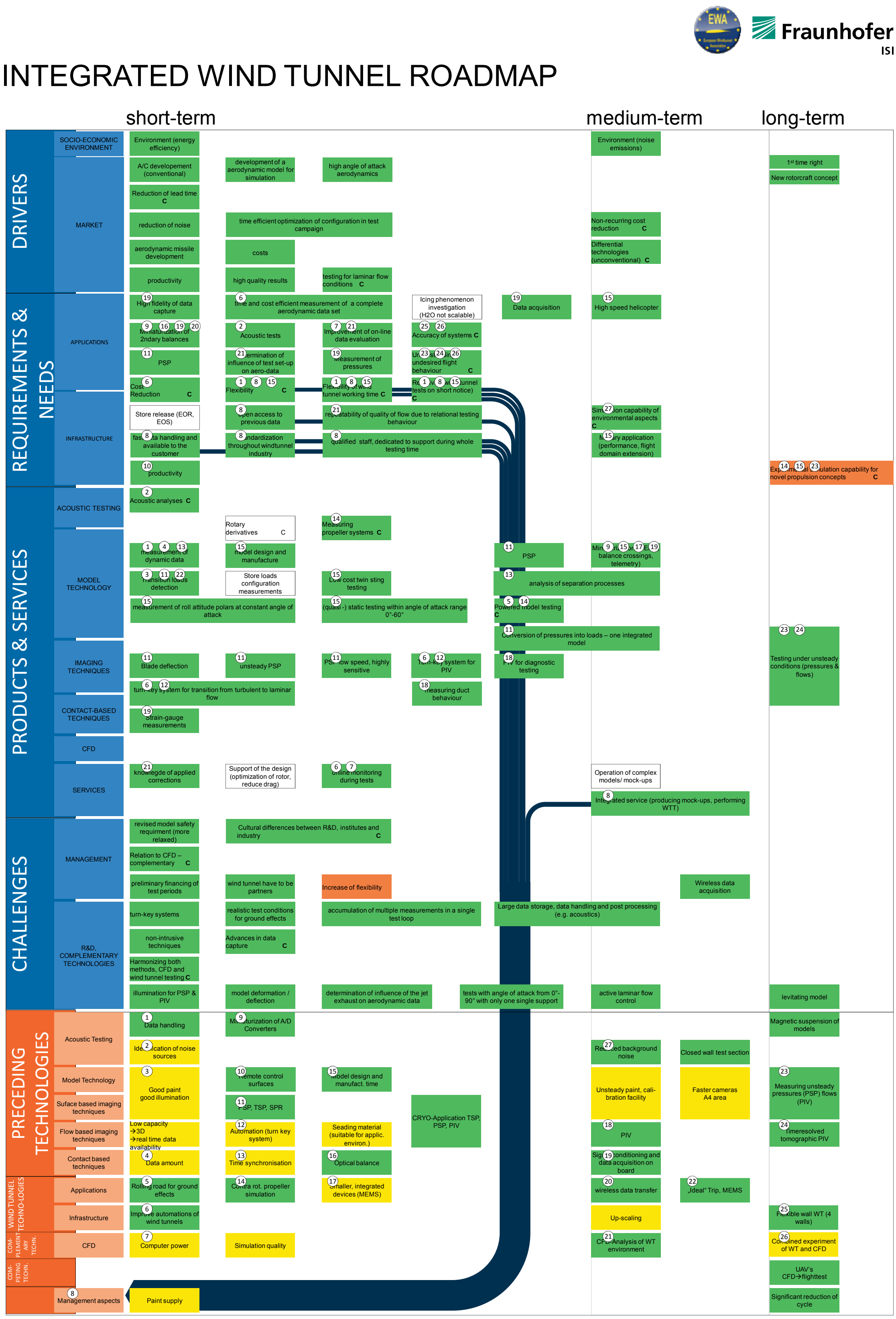

Figure 26 links from the product roadmap to "Management aspects"

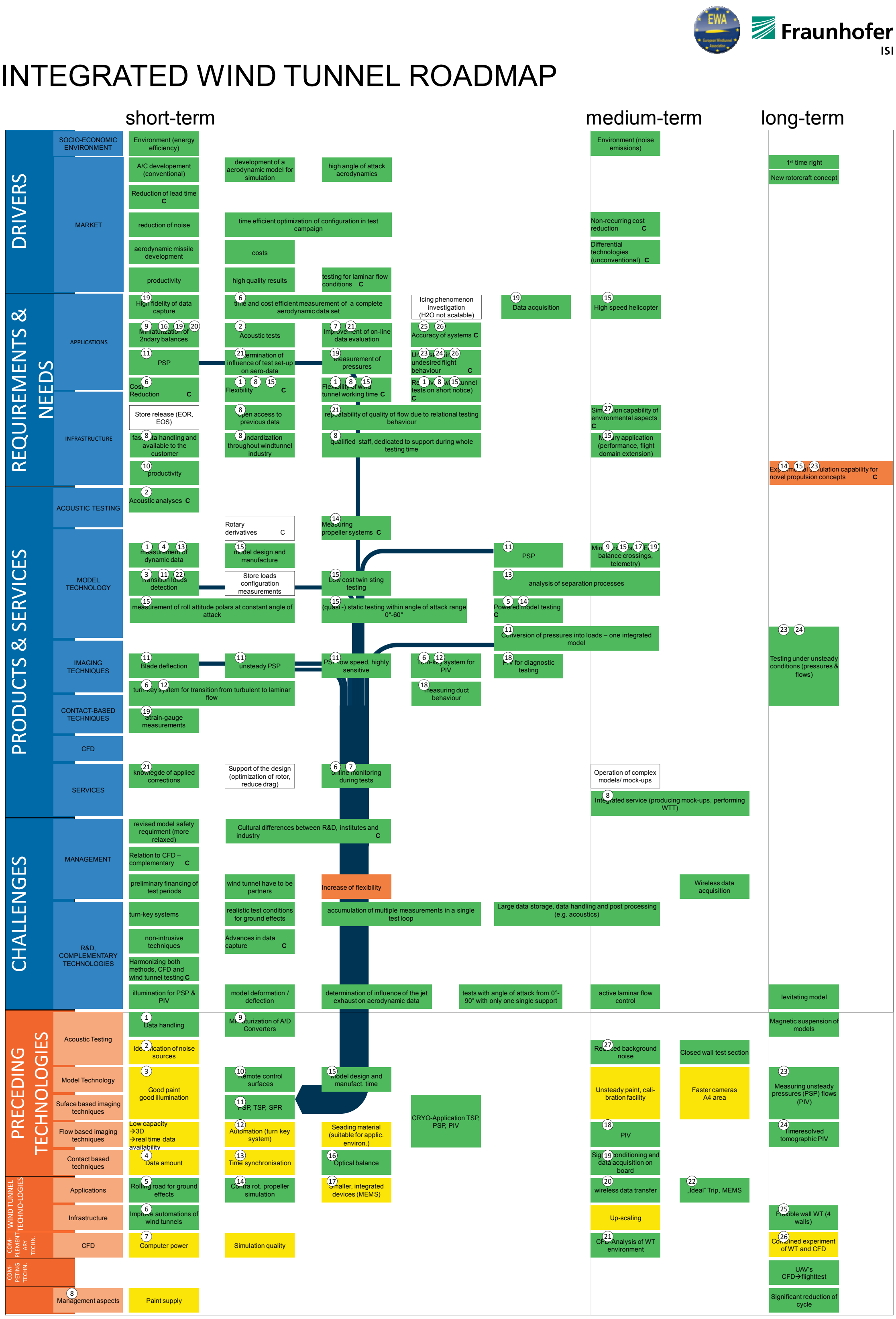

Figure 27 links from the product roadmap to “PSP, TSP, SPR”

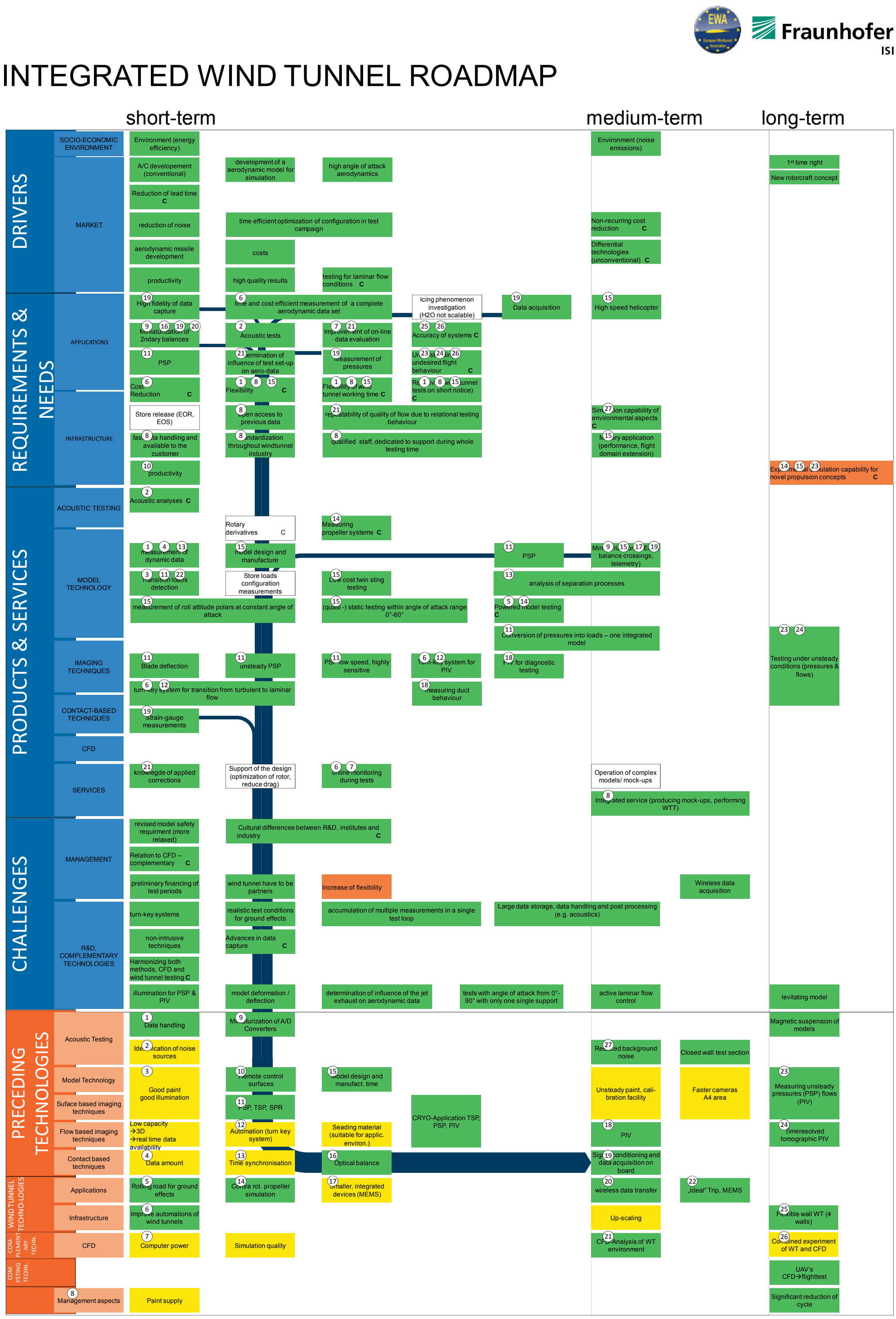

Figure 28 links to “Signal conditioning and data acquisition on board”

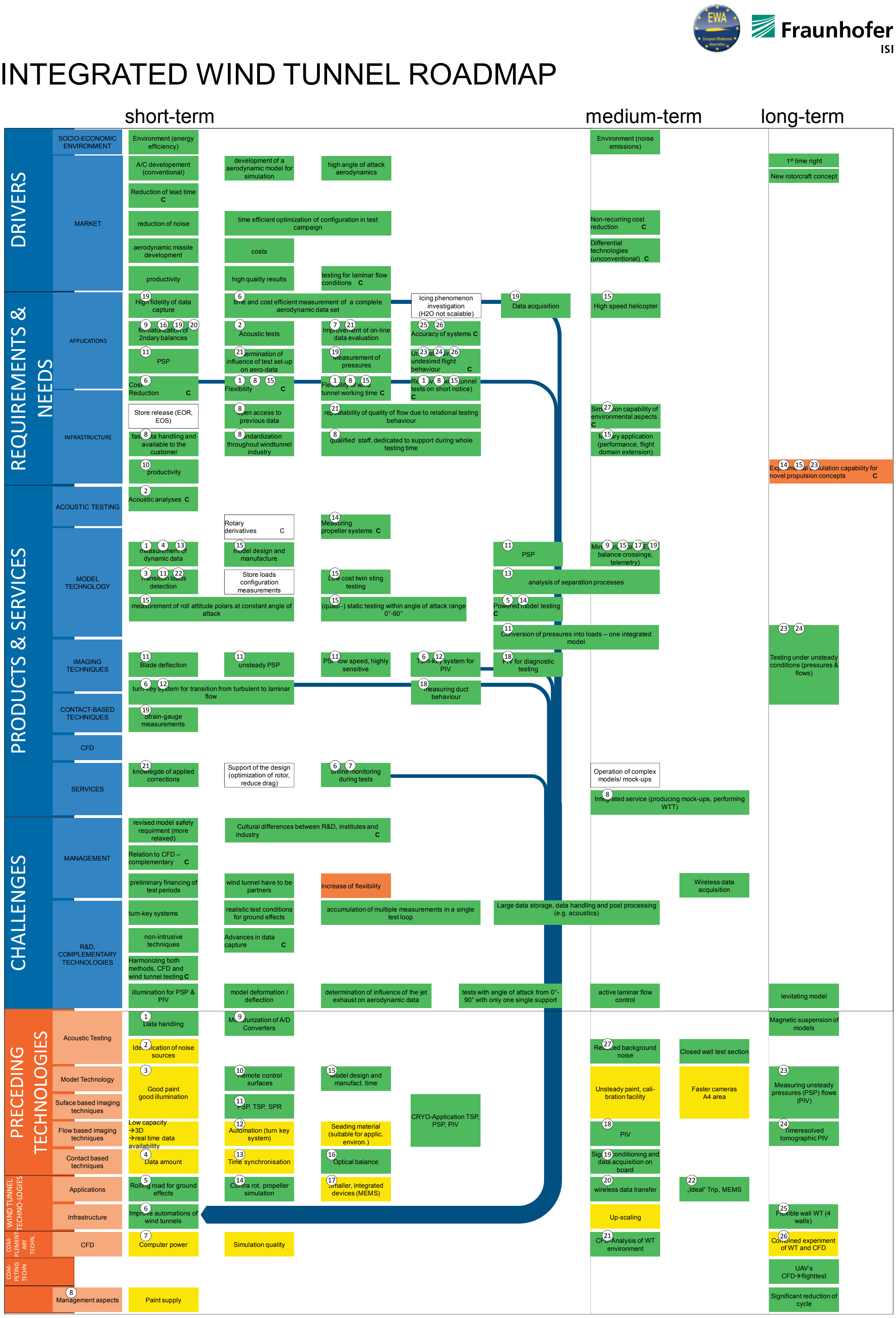

Figure 29 links from the product roadmap to “Improve automations of wind tunnels”

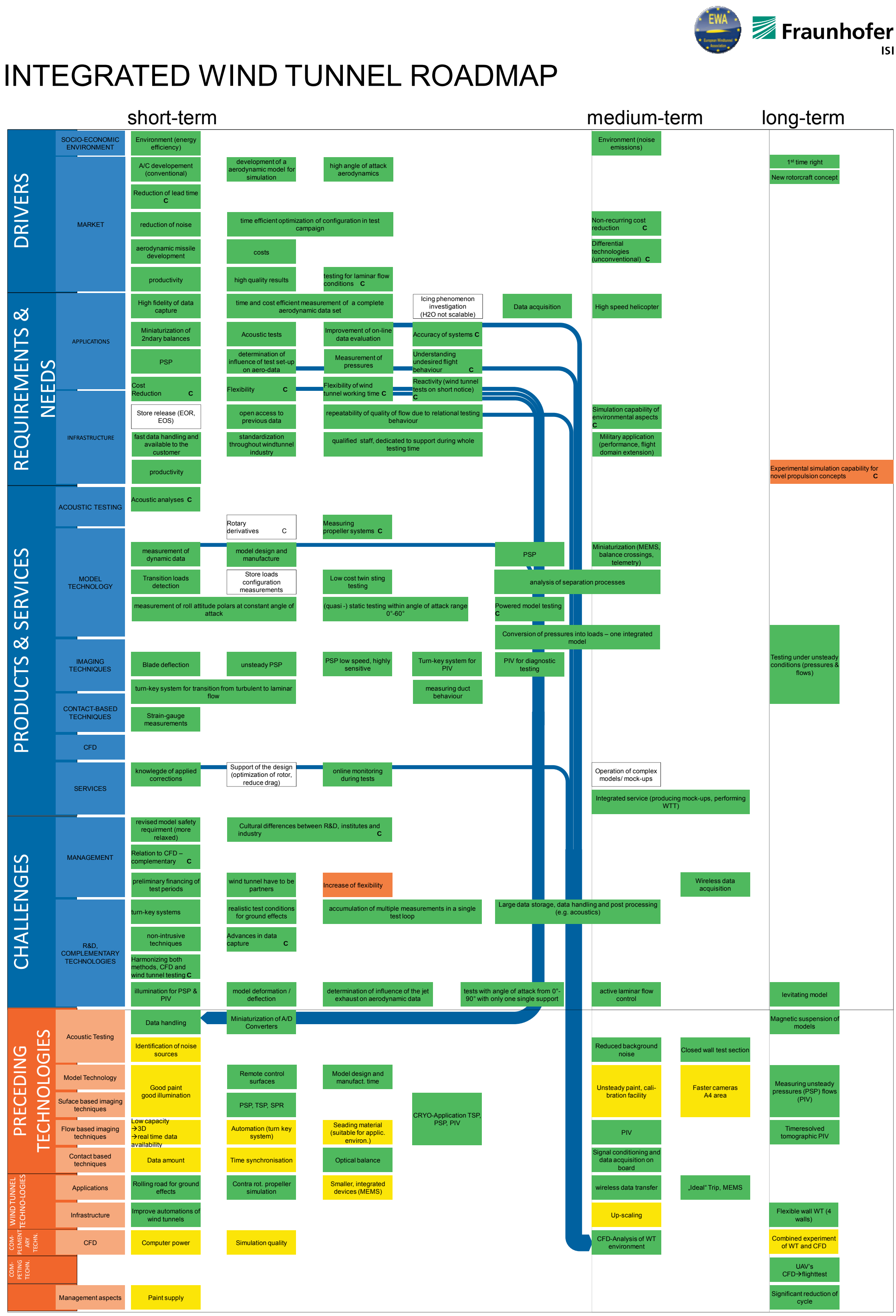

Figure 30 links to “Data Handling” and “CFD analysis of WT environment

Fraunhofer ISI

INTEGRATED WIND TUNNEL ROADMAP

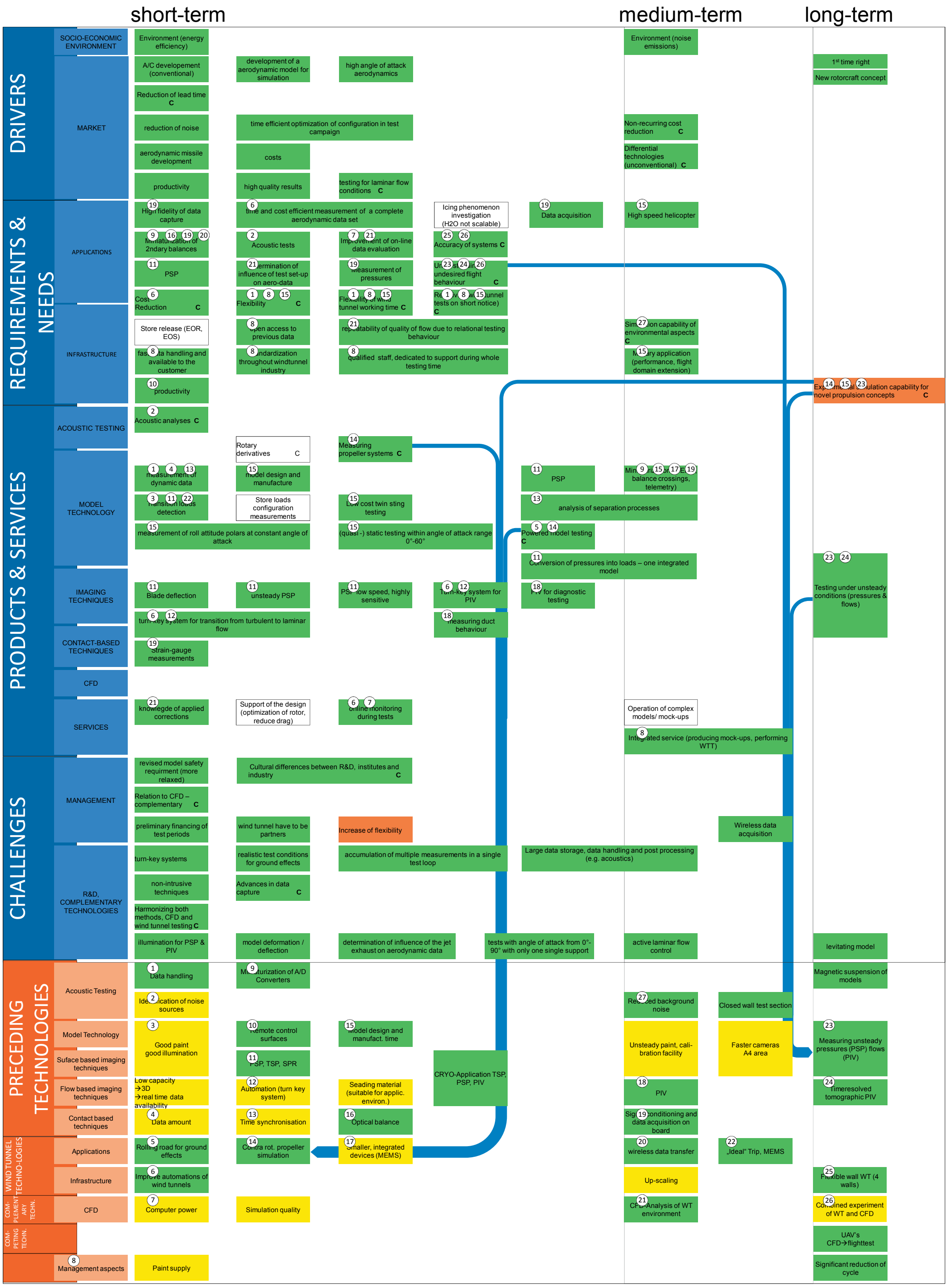

Figure 31 links to “Contra rot.prop.sys.” and “Measuring unsteady pressures / flows”

INTEGRATED WIND TUNNEL ROADMAP

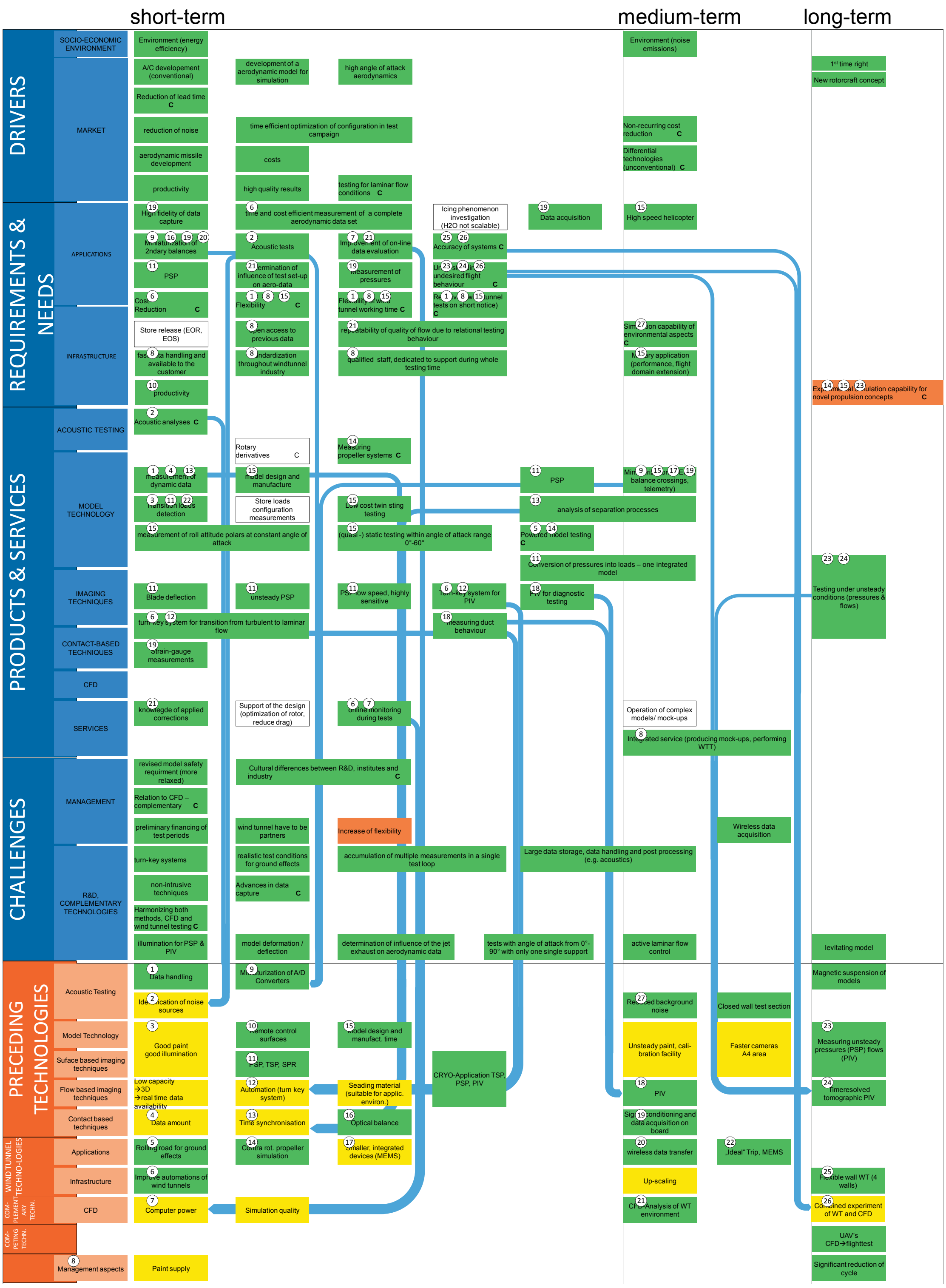

Figure 32 links from product roadmap with two different contributions

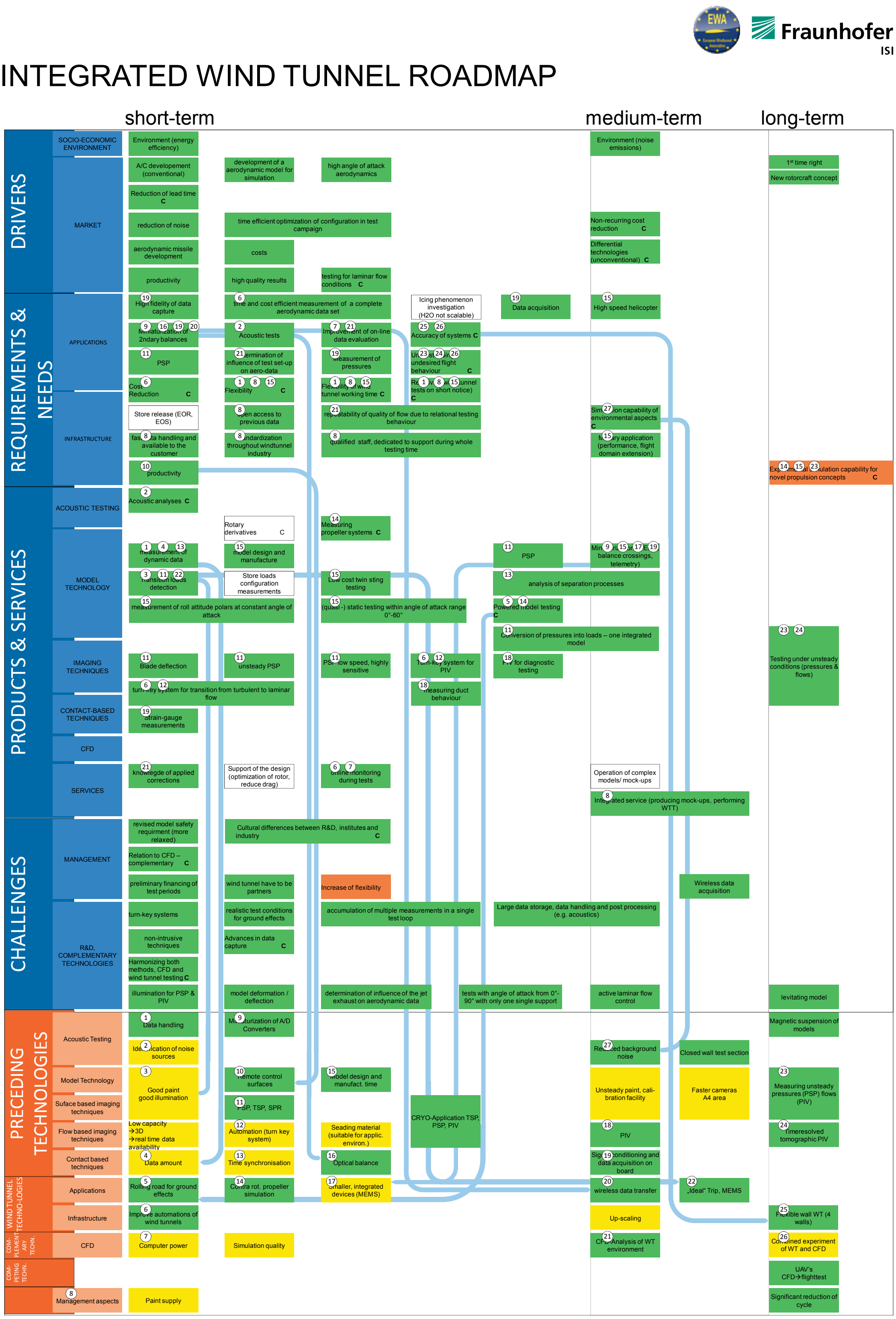

Figure 33 single links between product and technology roadmap

4 Analysis of the wind tunnel innovation system

From the results of the desk research summarized above in WP 2, the single elements of the wind tunnel technology innovation system in Europe will be identified and further described. Based on such an overview of the wind tunnel innovation system in Europe, an analysis on its particular incentive system will be carried out.

4.1 Objective and focus

In this chapter an overview of the wind tunnel technology innovation system shall be given with a regional focus on Europe. Particular emphasis was laid on the identification of leading agents. A further focus was also laid on the incentive system in Europe that is described separately.

4.2 Methods applied and procedure

Three research methods have been applied:

(i) literature study
(ii) innovation system analysis applied as heuristic and
(iii) a series of personal and telephone interviews.

4.3 Results and findings

The results and findings include:

- insight into the national innovation system of wind tunnels with emphasis on Europe
- insights of the technological innovation system
- description of the European incentive system
- a software-based tool for identifying single agents or groups of agents of the wind tunnel innovation system and identifying European research initiatives.

4.3.1 National innovation system

The concept of an innovation system puts emphasis on the interaction of the agents within the system. A balanced interaction of all participants involved is the basis to generate innovations continously. In other words wind tunnel industry alone is not able to innovate independently. The interplay is decisive on the innovative power of the whole system.

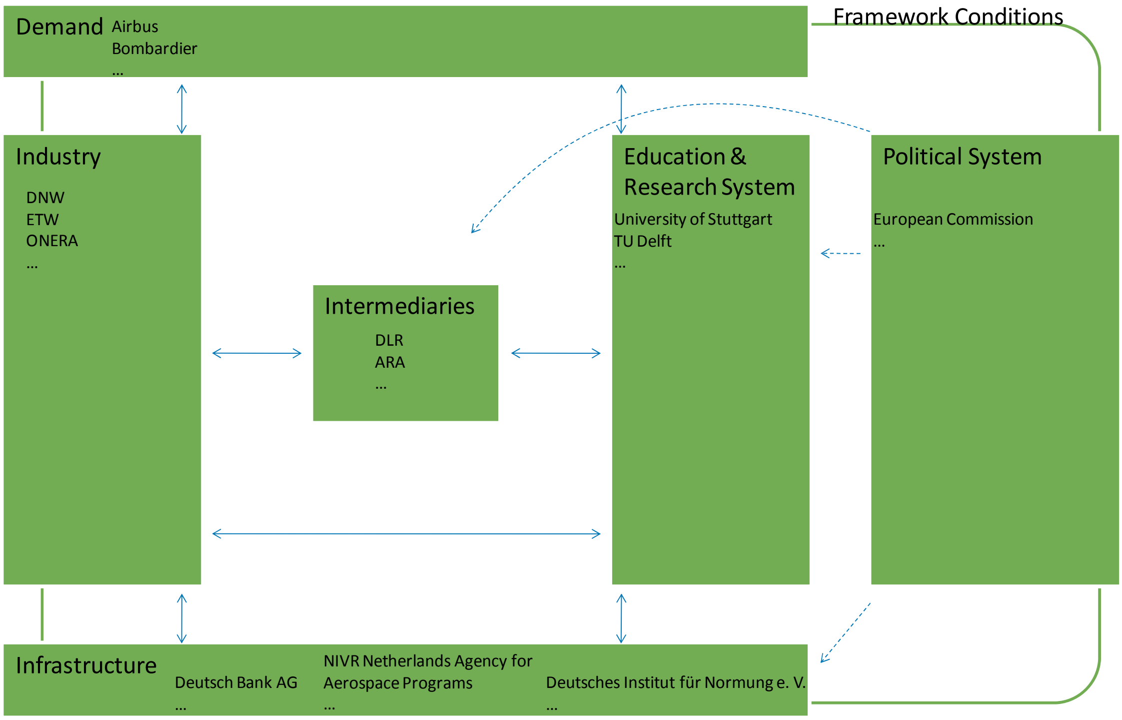

Figure 34 national innovation system of the wind tunnel industry

Such a national innovation system (NIS) is sketched in Figure 34. Adapting the concept of the national innovation system to wind tunnels the research facilities display the “Industry”. Customers like Airbus that run tests are positioned under “Demand”. Research institutions like DLR are placed best in “Intermediaries”, which function as brokers between fundamental research and industry. “Education and Research System” covers research at universities. In case of wind tunnels universities mostly have indirect contact to “Industry”. They are only weakly involved in the system. Another rather weak part of the system is called “Infrastructure” in the model. It consists of different support activities like financing or normalising activities.[7] The “Political system” with the commonly known players as a part of the innovation system can only indirectly effect the innovation activity of the whole system, for instance through incentives.

[7] Please note that “Infrastructure” in this case does *not* mean research infrastructure, which is the common terminology within networks and funding.

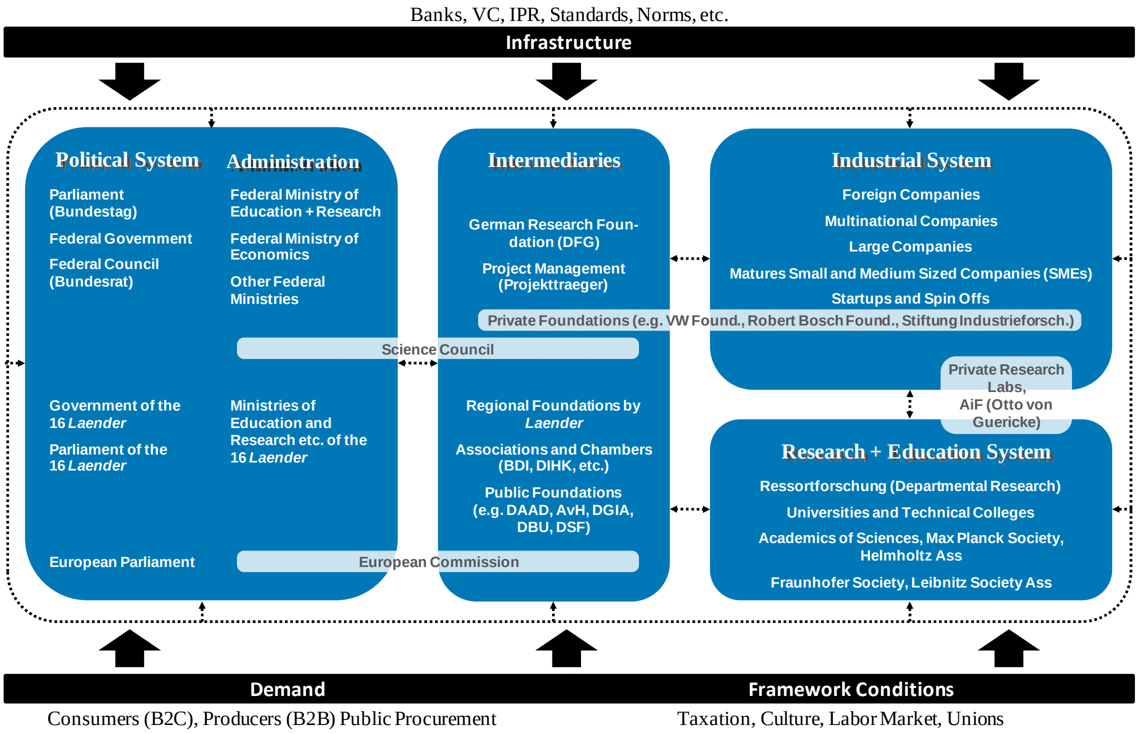

Figure 35 Germany’s Innovation System (Fraunhofer ISI et al. 2008, 5)

Comparing how political systems of different “nations” (e.g. Germany, Figure 35) guide research activities through incentives allows identifying a number of different strategies.

The European Commission’s funding policy is motivated to support projects that ameliorate the personal living conditions of European citizens. Thus the end customer, i.e. the citizen in Europe has a significant influence on funding policy. Funded topics are for instance safety and security enhancements, and environmental improvements. Another objective of research funding in Europe aims for a gap closure of the gap between science and society. Finally the European idea is substantiated by the fact that publicly supported research infrastructure within Europe should be of benefit for each country within the European Union. Thus funded facilities are obliged to grant open access.[8]

Looking to North America (Figure 36) the main difference consists in the North American funding of research projects also for military purposes. This is in line with the underlying motivation to more and more move frontiers of technology. In regard to cooperation with Europe the USA and Canada, like Israel, are associated countries in respect to the European frame programs.

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8 Please be aware of the difference between “open access“ and “free access“.

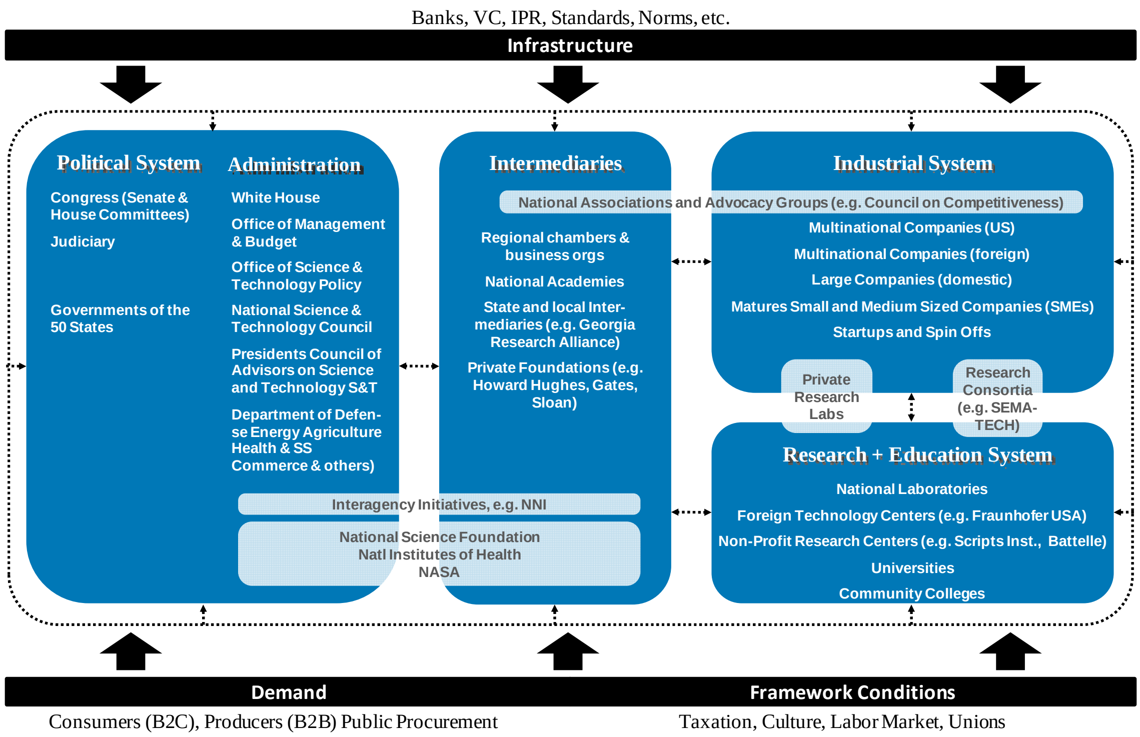

Figure 36 US National Innovation Governance System (Fraunhofer ISI et al. 2008, 16)

Russia is an example for a more visible country within the current frame program than the above mentioned countries even though it does not have the official status of an "associated country". With the motivation to keep smart minds in Russia funding activity is characterized by a pragmatic way of funding and bilateral treaties.

Looking to Far East, South Korea (Figure 37) is an example for growing co-operations and enhanced visibility also in European Research programs.

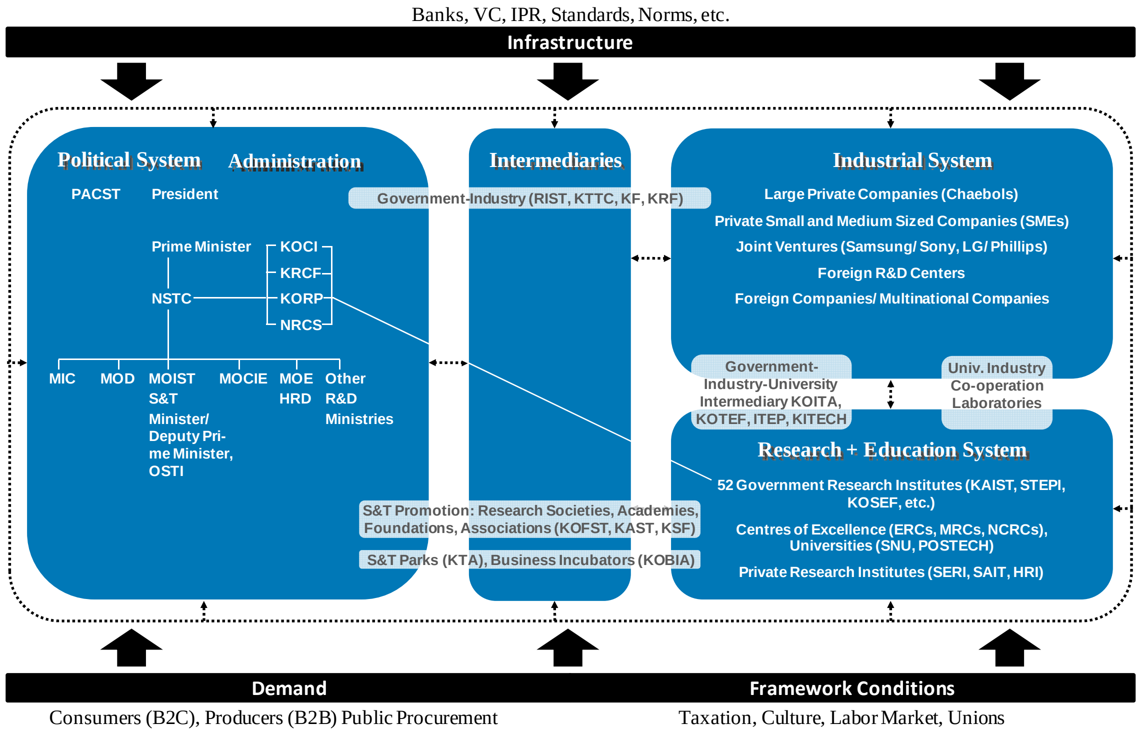

Figure 37 South Korea’s Innovation System (Fraunhofer ISI et al. 2008, 259)

However other Asian countries show protectionist behaviour (Figure 38). Thus co-operation with Japan has been difficult. China behaved similarly resulting in little outcomes from extensive negotiations. China also faces reluctance among local scientist due to fear of a drain of knowledge.

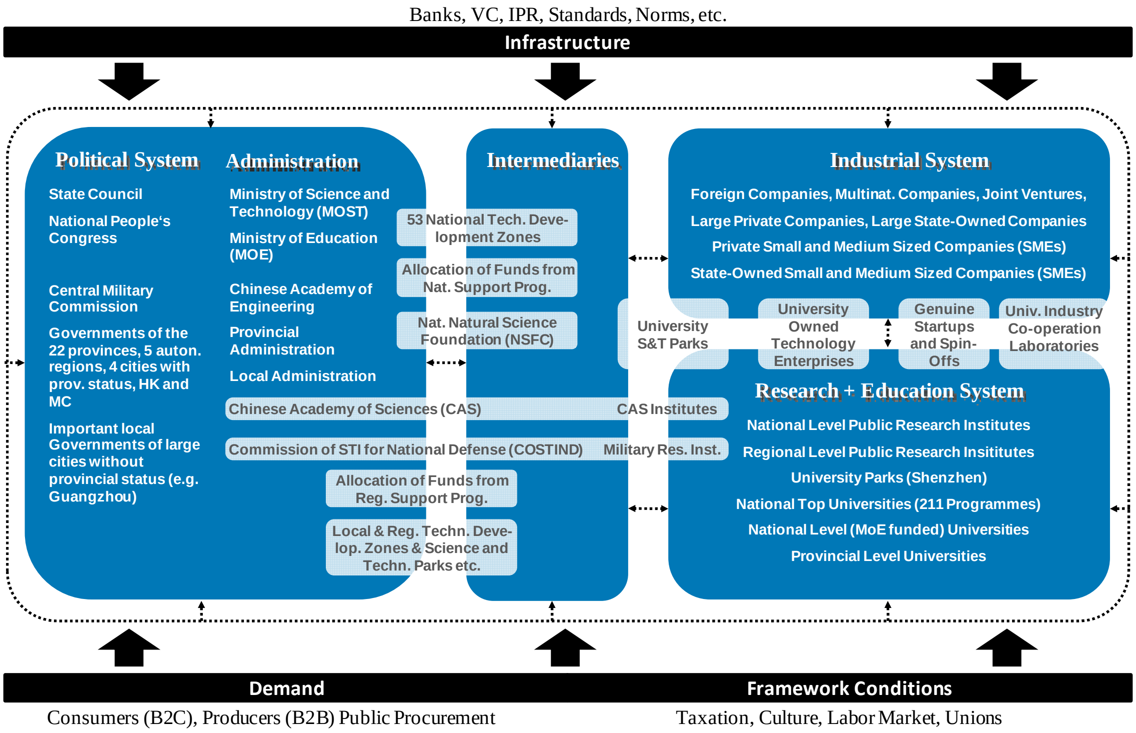

Figure 38 China's Innovation System (Fraunhofer ISI et al. 2008, 127)

4.3.2 Technological innovation system

Often it is quite difficult to analyse innovation systems in a certain country or at European level. In this case a technological innovation system may provide further insight, particularly concerning the dynamics of the behaviour of key agents. It allows describing the relationships of agents within the innovation system that directly influence the development, diffusion and use of wind tunnel technology and, thus, the performance of the wind tunnel innovation system.

The technological innovation system is a "socio-technical system focused on the development, diffusion, and use of a particular technology (in terms of knowledge, product or both)".[9] It serves as an analytical grid in order to identify possibilities to support the innovation activity and growth of the core technology.

The grid contains niches and regimes that represent different contributions in respect to their role for the innovation process. Regimes are defined at the level of industries or sectors. Niches refer to a single application context. Within niches radical innovations can emerge that destabilize the own niche whereas regimes create incremental innovations that strengthen the respective regimes. As a third concept the landscape gathers

9 Bergek et al., 2008

residual factors that impact the innovation process in the TIS without being influenced directly by its outcome.[10]

Figure 39 displays a sketch of the technological innovation system of the wind tunnel industry containing exemplary actors within. Manufacturers can be found for civil products, for military aircrafts or even covering both. Those manufacturers, which operate an own wind tunnel facility, even overlap with the core TIS of wind tunnels. The third regime sketched here contains research institutions represented by DLR.

Inside the TIS wind tunnels were grouped concerning their major technical characteristic. Hence, a niche for blow-down wind tunnels can be seen besides cryogenic wind tunnels for the generation of Reynolds numbers close to real flight conditions. Between these niches the infrastructural set-up differs significantly. This is also true for two remaining niches of an icing wind tunnel and a plasma wind tunnel.

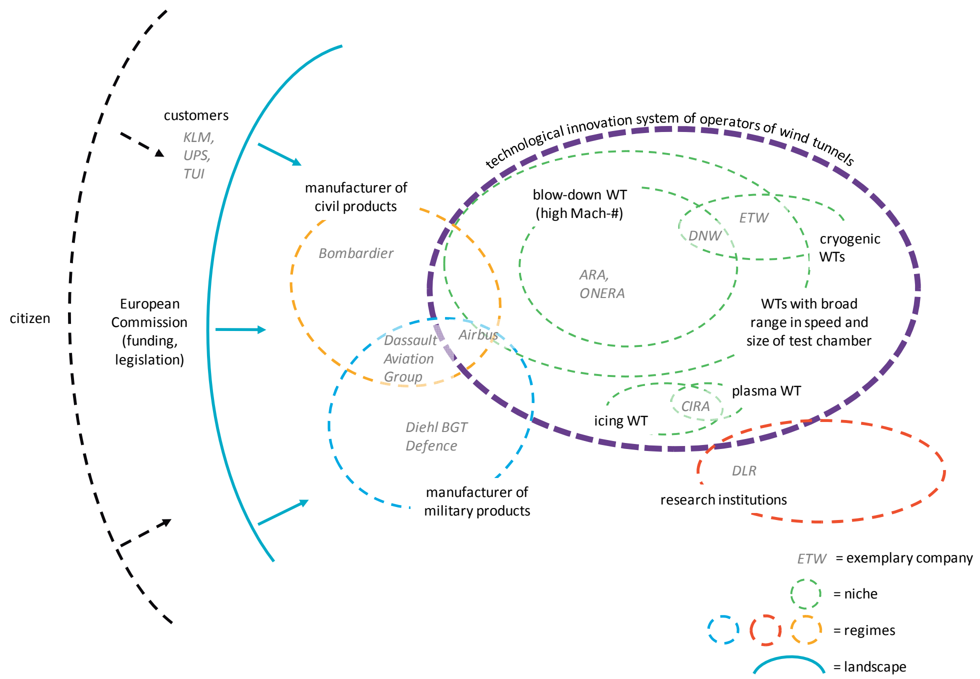

Figure 39 structure of the technological innovation system of the wind tunnel industry in Europe

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10 Markard et al., 2008

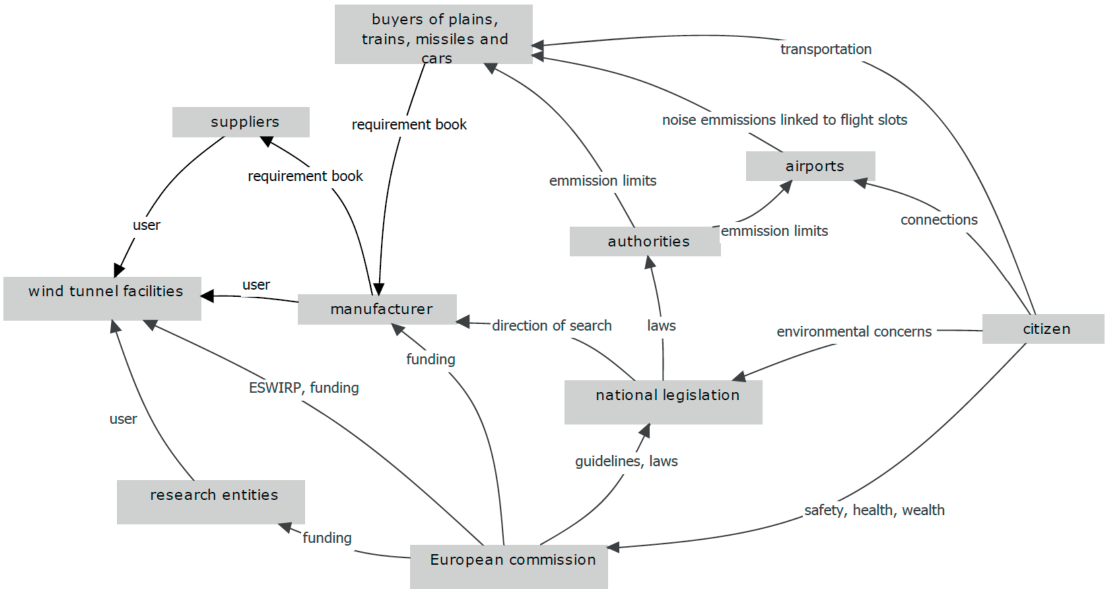

Figure 40 effect-relations between the actors of the innovation system

In Figure 40 the relations between actors in the wind tunnel industry-TIS are drawn. With “citizen” as the origin all arrows eventually lead to “wind tunnel facilities”. The highest number of direct and indirect influences on “wind tunnel facilities” can be assigned to “European Commission” thus being of highest importance for the operators of wind tunnel facilities. Second highest number of influences can be assigned to “manufacturers”. “Research entities” and “suppliers” follow on third place. These four players together are the important actors in the above sketched effect-relations-diagram.

Besides positioning actors in relation to others, the concept of TIS also contains seven functions that have been found to be decisive for an innovative functioning. “From a policy perspective, it is particularly important to understand the blocking mechanisms that shape the nature of the dynamics”.[11] The functions (or dynamics) are displayed in Figure 41. One function called “development of positive externalities” (e.g. enhanced number and variety of actors in the system) has not been mentioned due to the fact, that it can be seen as an overall indicator, which strengthens the other six factors.

In Figure 41 it is shown how blocking mechanisms that came up during investigation and interviews affect certain functions of the TIS and hence, reduce its capability for innovations. For instance missing standards result in a barrier that prevents further market formation. Once a customer adapted to the standard of one facility he faces the hurdle that he needs to adapt again to a different system when testing at another facility. Another example of a blocking mechanism is missing trust in the provided set of data (see 3.3.2.2.2). This not only questions the set of data but also affects the justifi-

[11] Bergek et al., 2008

cation for the test facility, i.e. its legitimating. These two examples shall display how certain conditions block the emergence of innovations in this technological innovation system.

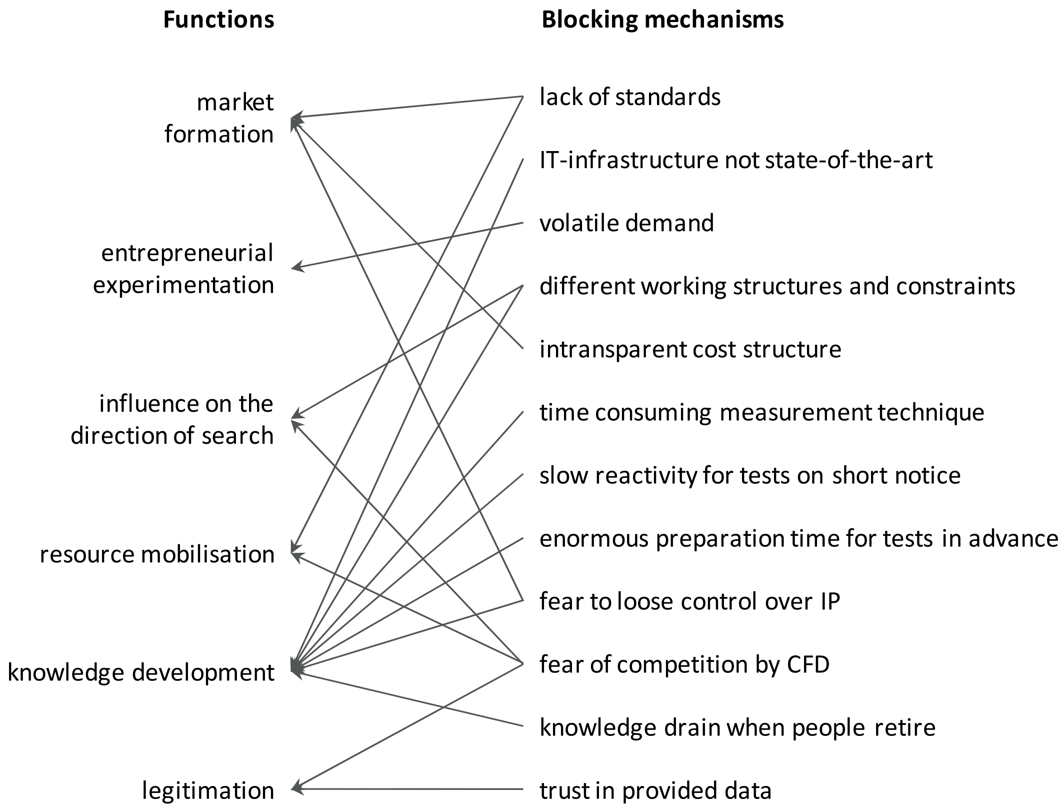

Figure 41 blocking mechanisms of functions of the TIS

4.3.3 Incentive System

As sketched in the effect-relations-diagram above the most influential institution on wind tunnel facilities is the European Commission. Main contributor to this fact is the direct funding activity and hence the incentive system.

In regard to the incentive system three questions can be assessed that will be discussed in the following paragraphs:

- Who assigns funding programs?
- Which are major programs?
- Which objectives are pursued by incentive activities?

Public funding happens in a national and supra-national context. In this regard it is referred to chapter 4.3.1 in which several countries are compared concerning their funding strategy. A detailed list of public institutions in Europe can be found in the database, which is described below in chapter 4.3.4.

One funding tool of the different funding instruments in Europe is called the “European Strategy Forum on Research Infrastructures (ESFRI)”. ESFRI is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.[12] In this context, a European Roadmap for Research Infrastructure has been established in 2006 and updated since. In the update report of year 2008 it has been recommended in the “landscape for engineering research” to initiate four projects, one of which is called “Centre for International Collaboration on Long Pipe Experiments (CICLoPE)”. This project concerns the field of fluid dynamics and will enable research in the field of high Reynolds number turbulent flows with a newly built large pipe flow facility. The proposed facility is currently in realisation in Predappio (Italy) and hosted by the University of Bologna (Italy).[13] Installations are done during this year with ramp-up in the fourth quarter 2010. International collaboration within this project unites seven universities and research institutes.[14] Moreover this project is part of the COST action MP0806 “Particles in Turbulence”.

Furthermore two other proposals for projects are recommended in the update report and concern the area of aeronautical research. One proposal with the acronym “LVR-HALE (High Altitude Long Endurance Flying Laboratory)” describes a flying laboratory capable to perform aeronautical research. This project is pursued by CIRA, which envisions a commissioning in 2013. An un-piloted flying platform at subsonic speed with an endurance of 30 days, a ceiling of 20 kilometres, and a payload of 100 kilograms has to be developed. The objected use lays in the validation of aeronautical technologies, aerodynamic research, and in testing of new structures, materials, and flight systems.

The third recommended project meanwhile became reality at DLR and is called the “Advanced Testing Research Aircraft (ATRA)”. ATRA will be deployed for testing of aeroelastic and acoustic measurements, atmospheric and engine measurements, measurements of turbulences and wake vortices, and testing of new flow based imaging techniques.[15]

All proposals can be expected to impact activities in wind tunnels either competing with or complementing them.

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12 “The ESFRI Roadmap identifies new Research Infrastructure (RI) of pan-European interest corresponding to the long term needs of the European research communities, covering all scientific areas, regardless of possible location. ... Potential new RI (or major upgrade) identified are likely to be realized in the next 10 to 20 years. ... The ESFRI roadmap is an ongoing process. First published in 2006, with 35 projects, it was updated in 2008 bringing the number of RIs of pan-European relevance to 44.”

13 http://www.ciclope.unibo.it/; http://mp0806.cineca.it/

14 KTH, Stockholm; IIT, Chicago; Caltech; University of Bologna; University of Rom; Princeton; EPFL Lausanne; ICTP Trieste;

15 http://www.dlr.de/en/desktopdefault.aspx/tabid-4777/7916_read-12006/

Within the Frame Program 6 (FP6) and FP7 of the European Commission a large number of projects have been funded in regard to aeronautics, many of which will influence wind tunnel customers. Some of them even will have direct involvement to wind tunnels. The entire list of can be found in the database described in 4.3.4.

In Europe a lot of activities in the field of aeronautics on many different levels have been established. A selection is listed in Table 7 and will be explained in the following paragraphs.

Table 7 listing of major development mechanisms and activities of research in the field of aeronautics in Europe

acronym	type of project	supported by EC	exists since	comments
GARTEUR	Forum	no	1973	parallel to European Commission; initiates projects
EREA	Network	no	1994	network of wind tunnels
ACARE	Initiative	yes	2001	founded in 2000 in sequence of a vision 2020 for aviation in Europe
KATnet II	co-ordinating action	yes	2002	
EWA	network of excellence	yes	2004	network, mainly between wind tunnels
AirTN	ERA-Net	yes	2006	
SESAR	joint undertaking	yes	2007	launches calls
CLEANSKY	joint technology initiative	yes	2008	launches calls
ESWIRP	Project	yes	2009	project of wind tunnels

The “Group for Aeronautical Research and Technology in Europe (GARTEUR)” was initiated early in the 1970s in order to join efforts in aeronautical research across Europe.

Also the “Association of European Research Establishments in Aeronautics (EREA)” was constituted by the initiative of its current members in order to strengthen and to ease networking between research facilities for aeronautical research in Europe.

All other major activates in the field of aeronautics listed in Table 7 were started later and were all supported or initiated by the European Commission.

ACARE for instance, the “Advisory Council for Aeronautics Research in Europe”, started as a result of recommendations concluded from a vision for aviation in Europe for the year 2020, which had been formulated by the European Commission. The elaboration of a Strategic Research Agenda (SRA) for Europe was the core task of this council that is very influential concerning publicly funded research in aeronautics.

The project “Key Aerodynamic Technologies to Meet the Vision 2020 Challenges (KATnet)” is designed directly to support the realisation of the SRA published by

ACARE. It is organised as a co-ordinating action and first has been funded in FP5. As “KATnet II” the project was re-launched in FP7.

The “European Wind tunnel Association Network of Excellence (EWA)” lays focus on technological improvements and thus enlargement of testing capabilities for wind tunnels taking advantage of EREA, which prepared the ground for good co-operation between European wind tunnels.

The aeronautics ERA-net “Air Transport Net (AirTN)” is supported since FP6. Along the concept of the funding instrument of ERA-nets research activities that are carried out on a regional or national level in the member states shall be co-ordinated and co-operations enhanced. An improved awareness for already existing supporting mechanisms is the declared goal of AirTN.

The AirTN overall objectives are:

1. to increase co-operation and co-ordination of research activities in aeronautics carried out at a national level through networking of research activities at EU level
2. to provide an effective platform to support the ACARE initiative and the development and implementation of the Strategic Research Agenda
3. to support EU and EUROCONTROL activities for implementation of a Single European Sky for a seamless Air Traffic Management all over Europe
4. to initiate joint actions

The joint undertaking “Single European Sky Air Traffic Management Research program (SESAR)” has been founded by Eurocontrol and the European Commission as a result of AirTN. Hereby the modernisation of the European air traffic management system shall be ensured by co-ordinating and concentrating all relevant research and development efforts across Europe.

A joint technology initiative CLEANSKY, which aims for breakthrough technologies in order to reduce the environmental impact of aviation in respect to noise and gas emissions, will impact wind tunnel industry at least indirectly. Some wind tunnels are even directly involved in this initiative as technology evaluators.

Since last year one research program launched by the European Commission started directly in the field of wind tunnels, which is called “European Wind tunnels Improved Research Potential (ESWIRP)”. As regards content a standard for wind tunnels will be created within the project on the basis of mathematical modelling. In general the technical capabilities of the participating three wind tunnels will be enhanced in the course of this program.

In order to elaborate the motivation for funding of the European Commission not mentioned yet the wind tunnel industry shall be characterized shortly in the following paragraph.

Wind tunnel industry has many facilities that complement each other and that try to cover one niche each. Hence it is difficult to argue for industry wide standards for e.g. common use of units, coordinate systems or data formats. Secondly this industry is characterized by a few and powerful customers that are influential on wind tunnels and their strategy. This might have contributed to the fact that industry itself appears to be focused and well organised. Mutual exchange of knowledge between wind tunnels and their partners, an important prerequisite for innovations, seems to work well and along defined channels. It can be expected that this setup only allows incremental innovations. There is only one possibility left for radical innovations which are the tremendous requirements from the military sector.

The intention of the European Commission for funding is more than the contents of a project. It aims to reduce blocking mechanisms of the innovation system like the ones listed in (see above) and partly repeated above. For instance a stimulus for innovation can be set through new constellations of actors. In this regard some universities, which are enabled by ESWIRP to do fundamental research at wind tunnels, may act as such stimuli. Another example for a tackled blocking mechanism is the establishment of standards, which is envisaged by the creation of mathematical models.

4.3.4 Software based tool

The national and technological innovation systems of the wind tunnel industry both contain a huge number of members. In order to make the list of members accessible and manageable a database has been created in a spreadsheet design. This software-based tool helps to identify key agents of the innovation system of wind tunnels with a fingertip.

The software-based tool consists of four elements:

- analysis grid of the national innovation system including regional selection (Figure 42)
- analysis grid of the technological innovation system (Figure 43)
- database covering agents within the wind tunnel innovation system
- database covering European research projects in the field of aeronautics

Sketches of the innovation systems on two different sheets allow to manoeuvre through the database and to select lists of members since it is hypermedia featured and connected with the database. For the sheet of the national innovation system it is also possible to make a regional selection (Figure 42).

With the help of the software-based tool, it is possible to identify all key agents of a single category within the wind tunnel innovation system. In addition various search strategies can be applied. For example it might be of interest to display all members of the category “intermediaries”. One click on the particular button generates the list and opens the result list. The result list can be used as a starting point for further investigation since each member’s homepage is hyperlinked.

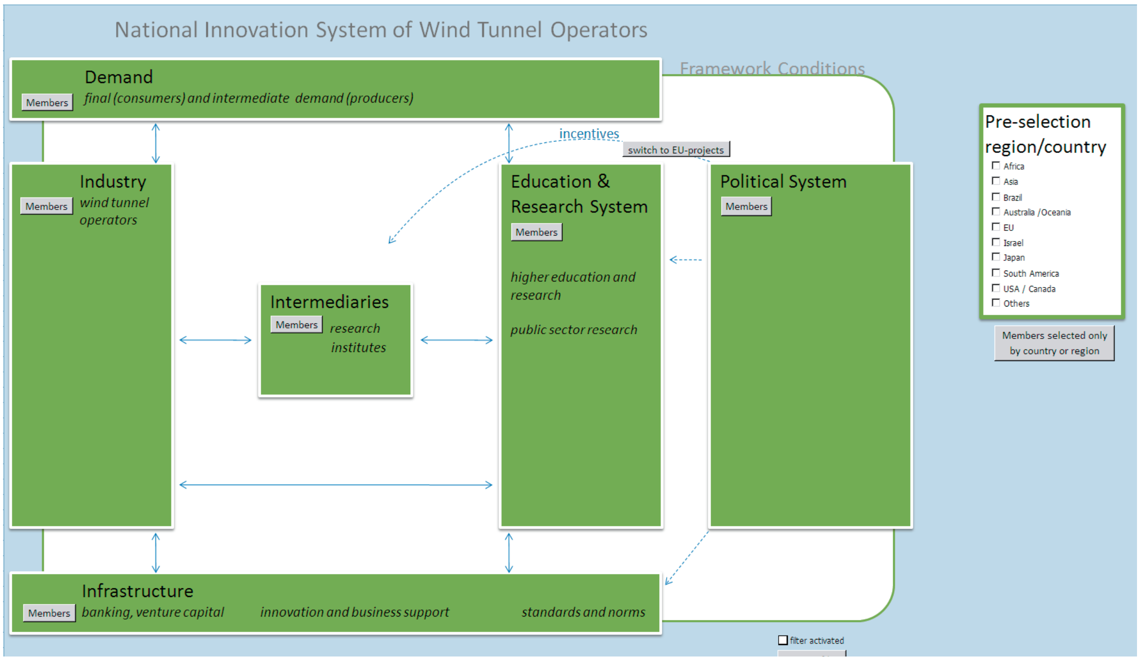

Figure 42 interface of the software-based tool for wind tunnel innovation system analysis, screenshot of the National Innovation System sheet

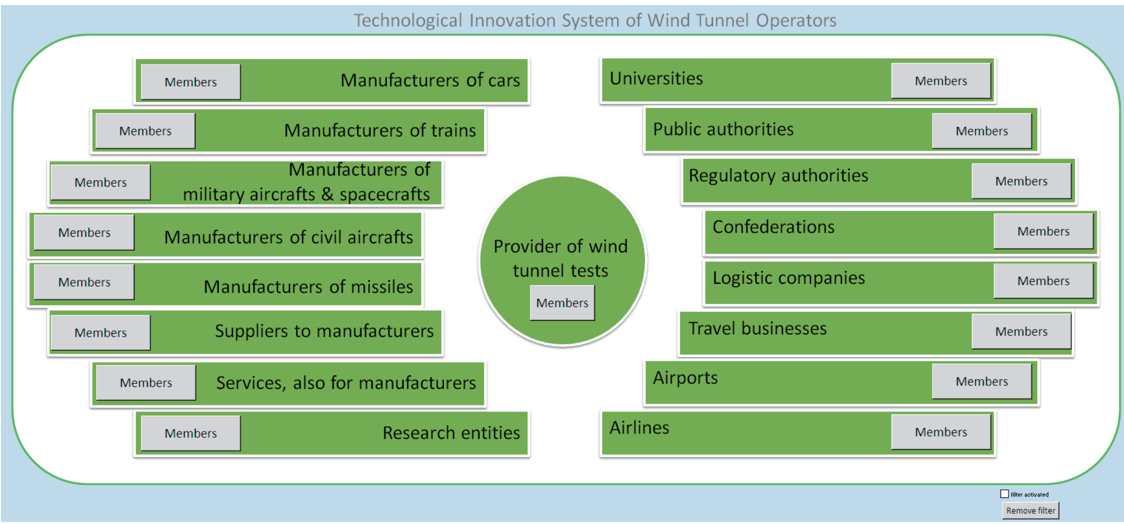

Figure 43 interface of the software-based tool for wind tunnel innovation system analysis, screenshot of the Technological Innovation System sheet

The database counts more than 1.000 entries (private and public institutions) and is designed for further extension (Figure 44). As starting point members of sixteen associations and other important entities were listed and categorized in regard to the national innovation system (NIS) and the technological innovation system (TIS). The list of could be broadened implementing information from the Worthey Connection, the Library of Congress, and the National Institute for Aviation Research.[16]

The categorization for TIS displays the more detailed view and comprises most of the listed entities. The allocation of memberships in different associations is mentioned in the rear columns. In order to directly learn more about a single entity the spreadsheet user can directly visit the respective internet presence using hyperlinks next to the entities' name.

Database of Members of the Innovation System

deactivate filter & go back to Overview_NIS

deactivate filter & go back to Overview_TIS

No.	Name	Website	Category in NIS	Function in TIS	Region/Country	Member of	Member of 2
1	328 Support Services GmbH	http://www.328support.de/		Services	EU	BDLI	
2	3D ConTech GmbH & Co. KG	http://www.3dcontech.de/	Innovation and business support	Services	EU	ALROUND	BDLI
3	a+i engineering GbR	http://www.a--i.com/	Innovation and business support	Services	EU	BBAA	
4	AAC Aviation & Airport Consult GmbH	http://www.airport-consult.de/	Innovation and business support	Services	EU	BBAA	Hanse Aerospa
5	ABAN Air	http://www.abanair.com/	Consumers	Airlines	OTHERS	BARIG	
6	AC&S Aerospace Consulting & Services GmbH	http://www.acns.de/	Innovation and business support	Services	EU	ALROUND	BDLI
7	Accenture GmbH	http://www.accenture.com/	Innovation and business support	Services	EU	BDLI	
8	ACCESS e.V. Materials + Processes	http://www.access.rwth-aachen.de/	Higher education and research	Universities	EU	ALROUND	
9	ACENTISS GmbH	http://www.acentiss.de/		Services	EU	BDLI	
10	ACI Europe	http://www.aci-europe.org/		Confederations	EU	ACARE	
11	ACM Air Charter Luftfahrtgesellschaft mbH	http://www.acm-air-charter.de		Services	EU	GBAA	
12	ADAC	http://www.adac.de/		Confederations	EU	BBAL	
13	ADDCON Europe GmbH	http://www.addcon.net/de/home/		Supplier to Aircraft Manufacturer	EU	ALROUND	
14	Adecco Personaldienstleistungen GmbH	http://www.adecco.de		Services	EU	Hanse Aerospace	
15	adm - airport design management	http://www.ad-m.com/		Services	EU	BBAA	
16	Adolf Würth GmbH & Co. KG	http://www.wuerth.com		Supplier to Aircraft Manufacturer	EU	GBAA	
17	Adria Airways	http://www.adria-airways.com/	Consumers	Airlines	EU	BARIG	
18	Advisory Council for Aeronautics Research in Europe	http://www.acare4europe.com/	Political System	Confederations	EU	ACARE	

Figure 44 screenshot of the database of members of the innovation system

A separate spreadsheet contains a list of research initiatives under the EU's Sixth Framework Programme (FP6) and Seventh Framework Programme (FP7), which have been launched by the Area of Research of the European Commission called Aeronautics (Figure 45). From the sketch of the national innovation system it is possible to access this list via a separate button. On the respective spreadsheet there is an internet link provided that allows approaching more information.

FP6 & FP7 Aeronautic Projects

further information to single projects

back to overview-NIS

Acronym	Name
AAS	Integrated airport apron safety fleet management
ABiTAS	Advanced Bonding Technologies for Aircraft Structures
ACCENT	Adaptive control of manufacturing processes for a new generation of jet engine components
ACFA 2020	Active Control of Flexible 2020 Aircraft
AD4	4D Virtual Airspace Management System
ADDSAFE	Advanced fault diagnosis for safer flight guidance and control
ADELINE	Advanced Air-Data Equipment for Airliners
ADHER	Automated Diagnosis for Helicopter Engines and Rotating parts
ADIGMA	Adaptive Higher-Order Variational Methods for Aerodynamic Applications in Industry
ADLAND	Adaptive Landing Gears for Improved Impact Absorption
ADMAP-GAS	Unconventional (Advanced) Manufacturing Processes for Gas-engine turbine components
ADVACT	Development of Advanced Actuation Concepts to Provide a Step Change in Technology Use in Future Aero-engine Control Systems
ADVICE	Autonomous Damage Detection and Vibration Control Systems
ADVITAC	ADVance Integrated Composite Tail Cone
AEROAFRICA-EU	Promoting European-South African research co-operation in aeronautics and air transport
AEROCHINA	Promoting scientific co-operation between Europe and China in the field of multiphysics modelling, simulation, experimentation and design methods in aeronautics
AEROCHINA2	Prospecting and promoting scientific co-operation between Europe and China in the field of multi-physics modelling, simulation, experimentation and design methods in aeronautics
AEROMAG	Aeronautical Application of Wrought Magnesium

Figure 45 screenshot of the database for European research initiatives

[16] http://www.worthey.net/windtunnels; Goodrich et al., 2008; http://www.niar.twse.edu/

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6 Annex

6.1 Interviews

Table 8 interview partners

No.	Name	Organisation	Affiliation and Position	Interview and Contrbution	Date
01	Dr. Luis P. Ruiz Calavera	Airbus Military	Head of CoC Flight Physics	Phone	April 21, 2010
02	Thilo Pinar	EADS	Senior Manager Defence & Security Military Air Systems Aircraft Physical Properties - MEG6	Phone	March 30, 2010
03	Gerhard Wolfrum	EADS	Defence & Security Military Air Systems	Phone	March 30, 2010
04	Uwe Gross	EADS	Defence & Security Military Air Systems	Phone	March 30, 2010
05	Giuseppe Crosta	AGUSTA-WESTLAND	Aerodynamic Laboratories & Wind Tunnel Technical Leader	Phone	March 31, 2010
06	Marc Allongue	Eurocopter	VP General Engineering	Personal	March 22, 2010
07	Gérard Icart	Airbus	Head of Wind Tunnel Testing, Aerodynamic Domain - EGAX	Personal	March 16, 2010
08	Dr.-Ing. Winfried Kühn	Airbus	Experimental Aerodynamics	Personal	March 16, 2010
09	Steve Roe	BAE Systems	Specialist Engineer - Wind Tunnel & General Systems, EIS	Personal	March 8, 2010
10	Craig F. Eckersley	BAE Systems	Senior Aerodynamicist	Personal	March 8, 2010
11	S. Eccleston	BAE Systems	Lead Aerodynamicist	Personal	March 8, 2010
12	G. Rigby	BAE Systems	Senior Aerodynamicist	Personal	March 8, 2010
13	Dr. N. Sellars	BAE Systems	Air Vehicle Manager – Strategic UAS	Personal	March 8, 2010
14	I. Whitmore	BAE Systems	Senior Aerodynamicist	Personal	March 8, 2010
15	Brian Cleator	BAE Systems	Business Development Manager	Personal	March 8, 2010

16	Peter Mangold	Diehl BGT Defence GmbH & Co. KG	Centre of Competence for System Technology, Team Leader for Aerdymics and System Layout	Phone	April 26, 2010
17	Prof. Dr.-Ing. Cord-Christian Rossow	DLR, German Aerospace Center	Head of the Institute of Aerodynamics and Flow Technology	Phone	April 27, 2010
18	Dr. Alexander Orellano	Bombardier	Manager, Center of Competence for Aerodynamics & Thermodynamics	Phone	April 27, 2010
19	Pascal Briant	Dassault Aviation	Head of Applied Aerodynamic Team	Phone	March 28, 2010
20	Marc Stojanowski	Dassault Aviation	Applied Aerodynamic Team	Phone	March 28, 2010
21	Maria Douka	European Commission	Programme officer, European Commission, DG Research, Directorate B-Structuring ERA, B3-Research Infrastructure	Personal	May 4, 2010

6.2 Items for Roadmapping

6.2.1 Technology Roadmap

Table 9 collection of wind tunnel technologies

Wind tunnel technologies
Small air-line bridges
Transition prediction methodology
"Ideal" trip (MEMS)
Laminar flow investigations
Non-intrusive separation detection
Data acquisition wireless
Unsteady signal data acquisition (high freq.)
Data base tools for advanced measurement techniques (huge amount of data)
Correct simulation of transition position
Lam. wing investigations
Novel simulators for novel engine concepts
Contra-rotating propeller simulation
Rolling road for ground effect (low speed)
Simulation and testing with miniaturized systems, easy to install and calibrate; interfaced with each other
Dynamic model testing
Wall correction advanced

Integrated environmental corrections - 1) theory 2)tools
Improve automation of wind tunnels
Flexible wall wind tunnels
Data acquisition

Table 10 collection of preceding technologies

Preceding technologies
High-capacity internal balances
Internal strain gauge balance & calibration
Fibre-optic balance
Pressure scanning systems >1000 ports
Localised loads on model - miniature S/G balances
HWA technology for WT testing - long term time to time will be updated
S/G balance on board acquisition e.g. wireless ethernet
Data handling
Specialised technologies (high pressure, low temp., small facil.)
More standards to reduce installation time
Unsteady/dynamic testing: facility & m/t
Micro systems in models
"Ideal" model support (no-support)
Magnetic suspension of models
Miniaturization of A/D converters
Acoustic mt in transonic
Aero-acoustics, microphone arrays
Acoustic tests in closed test sections
Modular models
Model design - rapid prototyping
Modular remote contr. "stingless" model
Model manufacture more detailed, cheaper, faster
Model surfaces remote actuation
Remote control all control devices of model
Particle tracking
Temperature sensitive paint
Pressure sensitive paint
Image capturing technology - steady, unsteady
Low-speed pressure sensitive point
Image analysis software
Ability to measure unsteady pressures (PSP) + flows (PIV)
Improvement of cameras and lasers
Particle image velocimetry
Optical inclinometers
Cryo-application (of TSP, PSP, PIV)

Table 11 collection of complementary technologies

Complementary technologies
CFD analysis of WT environment
Complementary CFD
Integration with CFD

Table 12 collection of competing technologies

Competing technologies
Moore's law in numerical capacity
UAVs CFD → flight test

Table 13 collection of management aspects

Management aspects
Reduce wind tunnel test cycle time by at least 50%
(DOE) Shorter test time ↔ more data per test
Combined integrated team (customer, WT, suppl.)
Reduce model manufacture time
Simulation and testing on a known basis where exp. results can be compared with STV and - taken both into account - results can be extrapolated to flight conditions
Simulation and testing all relevant physical quantities

6.2.2 Product Roadmap

Table 14 entire list of drivers mentioned

Drivers
1st time right
A/C development (conventional)
accreditation as an aerial vehicle, certification concerning flight safety
aeroacoustic requirements
aerodynamic missile development (small aspect ratio configurations)
certification concerning flight safety, icing conditions
CFD tool development
CFD tool development (validation)
costs
development of a reliable aerodynamic model for simulation purposes
differential technologies (unconventional)
energy saving (reduction of aerodynamic drag)
environment (energy efficiency)

environment (noise emissions)
high angle of attack aerodynamics
high quality results
homologation (safety requirements fulfilled)
increasing requirement on performance at lower development time and cost
motorised testing (future engine: open rotor, propelled VHBB, noise constraints)
new rotorcraft concept
new wind tunnel strategies (new corrections, special tests)
non-recurring cost reduction
productivity
pure R&D
reduction of lead time
reduction of noise
safety
speed enhancement in products
time constraints
time efficient optimization of configuration within wind tunnel test campaign
tool development for testing tools
unconventional configurations
validation of mission performance

Table 15 entire list of requirements and needs

requirements and needs
3D-PIV
accuracy of systems
accuracy of systems concerning temperature increase during testing, temperature insensitive sensors
acoustic testing (improvements in open test section, data handling, lead time)
acoustics (closed test sections, corrected aerodynamics)
acquisition of detailed and local information
advanced measurement techniques (TSP, acoustics, PIV, PSP)
availability of non-intrusive techniques
certification concerning flight safety
CFD tool development, validation of numerical data
combined measurements of aerodynamics and acoustics
combining the benefits from acoustics measured in closed and in open test sections
cost control (reduction)
cost reduction
cost structure of measuring methods
cost structure of measuring methods, identification of cost drivers
data acquisition
determination of influence of test set-up (sting, wind tunnel walls,...) on aero-data ==> Wind tunnel / free flight
dynamic derivatives

elimination / reduction of oscillations due to test setup
environmental friendly: aerodynamic efficiency, reduced noise emission)
fast data handling and available to the customer (prerequisite to high productivity, e.g. concerning adaptation of test program)
flexibility
flexibility of wind tunnel working time
full flutter expansion
high fidelity of data capture
high speed data acquisition technology due to large data sets
high speed helicopter
icing conditions (scale effect of water)
Improvement of on-line data evaluation (integration of customer's and Wind tunnel evaluation software)
large data storage, handling, post processing (e.g. acoustics, PIV)
manoeuvre simulation
measurement of aerokinetic heating
measurement of forces and moments
measurement of pressure distributions
measurement of pressures
measurement of unsteady conditions
Military applications: performance, flight domain extension
miniaturization (MEMS, balance crossings, telemetry, sensors)
miniaturization of flow control devices
miniaturization of load models
monitoring of aeroelastic deformations
motorised testing (future engine: open rotor, propelled VHBR, noise constraints)
open access to previous data (correction purpose; important for today's understanding)
PIV (vortex, interferences, high speed)
PIV synchronized with rotating units
productivity
productivity @ blow-down-wind tunnels
productivity concerning provided service
PSP
PSP on rotating blade combined with pressure taps
qualified staff, dedicated to support during whole testing time
reduction of the need for correction
remotely controlled movables (mainly low speed)
remotely controlled movables (mainly low speed); connection to model equipment and control during tests
repeatability of quality of flow due to relational testing behaviour
standardization (coordinate systems, units, data formats) throughout whole wind tunnel industry
state-of-the-art data acquisition
testing for laminar flow conditions
testing under extreme conditions assuring accuracy of data

thermic simulation (engine, cooling unit)
time and cost efficient measurement of a complete aerodynamic data set
true cost of using advanced techniques
TSP

Table 16 entire list of products and services

products and services
(quasi -) static testing within angle of attack range 0°-60° (angle of attack polars at constant roll attitude)
accuracy for good equilibrium drag and pitching
accurate force measurements
acoustic analyses
acoustic testing (improvements in open test section, data handling, lead time)
acoustics (closed test sections, corrected aerodynamics)
advanced measurement techniques (TSP, acoustics, PIV, PSP)
analysis of separation processes (removal of casings, emergency mechanism of self destruction of missiles)
blade deflection
characterization of the aerodynamic limit of the flight domain
competent support by a single person during wind tunnel tests
consulting concerning model design
consulting of customers with best practice approach to handle large volume of data
conversion of pressures into loads, one integrated model
conversion of pressures into loads, one integrated model, congruence of results between PSP and load data
data acquisition
diagnostic testing
diagnostic testing (3D-PIV)
diagnostic testing, for validation of test cases
drag pitching moments
dumping derivatives
end of rail, semi-release
end of stroke, semi-release, still attached
forces and moments (3+3)
full flutter expansion
hinge moments measurement
icing phenomenon investigation (water not scalable)
increase understanding within a transsonic design
increasing the number of tests per run
instationary PSP
integrated service (producing mock-up + performing wind tunnel tests)
integration of hinge moment measurements in other tests, synergy when using PSP
knowledge of applied wind tunnel corrections for increased understanding, more openness to WT-customers

low cost oscillatory testing
low cost rotary testing
low cost twin sting testing
measurement of dynamic data due to pitch / yaw rate
measurement of dynamic data due to roll rate (oscillations)
measurement of forces and moments
measurement of laminar / turbulent flow structure
measurement of pressure distribution (interesting if direct force measurements are not possible)
measurement of pressures
measurement of roll attitude polars at constant angle of attack
measuring duct behaviour (aerodynamics & acoustics)
measuring propeller systems
measuring propeller systems, UAV sector
miniaturization (MEMS, balance crossings, telemetry)
miniaturization of load models
model deformation measurement, model deflection
model design
model design and manufacture
model equipped with powered controls (rapid position changes)
motorised testing (future engine: open rotor, propelled VHBB, noise constraints)
online monitoring during tests, easy and flexible access to data in real time
operation of complex models / mock-ups
optical measurement techniques
PIV (vortex, interferences, high speed)
PIV for diagnostic testing
powered model testing
preliminary financing of test periods (e.g. until end of year)
PSP
PSP continuous load visualization
PSP for low speed wind tunnel testing, especially sensitive
reduction of the part of data correction in order to reduce overall uncertainty
remotely controlled movables (mainly low speed)
rotary derivatives
rotary derivatives (- unsteady pressure measurement - rotor wake pressure on the blades - rotor-fuselage-interaction - rotor-rotor-interaction)
rotary dynamic derivatives
rotary testing, low cost
simulation of docking (separation) manoeuvres
static load
store loads
store loads configurations measurements

store loads configurations measurements, UAV sector
store release
strain-gauge measurements
strain-gauge measurements, model design (sensor design)
support of the design (optimize rotor, reduce drag)
surface loads
switch from service provider to risk sharing partner
test of moving models (passing each other)
testing of climate conditions
testing under unsteady conditions (for pressures and flows forces)
transition loads
TSP
turbulences
turn-key system for PIV
turn-key system for PIV, availability of PIV
turn-key system for PIV, in general for optical flow field measurements
turn-key system for PIV, maturity of systems for industrial use
turn-key system for transition from turbulent to laminar flow (e.g. via IR)
twin sting testing, low cost
understand undesired flight / ride behaviour
understand undesired flight behaviour
unsteady pressures
use of CFD for correction
wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)

Table 17 entire list of challenges

challenges
"cultural" differences in between R&D, institutes and industry, maintain partnership
a levitating model to eliminate need for sting correction
accumulation of more and more measurements in a single test loop, parallel measurements
active laminar flow control
adaptive model / mock-up
advances in data capture
cleanliness of WT and model for laminar high Re testing
deformations (High, low speed), low speed gap - overlapping
deformations (High, low speed), low speed high lift configurations gap - overlapping
Derivation of "real flight zero-lift drag" from wind tunnel-measured data
determination of influence of the jet exhaust on aerodynamic data (control efficiency, manoeuvrability)
development of measurement techniques @ supplier similar to previously @ industry
effects of aeroelastic in-flight deformations on aerodynamic data
Effects of lateral jet exhaust on aerodynamic data (loads and pressure distribution)
finances

full flutter expansion
harmonizing both methods, CFD and wind tunnel testing
illumination for PIV
illumination for PIV, homogeneous particle distribution
illumination for PSP
illumination for PSP, PSP for rotating unit
Improved PSP accuracy to give loads measurements
integration of multiple experiments / measurements in a single run
knowledge retention at WT in case of retirement of experienced personnel
large data storage, handling, post processing (e.g. acoustics)
large data storage, handling, post processing (e.g. acoustics)
Measurement of store loads (including EOR = End of Rail / EOS = End of stroke) from small model
miniaturization of load models
model deformation measurement, model deflection
non-intrusive techniques
PIV for diagnostic testing (visualisation understanding flow behaviour)
PIV for high speed wind tunnel testing
PIV for high speed wind tunnel testing, industrial availability
possibility to change the intensity of turbulences in a single wind tunnel facility
powered mode testing
PSP incl. skin friction part
reactivity (wind tunnel tests on short notice)
realistic test conditions for ground effects
relation to CFD
relation to CFD - complementary
remote control surfaces in order to change configurations
revised model safety requirement (more relaxed)
self-trimming models
simulation of gusts
support-less system
tests with angle of attack from 0°-90° with only one single support
turn-key systems
wireless data acquisition
wireless data acquisition (telemetry, for high instrumentation, for rotating set-ups)

6.2.3 Integrated Roadmap

Table 18 product or requirement with links to 4 different technologies

Miniaturization (MEMS, balance crossings, telemetry)
Miniaturization of 2ndary balances

Table 19 product or requirement with links to 3 different technologies

Experimental simulation capability for novel propulsion concepts
Flexibility
Flexibility of wind tunnel working time
Measurement of dynamic data
Reactivity (wind tunnel tests on short notice)
Transition loads detection
Understanding undesired flight behaviour

Table 20 product or requirement with links to 2 different technologies

Accuracy of systems
improvement of online data evaluation
Improvement of on-line data evaluation
online monitoring during tests
Powered model testing
Testing under unsteady conditions (pressures & flows)
Turn-key system for PIV
turn-key system for transition from turbulent to laminar flow

Table 21 product or requirement with a link to 1 technology

(quasi -) static testing within angle of attack range 0°-60°
Acoustic analyses
Acoustic tests
analysis of separation processes
Blade deflection
Conversion of pressures into loads – one integrated model
Cost reduction
Data acquisition
determination of influence of test set-up on aero-data
fast data handling and available to the customer
High fidelity of data capture
High speed helicopter
Integrated service (producing mock-ups, performing WTT)
knowledge of applied corrections
Low cost twin sting testing
Measurement of pressures
measurement of roll attitude polars at constant angle of attack
measuring duct behaviour
Measuring propeller systems
Military application (performance, flight domain extension)
Model design and manufacture
Open access to previous data
PIV for diagnostic testing
Productivity
PSP (as a product - model technology)
PSP (as a requirement - application)
PSP low speed, highly sensitive

qualified staff, dedicated to support during whole testing time
repeatability of quality of flow due to relational testing behaviour
Simulation capability of environmental aspects
standardization throughout wind tunnel industry
Strain-gauge measurements
time and cost efficient measurement of a complete aerodynamic data set
unsteady PSP

Table 22 product or requirement with no link to any technology

Icing phenomenon investigation (H_2O not scalable)
Store release (EOR, EOS)
Rotary derivatives
Store loads configuration measurements
Support of the design (optimization of rotor, reduce drag)
Operation of complex models/ mock-ups

6.3 Sector Specific Insights

Table 23 consolidated answers of an aircraft manufacturer

aircraft construction

layers of the roadmap ↓	Relevance	time in years →	short term 1 2 3	medium term 5 7 9	long term >9
drivers (no. 1)		time constraints			
requirements and needs (no. 2)	x	data acquisition	x		
	x	high fidelity of data capture	x		
	x	accuracy of systems	x		
		measurement of forces and moments	x		
	x	measurement of pressures	x		
		cost and time reduction	x		
		true cost of using advanced techniques	x		
products and services (no. 3)		static loads	x		
		surface loads	x		
		strain-gauge measurements	x		
	x	model design and manufacture	x		
	x	turn-key system for PIV	x		
		store loads	x		
		store release		x	
		end of rail, semi-release	x		
		end of stroke, semi-release, still attached	x		
		transition loads		x	
		acoustic analyses		x	
	x	drag pitching moments		x	
		full flutter expansion		x	
		conversion of pressures into loads, one integrated model		x	
		diagnostic testing			x
		understand undesired flight behaviour (PIV, PSP etc)	x		
		low cost twin sting testing	x		
		low cost rotary testing	x		
		low cost oscillatory testing	x		
	x	powered model testing	x		
		model equipped with powered controls (rapid position changes)	x		
		measuring propeller systems	x		
		testing under unsteady conditions (for pressures and flows)	x		
		turbulences	x		
		PSP for low speed wind tunnel testing, especially sensitive	x		
		PSP continuous load visualization	x	x	
	x	PIV for diagnostic testing	x		
	x	measuring duct behaviour	x		
		hinge moments measurement	x		
challenges (no. 4)		model deformation measurement, model deflection		x	
		PIV for high speed wind tunnel testing	x		
	x	illumination for PSP	x		
	x	illumination for PIV	x		
	x	non-intrusive techniques	x		
		wireless data acquisition	x		
		self-trimming models			x
		harmonizing both methods, CFD and wind tunnel testing	x		
		remote control surfaces in order to change configurations	x		
		advances in data capture	x		
		a levitating model to eliminate need for sting correction			x
		Measurement of store loads (including EOR = End of Rail / EOS = End of stroke) from small model	x		
		Improved PSP accuracy to give loads measurements	x		
		PIV for diagnostic testing (visualisation understanding flow behaviour)	x		
		miniaturization of load models	x		

Table 24 consolidated answers of an aircraft manufacturer

aircraft construction

layers of the roadmap ↓	Relevance	time in years →	short term 1 2 3	medium term 5 7 9	long term >9
drivers (no. 1)		A/C development (conventional)	x		
	x	costs	x		
	x	productivity	x		
		reduction of lead time	x		
		high quality results	x		
	x	differential technologies (unconventional)	x	x	
		new wind tunnel strategies (new corrections, special tests)		x	
		pure R&D			x
		tool development for testing tools			x
		CFD tool development			x
	x	motorised testing (future engine: open rotor, propelled VHBR, noise contraints)	x	x	x
requirements and needs (no. 2)		productivity	x	x	x
		cost control (reduction)	x	x	x
		flexibility	x	x	x
		remotely controlled moveables (mainly low speed)	x	x	x
		flexibility of wind tunnel working time	x	x	x
	x	acoustic testing: improvements in open test section, data handling, lead time)	x		
		TSP	x	x	
		PSP	x	x	
		PIV (vortex, interferences, high speed)		x	
		miniaturization (MEMS, balance crossings, telemetry)		x	
	x	acoustics (closed test sections, correct aerodynamics)		x	
products and services (no. 3)	x	wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)	x	x	x
challenges (no. 4)		deformations (High, low speed), low speed high lift configurations gap - overlapping	x		
		"cultural" differences in between R&D, institutes and industry	x	x	x
	x	finances	x	x	x
		relation to CFD	x	x	x
	x	large data storage, handling, post processing (e.g. acoustics)	x	x	
		cleanliness of WT and model for laminar high Re testing	x	x	

Table 25 consolidated answers of an aircraft manufacturer

aircraft construction

layers of the roadmap ↓	Relevance	time in years →	short term 1	2	3	medium term 5	7	9	long term >9
drivers (no. 1)		time constraints		x					
		costs		x					
		productivity		x					
	x	reduction of lead time		x					
		high quality results		x					
		differential technologies (unconvetional)					x		
		tool development for testing tools		x					
		CFD tool development		x					
		safety							
	x	environment (noise emmissions)							
	x	environment (energy efficiency)							
	x	non-recurring cost reduction					x		
	x	new rotorcraft concept							x
	x	1st time right							x
requirements and needs (no. 2)		productivity							
		cost control (reduction)							
	x	flexibility							
		flexibility of wind tunnel working time							
		high fidelity of data capture		x					
		accuracy of systems		x					
		measurement of forces and moments							
		measurement of pressures							
		cost reduction							
		cost structure of measuring methods							
	x	icing conditions (scale effect of water)							
	x	high speed helicopter					x		
	x	Military applications: performance, flight domain extension							
	x	environmental friendly: aerodynamic efficiency, reduced noise emmission)							
products and services (no. 3)		static load		x					
		surface loads		x					
		strain-gauge measurements		x					
		model design					x		
		turn-key system for PIV							
		transition loads		x					
		acoustic analyses		x					
		drag pitching moments		x					
		full flutter expansion		x					
		conversion of pressures into loads, one integrated model		x					
		diagnostic testing		x					
	x	understand undesired flight behaviour		x					
		twin sting testing							
		rotary testing		x					
	x	rotary derivatives (unsteady pressure measurment ; rotor wake pressure on the blades; rotor-fuselage-interaction; rotor-rotor-interaction)					x		x
		powered mode testing							
		measuring propeller systems							
	x	testing under unsteady conditions (for pressures and flows)					x		x
		unsteady pressures		x					
		turbulances							
		PSP for low speed wind tunnel testing, especially sensitive							
		PSP continuous load visualization							
		PIV for diagnostic testing							
		blade deflection							
	x	icing phenomenon investigation (water not scalable)							
		motorised testing (future engine: open rotor, propelled VHBB, noise contraints)							
		remotely controlled moveables (mainly low speed)							
	x	acoustic testing: improvements in open test section, data handling, lead time)							
		TSP							
		PSP							
		PIV (vortex, interferences, high speed)							
	x	advanced measurement techniques (TSP, acoustics, PIV, PSP)							
		miniaturization (MEMS, balance crossings, telemetry)							
		acoustics (closed test sections, corrected aerodynamics)							
		data acquisition		x					
		miniaturization of load models							
	x	support of the design (optimize rotor, reduce drag)		x					
	x	integrated service (producing mock-up + performing wind tunnel tests)					x		
	x	operation of complex models / mock-ups					x		
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping		x					
		finances		x					
		relation to CFD - complementary							
		large data storage, handling, post processing (e.g. acoustics)		x					
		model deformation measurement, model deflection							
		PIV for high speed wind tunnel testing							
		illumination for PSP							
		illumination for PIV							
		non-intrusive techniques							
	x	wireless data acquisition					x		
		self-trimming models					x		
	x	harmonizing both methods, CFD and wind tunnel testing							
		remote control surfaces in order to change configurations							
	x	advances in data capture							
		a levitating model to eliminate need for sting correction					x		x

Table 26 consolidated answers of an aircraft manufacturer

aircraft construction

layers of the roadmap ↓	Relevance	time in years →	short term			medium term			long term
			1	2	3	5	7	9	>9
drivers (no. 1)		A/C development (conventional)		x					
	x	costs		x					
	x	motorised testing (future engine: open rotor, propelled VHBR, noise contraints)		x					
		time constraints		x					
		speed enhancement in products		x					
		certification concerning flight safety, icing conditions		x					
requirements and needs (no. 2)	x	cost control (reduction), cost reduction		x					
		acoustic testing: improvements in open test section, data handling, lead time)							
	x	PSP on rotating blade combined with pressure taps							
		PIV (vortex, interferences, high speed)							
		advanced measurement techniques (TSP, acoustics, PIV, PSP)							
	x	miniaturization (MEMS, balance crossings, telemetry)		x					
		acoustics (closed test sections, corrected aerodynamics)							
		data acquisition							
		high fidelity of data capture							
	x	accuracy of systems concerning temperature increase during testing, temperature insensitive sensors		x					
		cost structure of measuring methods		x					
		miniaturization of load models		x					
		combining the benefits from acoustics measured in closed and in open test sections					x		
		PIV synchronized with rotating units					x		
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)		x					
		static load		x					
		surface loads		x					
	x	strain-gauge measurements, model design (sensor design)		x					
		turn-key system for PIV, maturity of systems for industrial use		x					
		transition loads		x					
	x	acoustic analyses		x					
		drag pitching moments		x					
		full flutter expansion		x					
		conversion of pressures into loads, one integrated model		x					
		diagnostic testing		x					
		understand undesired flight behaviour		x					
	x	rotary testing, powered model testing		x					
		rotary derivatives		x					
		measuring propeller systems		x					
		testing under unsteady conditions (for pressures and flows)		x					
		unsteady pressures		x					
		turbulances		x					
		PSP for low speed wind tunnel testing, especially sensitive		x					
		PSP continuous load visualization							
		PIV for diagnostic testing		x					
		measuring duct behaviour		x					
		hinge moments measurement		x					
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping		x					
	x	model deformation measurement, model deflection		x					
	x	illumination for PSP, PSP for rotating unit		x					
	x	wireless data acquisition					x		x

Table 27 consolidated answers of an aircraft manufacturer

aircraft construction

			short term			medium term			long term
layers of the roadmap ↓	Relevance	time in years →	1	2	3	5	7	9	>9
drivers (no. 1)		A/C development (conventional)		x					
		costs		x					
	x	productivity		x					
		reduction of lead time		x					
	x	high quality results		x					
		differential technologies (unconvetional)		x					
		new wind tunnel strategies (new corrections, special tests)		x					
		motorised testing (future engine: open rotor, propelled VHBB, noise contraints)		x					
		time constraints		x					
		increasing requirement on performance at lower development time and cost		x					
requirements and needs (no. 2)		productivity		x					
		cost control (reduction)		x					
		flexibility		x					
		remotely controlled moveables		x					
		flexibility of wind tunnel working time		x					
		acoustic testing: improvements in open test section, data handling, lead time)							x
		PSP		x					
		PIV (vortex, interferences, high speed)		x					
		miniaturization (MEMS, balance crossings, telemetry)		x			x		
		acoustics (closed test sections, corrected aerodynamics)							x
		data acquisition		x					
	x	high fidelity of data capture		x					
		accuracy of systems		x					
		measurement of forces and moments		x					
		measurement of pressures		x					
		miniaturization of load models					x		
		certification concerning flight safety					x		x
		testing under extreme conditions assuring accuracy of data		x					
	x	fast data handling and available to the customer (prerequesit to high productivity, e.g. concerning adaptation of test program)		x					
products and services (no. 3)	x	wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)		x			x		x
		static load		x					
		surface loads		x					
		strain-gauge measurements		x					
		model design		x					
		turn-key system for PIV		x					
		store loads configurations measurements		x					
		store loads		x					
		store release		x					
		end of rail, semi-release		x					
		end of stroke, semi-release, still attached		x					
		transition loads					x		x
		acoustic analyses							x
		drag pitching moments					x		
		conversion of pressures into loads, one integrated model		x					
		diagnostic testing		x					
		understand undesired flight behaviour		x					
		twin sting testing		x					
		rotary testing					x		
		rotary derivatives					x		
		powered mode testing		x					
		measuring propeller systems		x					
		testing under unsteady conditions (for pressures and flows)					x		
		unsteady pressures							x
		turbulances							x
		PSP for low speed wind tunnel testing, especially sensitive		x					
		PSP continuous load visualization		x			x		
		PIV for diagnostic testing		x					
		measuring duct behaviour					x		
		hinge moments measurement		x					
	x	knowlegde of applied wind tunnel corrections for increased understanding, more openess to WT-customers		x					
	x	online monitoring during tests, easy and flexible access to data in real time		x					
challenges (no. 4)		finances					x		x
		relation to CFD					x		x
		large data storage, handling, post processing (e.g. acoustics)		x					
		PIV for high speed wind tunnel testing, industrial availability		x					
		illumination for PSP		x					
		illumination for PIV		x					
		wireless data acquisition		x					
	x	harmonizing both methods, CFD and wind tunnel testing					x		x
		remote control surfaces in order to change configurations		x					
		advances in data capture		x					
		a levitating model to eliminate need for sting correction							x
	x	revised model safety requirment (more relaxed)		x					
		support-less system							x

Table 28 consolidated answers of a manufacturer of transportation systems

transportation systems

			short term			medium term			long term
layers of the roadmap ↓	Relevance	time in years →	1	2	3	5	7	9	>9
drivers (no. 1)		high quality results		x					
		tool development for testing tools		x					
		CFD tool development		x					
		motorised testing (future engine: open rotor, propelled VHBB, noise contraints)		x					
		homologation (safety requirements fulfilled)		x					
		energy saving (reduction of aerodynmaic drag)		x					
		aeroacoustic requirements		x			x		
requirements and needs (no. 2)		productivity		x					
		cost control (reduction)		x					
		acoustic testing: improvements in open test section, data handling, lead time)		x					
		PIV (vortex, interferences, high speed)		x					
		acoustics (closed test sections, corrected aerodynamics)		x					
		data acquisition		x					
		high fidelity of data capture		x					
		accuracy of systems		x					
		measurement of forces and moments		x					
		measurement of pressures		x					
		cost structure of measuring methods, identification of cost drivers		x					
		thermic simulation (engine, cooling unit)		x					
	x	standardization (coordinate systems, units, data formats) throughout whole windtunnel industry		x					
products and services (no. 3)		static load		x					
		surface loads		x					
		strain-gauge measurements					x		
		turn-key system for PIV		x					
		acoustic analyses							
		diagnostic testing, for validation of test cases		x					
		understand undesired flight / ride behaviour					x		
		rotary testing, low cost		x					
		testing under unsteady conditions (for pressures and flows)					x		
		unsteady pressures					x		
		turbulances					x		
		PIV for diagnostic testing		x					
		hinge moments measurement					x		
		testing of climate conditions		x					
		test of moving models (passing each other)					x		
		forces and moments (3+3)		x					
challenges (no. 4)		illumination for PIV, homogeneous particle distribution		x					
		non-intrusive techniques		x					
		PSP incl. skin friction part							
	x	realistic test conditions for ground effects		x					
		simulation of gusts					x		
		adaptive model / mock-up					x		
		powered mode testing							x

Table 29 consolidated answers of an aircraft manufacturer

aircraft construction

layers of the roadmap ↓	Relevance	time in years →	short term			medium term			long term
			1	2	3	5	7	9	>9
drivers (no. 1)		A/C development (conventional)		x					
		costs		x					
		productivity		x					
		reduction of lead time		x					
	x	high quality results		x					
		new wind tunnel strategies (new corrections, special tests)		x					
		tool development for testing tools		x					
		CFD tool development		x					
		time constraints		x					
	x	reduction of noise		x					
requirements and needs (no. 2)		productivity		x					
		cost control (reduction)		x					
		flexibility		x					
		remotely controlled moveables (mainly low speed)		x					
		flexibility of wind tunnel working time		x					
		acoustic testing: improvements in open test section, data handling, lead time)					x		
		miniaturization (MEMS, balance crossings, telemetry)					x		
		acoustics (closed test sections, corrected aerodynamics)					x		
		high speed data acquisition technology due to large data sets		x					
		high fidelity of data capture		x					
		accuracy of systems		x					
		measurement of forces and moments		x					
		measurement of pressures		x					
		miniaturization of load models					x		
		certification concerning flight safety		x					
		large data storage, handling, post processing (e.g. acoustics, PIV)		x					
		measurement of unsteady conditions		x					
		acquisition of detailed and local information		x					
		combined measurements of aerodynamics and acoustics					x		
		availability of non-intrusive techniques		x					
		reduction of the need for correction		x					
products and services (no. 3)		static load		x					
		surface loads		x					
		turn-key system for PIV, availability of PIV		x					
		store loads configurations measurements		x					
		store loads		x					
		store release		x					
		end of rail, semi-release		x					
		end of stroke, semi-release, still attached		x					
		transition loads		x					
		acoustic analyses					x		
		conversion of pressures into loads, one integrated model							
		diagnostic testing		x					
		measuring propeller systems		x					
		testing under unsteady conditions (for pressures and flows)		x					
		unsteady pressures		x					
		turbulances		x					
		PSP for low speed wind tunnel testing, especially sensitive		x					
		PSP continuous load visualization		x					
		PIV for diagnostic testing		x					
		measuring duct behaviour		x					
		hinge moments measurement		x					
		TSP		x					
		PSP		x					
		PIV (vortex, interferences, high speed)		x					
		advanced measurement techniques (TSP, acoustics, PIV, PSP)		x					
		model deformation measurement, model deflection		x					
		characterization of the aeordynamic limit of the fligth domain		x					
		accuracy for good equilibrium drag and pitching		x					
		use of CFD for correction		x					
		dumping derivatives		x					
		increase understanding within a transsonic design					x		
		reduction of the part of data correction in order to reduce overall uncertainty		x					
		integration of hinge moment measurements in other tests, synergy when using PSP		x			x		
		increasing the number of tests per run		x			x		
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping		x					
		"cultural" differences in between R&D, institutes and industry, maintain partnership		x					
	x	wireless data acquisition					x		
		remote control surfaces in order to change configurations					x		
		advances in data capture		x					
		integration of multiple experiments / measurements in a single run		x			x		

Table 30 consolidated answers of a manufacturer of aerosystems

aerosystems

layers of the roadmap ↓	Relevance	time in years →	short term (1 2 3)	medium term (5 7 9)	long term (>9)
drivers (no. 1)	x	costs	x		
		reduction of lead time	x		
		high quality results	x		
		new wind tunnel strategies (new corrections, special tests)	x		
		tool development for testing tools	x		
		CFD tool development	x		
		time constraints	x		
	x	time efficient optimization of configuration within wind tunnel test campaign	x		
	x	aerodynamic missile development (small aspect ratio configurations)	x		
	x	high angle of attack aerodynamics	x		
	x	development of a reliable aerodynamic model for simulation purposes	x		
requirements and needs (no. 2)		productivity @ blow-down-wind tunnels	x		
		cost control (reduction)	x		
		miniaturization (MEMS, balance crossings, telemetry)	x		
		data acquisition	x		
		high fidelity of data capture	x		
		accuracy of systems	x		
		measurement of forces and moments	x		
		measurement of pressure distributions	x		
		miniaturization of load models	x		
	x	time and cost efficient measurement of a complete aerodynamic data set	x		
		measurement of aerokinetic heating	x		
		elimination / reduction of oscillations due to test setup	x	x	x
	x	determination of influence of test set-up (sting, wind tunnel walls,...) on aero-data ==> Windtunnel / free fligh	x		
	x	Improvement of on-line data evaluation (integration of customer's and Windtunnel evaluation software)			
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)	x		
		static load	x		
		surface loads	x		
		strain-gauge measurements	x		
		store loads configurations measurements, UAV sector		x	
		store loads		x	
		store release		x	
		end of rail, semi-release		x	
		end of stroke, semi-release, still attached		x	
		full flutter expansion	x	x	
		understand undesired flight behaviour	x		
		rotary testing	x		
		rotary derivatives	x		
		measuring propeller systems, UAV sector		x	
		testing under unsteady conditions (for pressures and flows)	x		
		unsteady pressures	x		
		turbulences	x		
		measuring duct behaviour	x		
		hinge moments measurement	x		
		measurement of pressure distribution (interesting if direct force measurements are not possible)	x		
	x	(quasi -) static testing within angle of attack range 0°-60° (angle of attack polars at constant roll attitude)	x		
	x	measurement of roll attitude polars at constant angle of attack	x		
	x	measurement of dynamic data due to roll rate (oscillations)	x		
	x	measurement of dynamic data due to pitch / yaw rate	x		
	x	analysis of separation processes (removal of casings, emergency mechanism of self destruction of missiles)	x	x	
challenges (no. 4)		effects of aeroelastic in-flight deformations on aerodynamic data		x	
		model deformation measurement, model deflection			
		wireless data acquisition		x	
		harmonizing both methods, CFD and wind tunnel testing	x	x	x
	x	a levitating model to eliminate need for sting correction			x
		Derivation of "real flight zero-lift drag" from windtunnel-measured data	x		
		knowledge retention at WT in case of retirement of experienced personnel	x		
		possibility to change the intensity of turbulances in a single wind tunnel facility		x	
	x	tests with angle of attack from 0°-90° with only one single support	x		
	x	determination of influence of the jet exhaust on aerodynamic data (control efficiency, manoeuverability)	x		
		Effects of lateral jet exhaust on aerodynamic data (loads and pressure distribution)			

Table 31 consolidated answers of a research association

research association

layers of the roadmap ↓	Relevance	time in years →	short term 1	2	3	medium term 5	7	9	long term >9
drivers (no. 1)	x	costs		x					
	x	high quality results		x			x		x
	x	differential technologies (unconventional)		x			x		x
		new wind tunnel strategies (new corrections, special tests)		x			x		x
		pure R&D		x			x		x
		tool development for testing tools		x			x		x
		CFD tool development (validation)		x			x		x
		unconventional configurations					x		x
requirements and needs (no. 2)		cost control (reduction)		x					
		flexibility		x					
		remotely controlled moveables		x			x		
	x	acoustic testing: improvements in open test section, data handling, lead time)		x			x		
		TSP		x					
		PSP		x					
		PIV (vortex, interferences, high speed)		x					
		advanced measurement techniques (TSP, acoustics, PIV, PSP)					x		
		miniaturization (MEMS, balance crossings, telemetry)		x			x		
	x	acoustics (closed test sections, corrected aerodynamics)		x			x		
		state-of-the-art data acquisition		x			x		x
		high fidelity of data capture		x			x		x
		accuracy of systems		x			x		x
		measurement of forces and moments		x			x		x
		measurement of pressures		x			x		x
		dynamic derivatives		x			x		
		manoeuver simulation					x		x
		miniaturization of flow control devices					x		
		3D-PIV		x					
	x	testing for laminar flow conditions		x			x		x
		monitoring of aeroelastic deformations		x			x		x
	x	motorised testing (future engine: open rotor, propelled VHBR, noise contraints)		x			x		
		large data storage, handling, post processing (e.g. acoustics)		x					
		full flutter expansion					x		x
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)		x			x		x
		static load		x					
		surface loads		x					
		strain-gauge measurements		x					
		consulting concerning model design		x					
	x	turn-key system for PIV		x					
	x	acoustic analyses		x			x		x
		full flutter expansion					x		x
		diagnostic testing (3D-PIV)					x		
		understand undesired flight behaviour		x			x		
		rotary testing, low cost (rotors)		x			x		
		dynamic derivatives		x			x		
		powered mode testing		x					
		measuring propeller systems		x					
		testing under unsteady conditions (for pressures and forces)		x			x		x
	x	PSP for low speed wind tunnel testing, especially sensitive		x					
		measuring duct behaviour (aerodynamics & acoustics)		x					
		hinge moments measurement					x		
		simulation of docking (separation) manoeuvers					x		x
		accurate force measurements		x					
		measurement of laminar / turbulent flow structure		x					
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping		x					
		"cultural" differences in between R&D, institutes and industry		x			x		x
		finances		x			x		x
		PIV for high speed wind tunnel testing					x		
		illumination for PSP		x			x		
		illumination for PIV		x			x		
		wireless data acquisition					x		x
		self-trimming models					x		x
	x	harmonizing both methods, CFD and wind tunnel testing					x		x
		remote control surfaces in order to change configurations					x		x
	x	active laminar flow control					x		
		full flutter expansion					x		x

Table 32 consolidated answers of an aerospace company

aerospace company

layers of the roadmap ↓	Relevance	time in years →	short term (1 2 3)	medium term (5 7 9)	long term (>9)
drivers (no. 1)	x	A/C development (conventional)	x	x	x
		validation of mission performance	x	x	x
		accreditation as an aerial vehicle, certification concerning flight safety	x	x	x
requirements and needs (no. 2)	x	productivity concerning provided service	x	x	x
		cost control (reduction)	x	x	x
		flexibility	x	x	x
		remotely controlled moveables; connection to model equipment and control during tests	x	x	x
	x	flexibility of wind tunnel working time	x	x	x
		PSP	x	x	x
		PIV (vortex, interferences, high speed)	x	x	x
		advanced measurement techniques (TSP, acoustics, PIV, PSP)	x	x	x
		miniaturization (telemetry, sensors)	x	x	x
		data acquisition	x	x	x
		cost reduction	x	x	x
		cost structure of measuring methods	x	x	x
		CFD tool development, validation of numerical data	x	x	x
	x	qualified staff, dedicated to support during whole testing time	x	x	x
	x	open access to previous data (correction purpose; important for today's understanding)	x	x	x
	x	repeatability of quality of flow due to relational testing behaviour	x	x	x
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)	x	x	x
		static load	x	x	x
		surface loads	x	x	x
		strain-gauge measurements	x	x	x
		model design	x	x	x
	x	turn-key system for PIV, in general for optical flow field measurments	x	x	x
		store loads configurations measurements	x	x	x
		store loads	x	x	x
		store release	x	x	x
		end of rail, semi-release	x	x	x
		end of stroke, semi-release, still attached	x	x	x
		transition loads	x	x	x
		acoustic analyses	x	x	x
		drag pitching moments	x	x	x
		full flutter expansion	x	x	x
		conversion of pressures into loads, one integrated model, congruence of results between PSP and load data	x	x	x
		diagnostic testing	x	x	x
		understand undesired flight behaviour	x	x	x
		twin sting testing	x	x	x
		rotary testing	x	x	x
		rotary derivatives	x	x	x
		powered model testing	x	x	x
		measuring propeller systems	x	x	x
		testing under unsteady conditions (for pressures and flows)	x	x	x
		unsteady pressures	x	x	x
		turbulances	x	x	x
	x	PSP for low speed wind tunnel testing, especially sensitive	x	x	x
		PSP continuous load visualization	x	x	x
		PIV for diagnostic testing	x	x	x
		measuring duct behaviour	x	x	x
		hinge moments measurement	x	x	x
		measurement of forces and moments	x	x	x
		measurement of pressures	x	x	x
		competent support by a single person during wind tunnel tests	x	x	x
		optical measurement techniques	x	x	x
	x	instationary PSP	x	x	x
	x	turn-key system for transition from turbulent to laminar flow (e.g. via IR)	x	x	x
	x	preliminary financing of test periods (e.g. until end of year)	x	x	x
		consulting of customers with best practice approach to handle large volume of data	x	x	x
		switch from service provider to risk sharing partner	x	x	x
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping	x	x	x
	x	"cultural" differences in between R&D, institutes and industry	x	x	x
		PIV for high speed wind tunnel testing	x	x	x
		non-intrusive techniques	x	x	x
		wireless data acquisition (telemetry, for high instrumentation, for rotating set-ups)		x	x
		advances in data capture	x	x	x
	x	accumulation of more and more measurements in a single test loop, parallel measurements	x	x	x
	x	turn-key systems	x	x	x
		development of measurement techniques @ supplier similar to previously @ industry	x	x	x

6.4 Questionnaire

The questionnaire below was used in the first interview as a basic structure for discussion both, for wind tunnel product roadmapping and innovation system analysis:

Wind tunnel test needs devided by speed relative to each other

- Which kind of information is required that today can be provided by wind tunnel tests?
- How much test capacity is needed and how is it distributed between different wind tunnel technologies? (low speed, high speed, transsonic, supersonic, hypersonic)
- How will this partitioning change, e.g. by innovations in the aeronautic sector?
- And how does the partitioning change through competing technologies (i.e. simulation)?
- Do you see upcoming changes of the importance of existing propulsion concepts in relation to each other?
- Can you foresee the dissappearance of propulsion concepts leading to a change?
- Are new propulsion concepts provoking a shift in the kind of information needed? (propeller drive, jet propulsion, scramjet)
- What are now the technologies used in order to get the required information / test data / data sets?
- How is the split between them if they can be used alternatively?
- What is your impression, how the use of these technologies will change in future?

Services of the wind tunnel facility

- Which kind of services concerning wind tunnel testing are required? (construction of a model of the aircraft, simulation, measuring necessary data, interpretation of data)
- Which of them do you order internally, which of them are outsourced?
- Will you outsource additional services in future?
- Which ones?
- Will there be a change in the services needed? (new services, obsolete services)
- How can these services be provided, by an internal infrastructure or by an external provider? (changes along the value chain)

Identification of most interesting technologies named in the technology roadmap

- What are the most interesting aspects of the technology roadmap from your perspective?

Regional development of wind tunnel test capacities

- Can you please quantify the need for information from wind tunnel tests in different regions? (Europe, North America, China, Russia, others: Brasil, India, Japan, Turkey)
- Do you know that regions need onyl certain information from these tests (e.g. low speed)?
- How will this need for tests of the regions change?
- Who will start to establish new test facilities and where?
- How will this affect the hitherto built test facilities? (Less no. of ordered tests)
- Can you tell us, when you do expect the changes coming up?

Impact of regulation and standardization (i.e. in aviation) on wind tunnel testing

- Can you please tell us some examples where regulation influences the wind tunnel testing? (technology, frequency of use, development, maybe through regulations and standardization in aeronautics, noise emission, energetic restrictions, self obligations)
- What are the existing regulations?
- Where do you see regulations emerging and which are regulations you expect to be of future relevance?
- How would these influence your work?

Co-operation in wind tunnel testing with research institutions and technology providers

- Can you please describe your co-operation with research institutions (e.g. universities)?
- How important do you judge such cooperations for progress in wind tunnel technology?
- Is such co-operation publicly supported?
- Can you name examples for incentives?
- Do you have a certain way to realize co-operative research projects with e.g. universities? (personal exchange, PhD-theses, internships)
- How do you see research co-operations changing, in their impact on wind tunnel technology and their importance for progress, in the way they are realized?

Changes in recruitment needs for running wind tunnels

- What kind of educational background do you need for employees working with wind tunnels?
- Will this job profil shift in future, e.g. towards simulation?
- Do you need adaptations in the educational system (topics taught at university) to reflect this expectation and adapt to future needs?
- Where do you recruit your personal, what are your most important sources for new employees?

Technology transfer from wind tunnel testing to the public sector

- Can you please describe how technology transfer happens today from your company towards the public sector?
- Via research cooperations?
- Which changes do you expect?

Based on first experiences, the basic set of questions was further developed and elaborated to a more straightforward format of interview (Figure 46). This format makes it possible to use the expertise of wind tunnel users more or less directly for the development of the wind tunnel product roadmap.

instruction:

1. please check the list of topics if it is correct (for elimination please use the "strike out"-function)
2. please complete the list if topics are missing
3. please verify the position of each topic concerning the layers (i.e. drivers, requirements, products, challenges); please indicate changes by number (1-4) in front of the topic
4. please mark the position of each topic on the time axis (short term-mid term-long term) with an **X** concerning its relevance

layers of the roadmap ↓	relevance	time in years →	short term 1	2	3	medium term 5	7	9	long term >9
drivers (no. 1)		A/C development (conventional)							
		costs							
		productivity							
		reduction of lead time							
		high quality results							
		differential technologies (unconventional)							
		new wind tunnel strategies (new corrections, special tests)							
		pure R&D							
		tool development for testing tools							
		CFD tool development							
		motorised testing (future engine: open rotor, propelled VHBR, noise contraints)							
		time constraints							
requirements and needs (no. 2)		productivity							
		cost control (reduction)							
		flexibility							
		remotely controlled moveables (mainly low speed)							
		flexibility of wind tunnel working time							
		acoustic testing: improvements in open test section, data handling, lead time)							
		TSP							
		PSP							
		PIV (vortex, interferences, high speed)							
		advanced measurement techniques (TSP, acoustics, PIV, PSP)							
		miniaturization (MEMS, balance crossings, telemetry)							
		acoustics (closed test sections, corrected aerodynamics)							
		data acquisition							
		high fidelity of data capture							
		accuracy of systems							
		measurement of forces and moments							
		measurement of pressures							
		cost reduction							
		cost structure of measuring methods							
		miniaturization of load models							
		certification concerning flight safety							
products and services (no. 3)		wind tunnels have to be partners (knowledge, experiences, data validation, data corrections)							
		static load							
		surface loads							
		strain-gauge measurements							
		model design							
		turn-key system for PIV							
		store loads configurations measurements							
		store loads							
		store release							
		end of rail, semi-release							
		end of stroke, semi-release, still attached							
		transition loads							
		acoustic analyses							
		drag pitching moments							
		full flutter expansion							
		conversion of pressures into loads, one integrated model							
		diagnostic testing							
		understand undesired flight behaviour							
		twin sting testing, low cost							
		rotary testing, low cost							
		rotary derivatives							
		powered mode testing							
		measuring propeller systems							
		testing under unsteady conditions (for pressures and flows)							
		unsteady pressures							
		turbulances							
		PSP for low speed wind tunnel testing, especially sensitive							
		PSP continuous load visualization							
		PIV for diagnostic testing							
		measuring duct behaviour							
		hinge moments measurement							
challenges (no. 4)		deformations (High, low speed), low speed gap - overlapping							
		"cultural" differences in between R&D, institutes and industry							
		finances							
		relation to CFD							
		large data storage, handling, post processing (e.g. acoustics)							
		model deformation measurement, model deflection							
		PIV for high speed wind tunnel testing							
		illumination for PSP							
		illumination for PIV							
		non-intrusive techniques							
		wireless data acquisition							
		self-trimming models							
		harmonizing both methods, CFD and wind tunnel testing							
		remote control surfaces in order to change configurations							
		advances in data capture							
		a levitating model to eliminate need for sting correction							

Figure 46 initial form used in telephone interview

6.5 Electronic supplements

All documents provided along the project are available as electronic supplements and they are sent the DNW e.g. for further devopments and updating.

Electronic supplements include:

- project report
- roadmaps
- software-based tool for analysing the wind tunnel innovation system

IMPRINT

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The Fraunhofer Institute for Systems and Innovation Research ISI analyzes the framework conditions for innovations. We explore the short- and long-term developments of innovation processes and the societal impacts of new technologies and services. On this basis, we provide our clients from industry, politics and science with recommendations and perspectives for key decisions. Our expertise lies in a broad scientific competence as well as an interdisciplinary and systemic research approach.

With 190 staff members from science, technology and infrastructure, we are a highly motivated team, whose scientific expertise and systemic research approach fulfills the diverse requirements of our clients. The increase of our annual budget to almost 20 million euros in 350 projects documents this successful work.