# EDUCATIONAL APPROACHES TO EXPERIMENTAL AERODYNAMICS OF OPEN-FLOW SUBSONIC WIND TUNNELS

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***Abstract:*** *The educational approach to aerodynamics through open-flow wind tunnels (Eiffel type) represents one of the most effective methods of transforming abstract theoretical concepts into tactile and visual experiences under conditions of quantifiable resource allocations.*

*The paper presents a curricular management regarding the efficient use of open-flow subsonic wind tunnels starting from establishing the requirements for the acquisition of a wind tunnel to identifying the types of teaching and research activities correlated with levels of equipment with data acquisition elements. The curricular management analysis is instrumented using the AHP method for 3 experimental facilities (wind tunnels) used in the university educational area.*

***Key words:*** *tunnel wind, Analytical Hierarchy Process, data acquisition, curricular management*

**Acronyms**

| | | | |
|---|---|---|---|
| *M* | *Nr. Mach* | *AHP* | *Analytic Hierarchy Process* |
| *L* | *lungimea* | $F_D$ | *Drag force* |
| *CAGR* | *Compound Annual Growth Rate* | *DAQ* | *Data Acquisition* |
| *CFD* | *Computational Fluid Dynamics* | $L_T$ | *Total lenght* |
| $L_{CE}$ | *Experimental chamber lenght* | *V* | *Air speed* |

## 1. INTRODUCTION

### *1.1. Global technical and economic aspects*

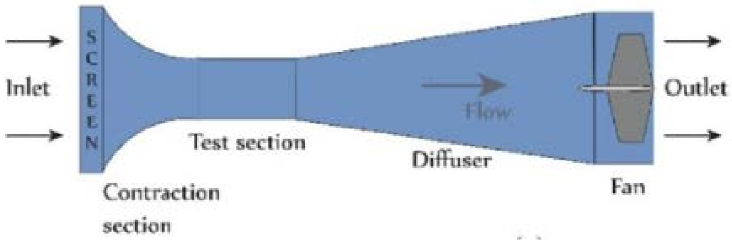
Conceptually and practically, a wind tunnel is an experimental aerodynamics facility that provides a regulated volume of air to examine the relationship between airflow and experimental models (aerodynamic forces, surface pressures, and velocity fields), under conditions of precise control of airflow speed, temperature, and turbulence. Wind tunnels are used for testing designs to validate relevant numerically simulated performance prior to production to validate design decisions (reduction of drag, energy efficiency) in the aerospace, automotive, and renewable energy sectors [1].

According to market analyses [2], the continuous need to optimize energy efficiency determines an increase in the use of wind tunnels across the range of types and sizes, the market size in 2025 of 2.34 billion USD, in 2026 2.47 billion USD with a forecast of 3.18 billion USD in 2034 with an annual growth rate (CAGR) in the period 2026-2032 of 3.22%.

### *1.2. Objectives of the work*

The objectives are focused on an analysis of the curricular management applied to experimental aerodynamics equipment, in particular open-flow subsonic wind tunnels with different levels of equipment with elements necessary for data acquisition.

A comprehensive approach encompasses the stages of the wind tunnel life cycle, such as: the stage with the acquisition requirements (specifications), the test-calibration stage (test and validation plan), the stage of experimental didactic and research activities, maintenance activities (predictive and corrective).

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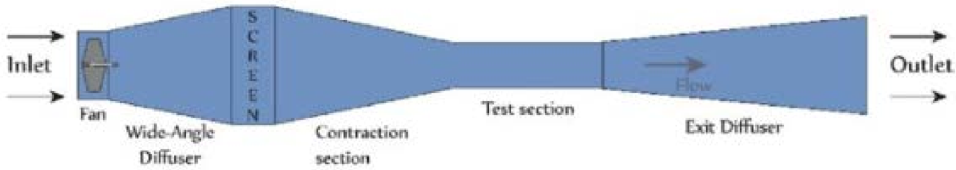


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**FIG. 1** Typology of open-flow subsonic wind tunnels, a. with suction, b. with discharge, [3]

According to references [3-6], the typology of open-flow subsonic wind tunnels includes a classification regarding the fan position (with suction, with discharge), see FIG.1, the type of experimental chamber (open or closed), see FIG. 2, a function of Mach No. (incompressible subsonic M<0.3, compressible subsonic 0.3<M<0.7), a function of the level of equipment of the data sensors (analog, digital), a function of the relevant use (for airfoils, for boundary layer).

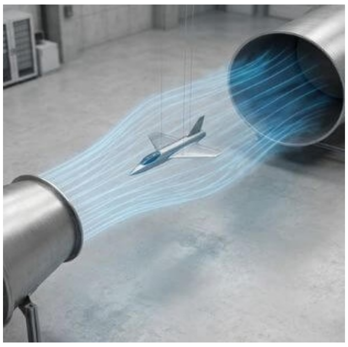

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**FIG.2** Typology of experimental chambers of open-flow subsonic wind tunnels,
a. closed chamber , b. open chamber

The criterial classification of wind tunnels can also be focused on the dimensions of the experimental chamber (for reduced-scale models, for real models), see FIG. 3 [7, 8].


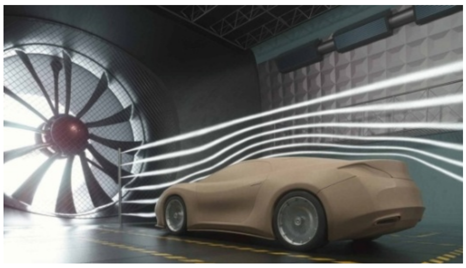

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**FIG. 3** Experimental chamber typology a.for reduced scale model [7], for real model [8]

## 2. THEORETICAL ASPECTS

### *2.1. Geometric elements and operating performances of an open-flow subsonic wind tunnel*

*a.Geometrical parameters.* According to the scientific literature [9], it is recommended to optimize the geometry of the component elements depending on the total length of the wind tunnel (L), see FIG. 4.

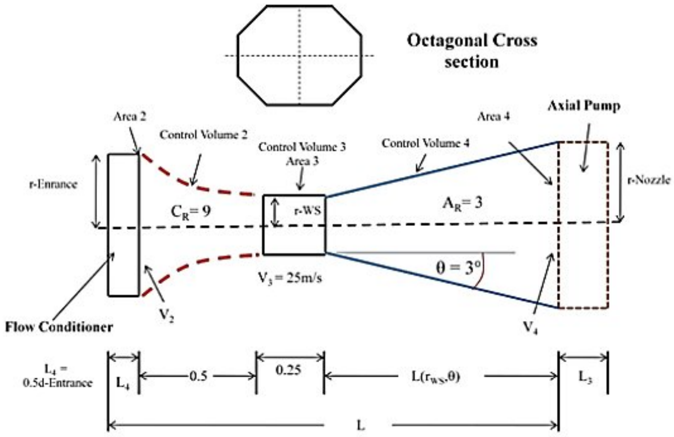


**FIG. 4** Geometry of an open-flow subsonic wind tunnel, [9]

The aspects of geometric optimization are dependent on obtaining a maximum velocity in the experimental vein as well as on the quality of the air flow (turbulence values) in the recommended speed range under the conditions of using a selected air generator (electric fan).

*b.Operating performance.* Operating performance directly defines its ability to generate a stable, homogeneous and controllable airflow in the test chamber with minimal energy consumption, performances that are directly influenced by the ambient environment and the geometry of the constructive elements [10-13].

The most relevant performances are translated into the following indicators: the tunnel efficiency coefficient (energy efficiency between 0.4 and 1.2) see equation 1, the quality and guarantee of the airflow (turbulence intensity below 1%), the uniformity of the velocity profile (±1%) and the pressure gradient.

$$\eta_w = \frac{\rho \cdot A \cdot v^3}{2 \cdot P_f} \tag{1}$$

$$T_u = \frac{v}{U_\infty} \tag{2}$$

*where*

| | |
|---|---|
| *$\rho$ -air flow density* | *A-experimental chamber section area* |
| *$v$-air flow medium speed* | *$P_f$-fan power* |
| *$T_u$-air turbulence intensity* | *$U_\infty$-undisturbed air flow speed* |

The dependence of performance on component geometry is determined by the values of the contraction ratio (ratio between the area of the stilling chamber and the area of the experimental chamber between 4:1 and 9:1), see equation 3, the length of the experimental chamber, aerodynamic load losses (friction and shape losses), the efficiency of the diffuser and the performance of the electric fan.

$$CR = \frac{A_1}{A_{exp}} \tag{3}$$

*where CR- contraction ratio*

*$A_1$- area of the air flow equalization (stillation) chamber*

*$A_{exp}$- area of the experimental chamber*

The performance limitations of the open-flow subsonic wind tunnel refer to both the sensitivity to the atmospheric environment in the laboratory (atmospheric pressure, changes in laboratory space boundaries / doors / windows) and to the noise and vibrations of the electric fan, which can induce noise and vibrations with influences on the accuracy of the operation of the load cell sensors of the aerodynamic balance.

*c.Data acquisition.* Data acquisition (DAQ) systems used in experimental aerodynamics as well as open-flow subsonic wind tunnel systems have the role of taking physical signals from sensors (pressures, forces, temperatures), conditioning them, digitizing them and transmitting them to a computer for analysis and post-processing.

According to the specialized literature [10, 14, 15, 16] data acquisition systems are classified as follows: depending on the architecture and level of integration (PC-based industrial systems, compact stand-alone DAQ systems, low-cost microcontroller/educational systems); depending on the type of signal processed (analog/traditional DAQ systems, bus-based digital DAQ systems); depending on the signal sampling mode (with multiplexed/successive sampling, with simultaneous sampling); depending on the bandwidth and dynamics of the data flow (static/quasi-static acquisition systems, dynamic/high frequency acquisition systems).

***2.2. Pedagogical and research approaches to the use of open-flow subsonic wind tunnels***

*a. Design and/or acquisition requirements.* The design and/or acquisition of a subsonic open-flow wind tunnel involves a series of requirements according to the level of teaching and research activities in the low-cost concept. Here are some types of relevant requirements: requirements regarding the general architecture and dimensional values (sizes of the inlet sections, contraction section, experimental chamber, diffuser), technical and performance requirements (maximum speed, Reynolds No. and quality of the air flow, materials used), requirements regarding the wind generator (electric fan flow, type of control), requirements regarding the data acquisition system (type of sensors based on pressure differences and electrical/voltage signals), requirements regarding the operational aspects and maintenance of the wind tunnel.

*b.Teaching and research activities*

The main teaching and methodological approaches through laboratory applications can be: experiments focused on visualizing the aerodynamic flow around test models through visualization techniques (FIG. 5); quantitative experiments and measurements of forces and moments using the aerodynamic balance; experiments applied to error analysis and experimental validation (preliminary CFD simulation versus experimental measurements).

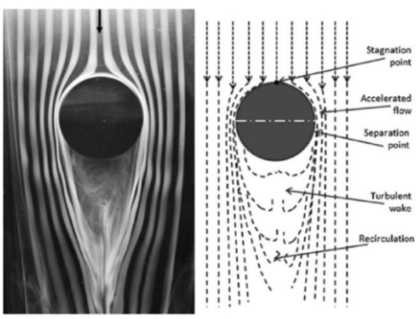


**FIG. 5** Smoke visualization techniques, [18]

**FIG. 6** Quantitative experiments on forces and moments, [19]

## 3. MANAGEMENT ANALYSES ON CURRICULAR MANAGEMENT

3.1. Objective of the analysis

The objective of the analysis is to optimally highlight the experimental facilities (wind tunnels) regarding the didactic objectives and the skills that the students must acquire.

The objective is focused on an AHP (Analytic Hierarchy Process) analysis regarding the curriculum management, applied to 3 experimental aerodynamics equipment, in particular open-flow subsonic wind tunnels with different geometries and equipment levels regarding data acquisition. The constructive and performance data are presented in Table 1.

Table 1. Geometrical and performances

| Wind tunnel type | Geometrical | Performances | Senzors |
|---|---|---|---|
| Tunell custom | $L_T$=1610 mm<br>$L_{CE}$=430 mm | V=15 m/s | Tub Pitot, analogic sensor |
| Tunell SES115 | $L_T$=3000 mm<br>$L_{CE}$=750 mm | V=27 m/s | Aerodynamic balances<br>2 forces/1 moment |
| Tunell ELECO | $L_T$=4900 mm<br>$L_{CE}$=750 mm | V=40 m/s | Aerodynamic balances<br>3 forces 3 moments |

Figure 7 shows the three wind tunnels of the aerodynamics and flight mechanics laboratory.


**FIG. 7** Wind tunnel, a Tunell custom (WT1), b Tunell SES 115 (WT2), c Tunell ELECO (WT3)

3.2.AHP analysis (Analytic Hierarchy Process)

*a.Defining the hierarchical structure of the problem.* According to [22, 23], the diagram in Figure 8 highlights: the objective, the criteria and the alternatives analyzed (wind tunnels considered). The criteria considered are: didactic and pedagogical value (C1); technical and research complexity (C2); sustainability and operational management (C3).

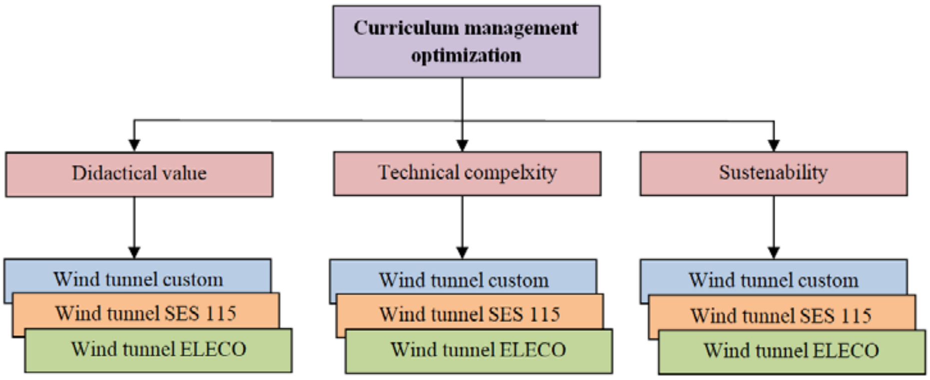


**FIG. 8** Hierarchical structure of AHP analysis

*b. Comparison matrix for criteria.* The Saaty scale (1-9) is applied to establish the relative importance of the criteria from the point of view of curriculum management [20], in Table 2 we have the comparison matrix.

Table 2. Weight of criteria

| Criterion | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|
| $C_1$ | 1 | 2 | 3 |
| $C_2$ | 0,5 | 1 | 2 |
| $C_3$ | 0,33 | 0,5 | 1 |
| | 1,83 | 3,5 | 6,00 |

C1 is considered moderately more important than C3 (grade 3) because in a curricular management the main goal is student instruction. The calculation algorithm (through normalization) generates the weight vector (W), as follows: WC1=0.54; WC2=0.297; WC3=0.163.

*c.Evaluation of alternatives in relation to the criteria*

-in relation to C1 (didactic value): WT1_C1=0.6; WT2_C1=0.3; WT3_C1=0.1.

Didactically, the custom wind tunnel (WT1) and SES 115 (WT2) are superior to the complex one (ELECO/WT3) because they allow the rapid running of laboratories with large groups of students, see table 3.

Table 3. Didactic value

| Alternative | WT1 | WT2 | WT3 |
|---|---|---|---|
| WT1 | 1,00 | 2,00 | 6,00 |
| WT2 | 0,50 | 1,00 | 3,00 |
| WT3 | 0,167 | 0,33 | 1 |

-relative to C2 (technical complexity): WT1_C2=0.1; WT2_C2=0.3; WT3_C2=0.6.

Here the advanced wind tunnel (ELECO/WT3) clearly dominates due to its data acquisition capabilities and experimental flexibility for bachelor's and master's theses, see table 4.

Table 4. Technical complexity

| Alternative | WT1 | WT2 | WT3 |
|---|---|---|---|
| WT1 | 1,00 | 0,33 | 0,167 |
| WT2 | 3,00 | 1,00 | 0,50 |
| WT3 | 6,00 | 2,00 | 1,00 |

-relative to C3 (sustainability): WT1_C3=0.7; WT2_C3=0.2; WT3_C3=0.1.

The small custom wind tunnel (WT1) consumes the least and is set up in 15 minutes, while the start-up and calibration of the WT3 gun requires specialized technical personnel and higher costs, see table 5.

Table 5. Sustenability

| Alternative | WT1 | WT2 | WT3 |
|---|---|---|---|
| WT1 | 1,00 | 3,50 | 7,00 |
| WT2 | 0,286 | 1,00 | 2,00 |
| WT3 | 0,143 | 0,50 | 1,00 |

*d. Calculation of the overall score.* The value of curriculum management is obtained from the product of the weights of the criteria with the performances of the alternatives considered (selected wind tunnels):

The synthesis matrix is:

$$\begin{pmatrix} 0{,}6 & 0{,}1 & 0{,}7 \\ 0{,}3 & 0{,}3 & 0{,}2 \\ 0{,}1 & 0{,}6 & 0{,}1 \end{pmatrix} \times \begin{pmatrix} 0{,}54 \\ 0{,}297 \\ 0{,}163 \end{pmatrix} = \begin{pmatrix} 0{,}467 \\ 0{,}283 \\ 0{,}249 \end{pmatrix} \quad (4)$$

The final rank is recorded in table 6.

Table6. Final rank

| Alternative | WT1 | WT2 | WT3 | Global score |
|---|---|---|---|---|
| WT1 | 0,324 | 0,030 | 0,114 | 46,7% |
| WT2 | 0,262 | 0,089 | 0,032 | 28,3% |
| WT3 | 0,054 | 0,178 | 0,016 | 24,8% |

-custom wind tunnel score (WT1)=0.467;

-SES115 wind tunnel score (WT2)=0.283;

-ELECO research wind tunnel score (WT3)=0.248.

Consistency check (validation check) is 0.77% (≤ 10%)

*e. Decisional interpretation.*Although from an academic/scientific point of view there is a tendency to prioritize the most complex infrastructure (WT3), the AHP analysis demonstrates that for global curricular objectives (serving large volumes of students), although it has the lowest degree of complexity, the custom wind tunnel (WT1) is the critical resource that must be financed and programmed with priority.

The WT3 tunnel will be used strictly curricularly in niche disciplines (master/doctorate), thus optimizing energy costs and wear and tear of high-precision equipment.

## CONCLUSIONS

The article presented a direct approach to a decision-making evaluation based on the AHP method [20-23]. The use of decision-making methods based on the AHP method can relevantly instrument educational curricular scenarios regarding the efficient use of didactic logistical resources to obtain results in the training process in the aeronautical field.

However, for relevant results of these types of AHP evaluations, it is necessary to use a large number of criteria and options to generate results with relevant degrees of confidence, results that can be selected in the university didactic process. In the future, the options (experimental facilities) for AHP analysis must be selected multidisciplinary and transdisciplinary by setting comprehensive uses.

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