Founded in 2002, STC is a pioneering product development company headquartered in Alpignano (Turin – Italy). With a steadfast commitment to research and innovation, STC operates at the forefront of the Product Development & Optimization field, with strong focus on Green Economy and Circular Economy sectors, shaping sustainable solutions for better products.

FUNCTIONAL ANALYSIS AND DECISION MATRIX: A DATA-DRIVEN APPROACH TO NEXT-GENERATION INTERNAL COMBUSTION ENGINE DESIGN

STC Company's vision of business development, considering current trends

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1. Introduction

The internal combustion engine (ICE), once the undisputed workhorse of modern industry and mobility, is under increasing scrutiny. The tightening grip of global emissions regulations - Euro 7 in the European Union, Tier 4 in the United States and analogous standards in Asia - compels manufacturers to innovate under intense constraints. Contrary to the perception that ICE development is plateauing, these pressures are catalysing a renaissance in combustion science, materials engineering and control systems design.

This resurgence, however, must be managed methodically. Gone are the days of trial-and-error or design-by-experience. The complexity of integrating multi-physics phenomena, emissions compliance and customer expectations necessitates a rigorous, data-driven framework for decision-making. In this context, the convergence of **Functional Analysis (FA)** and the **Decision Matrix (DM)** emerges as a powerful paradigm allowing engineers to deconstruct complexity and rationalize trade-offs in a structured and defensible manner.

This paper provides a comprehensive exposition of these two methodologies, illustrating how their application can revolutionize the development of the next generation of internal combustion engines - engines that are not only cleaner, but also more efficient, robust and economically viable.

2. Functional Analysis: Structuring the Engine’s Purpose

2.1 Principles of Functional Decomposition

At its essence, Functional Analysis is the art and science of defining what a system must do abstracted from the details of how it will do it. This methodology, rooted in systems engineering and widely adopted in aerospace, defence and complex product development, allows engineers to identify, rank and interrelate the functional requirements of a system.

In ICE design, the use of FA allows the transformation of vague, top-level requirements (e.g., “reduce CO_2 emissions”) into specific, actionable and measurable sub-functions (e.g., “minimize fuel enrichment during transient accelerations” or “optimize intake valve timing to reduce pumping losses”).

The process typically begins with the identification of:

- **Primary functions**, which directly fulfil the main purpose of the system. For an ICE, this might include energy conversion, exhaust gas expulsion and thermal regulation.
- **Secondary functions**, which support or enhance the primary objectives, such as diagnostics, noise suppression and friction reduction.

This hierarchical function breakdown is often visualized through Functional Block Diagrams (FBDs) or FAST (Function Analysis System Technique) diagrams, which expose interdependencies, redundancies and potential innovation opportunities.

2.2 Functional Domains in Modern ICE Design

Applying FA to a modern powertrain reveals several critical function domains, each representing a complex interplay of physical subsystems:

- **Combustion Management**: control of fuel-air mixture formation, ignition timing, turbulence intensity and heat release rate.
- **Thermal Energy Recovery**: implementation of exhaust gas recovery (e.g., turbocompounding, Rankine cycles), variable cooling strategies and smart thermostats.
- **Emission Control**: design and integration of aftertreatment systems (DPF, SCR, LNT), thermal management strategies for catalyst activation and exhaust flow modulation.

- **Fuel Adaptability**: capacity to operate efficiently on varied fuel blends (e.g., E85, B20, H_2-diesel mixtures), requiring adaptive combustion control algorithms and robust fuel system materials.
- **Durability and Lifecycle Management**: resistance to wear, thermal fatigue, oil degradation and the impact of exhaust recirculation on lubricant chemistry.

Each of these domains cascades into dozens of sub-functions, each carrying implications for hardware design, control architecture, material selection and ultimately cost and performance.

2.3 Functional Analysis in Practice: A Case Example

Consider the challenge of reducing cold-start emissions in a gasoline direct injection (GDI) engine. A traditional approach might involve richer fueling or early catalyst heating, but FA would frame the problem more broadly:

- Primary function: "Ensure rapid catalyst light-off."

- Secondary functions: "Optimize exhaust gas temperature post-combustion," "Reduce heat losses to cylinder walls, "Accelerate engine warm-up through dynamic coolant flow control"

By surfacing such detailed sub-functions, FA enables the exploration of non-obvious solutions such as applying variable valve timing to trap hot residual gases or utilizing electrically heated catalysts driven by regenerative braking energy.

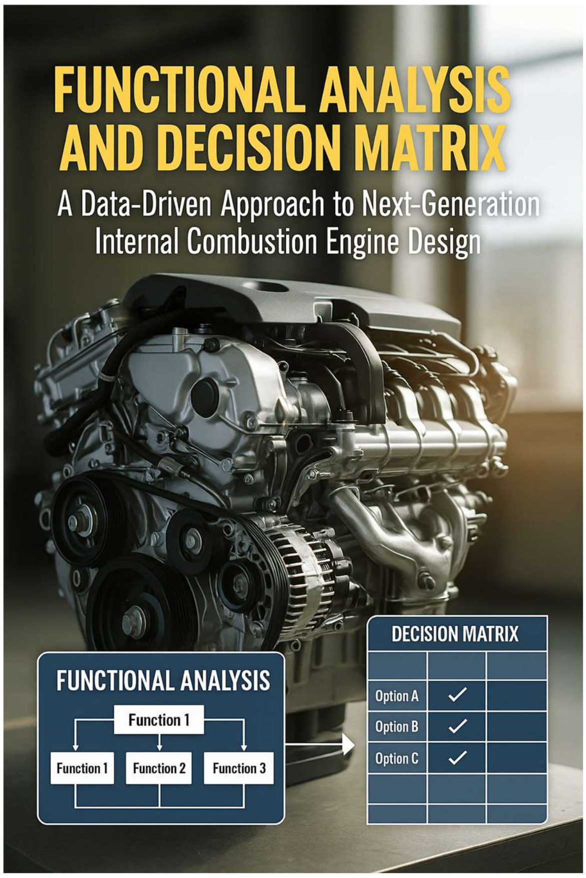
3. Decision Matrix: Managing Trade-offs through Quantitative Prioritization

3.1 The Complexity of Modern Engine Design Trade-offs

Internal combustion engines operate within an unforgiving landscape of compromises. Every design choice represents negotiation among multiple, often contradictory, performance indicators. An increase in exhaust gas recirculation (EGR) may lower NOx but increase particulate matter. Higher compression ratios improve thermal efficiency but increase the risk of knock. Turbocharging improves specific power but raises thermal stress and cost. It is no longer tenable to optimize any single metric in isolation.
Hence, the engineering team must make **multi-criteria decisions**, balancing:

- **Environmental criteria** (NOx, PM, CO_2, unburned hydrocarbons, …)
- **Performance metrics** (torque curve, power density, transient response, …)
- **Economic drivers** (total cost of ownership, warranty cost, manufacturing complexity, …)
- **Customer value propositions** (NVH comfort, fuel flexibility, longevity, …)

The Decision Matrix formalizes this negotiation.



3.2 Methodology: From Qualitative Insight to Quantitative Ranking

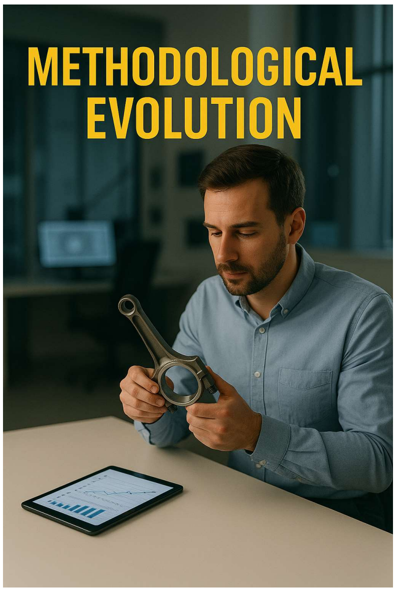
A robust Decision Matrix involves the following structured steps:

1. **Define the decision context**: engine application (passenger car, marine, off-highway), fuel type, target markets.
2. **Identify design alternatives**: for instance, variable geometry turbocharger vs twin-scroll turbo; closed-loop lambda control vs open-loop.
3. **Establish evaluation criteria**: derived from functional analysis and stakeholder objectives.
4. **Assign weights**: based on strategic importance, regulatory urgency or cost impact.
5. **Score alternatives**: using simulation results, test bench data or expert elicitation.
6. **Calculate weighted scores**: to generate a rationalized preference ranking.

For high-fidelity applications, the matrix can be extended to **multi-attribute utility theory (MAUT)** or **analytic hierarchy process (AHP)** models, which introduce pairwise comparisons and consistency checks.

3.3 Applied Scenario: Hydrogen-Ready Engine Architecture

Consider the development of a dual-fuel diesel-hydrogen engine for stationary power generation.



Design alternatives might include:

- High-pressure direct injection of hydrogen
- Port-fuel injection with pre-mixed lean combustion
- Dual-injection strategies with diesel pilot ignition

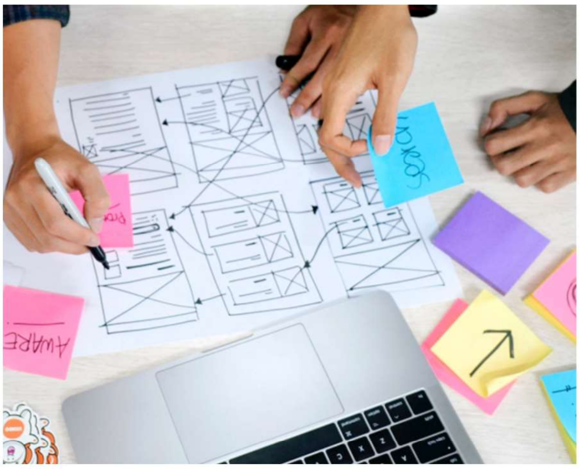
Evaluation criteria could include:

- Brake thermal efficiency
- NOx and ammonia slip
- System cost
- Combustion stability under variable load

The Decision Matrix could integrate outputs from combustion CFD models, ignition delay maps and cost models to derive a weighted ranking, balancing innovation with feasibility.

4. Synergistic Use of Functional Analysis and Decision Matrix

While Functional Analysis and the Decision Matrix are powerful independently, their true potential is realized when applied **in tandem**.



4.1 Iterative, Cross-Disciplinary Design Flow

In a modern ICE development workflow:

- FA is used early to define system needs, uncover latent requirements and drive innovation ideation.
- DM is employed at decision gates to down-select among competing architectures, control strategies or component suppliers.

Critically, the feedback loop between the two allows the design process to remain agile. As new performance data or regulations emerge, functions can be re-evaluated and trade-offs re-balanced.

4.2 Embedding the Framework in Digital Engineering Environments

State-of-the-art powertrain development increasingly leverages **model-based systems engineering (MBSE)** platforms. Here, Functional Analysis and Decision Matrices are embedded in digital twins, enabling real-time decision support. For example:

- Simulink/Stateflow can model control logic traceable to functional definitions.
- Digital mock-ups (e.g., in Siemens NX or Dassault Systèmes) can simulate the thermal or vibration implications of trade-offs evaluated in the DM.
- AI-based design space exploration tools, such as those in mode FRONTIER or HEEDS, automate multi-objective optimization guided by FA constraints and DM outputs.

5. Conclusion

The internal combustion engine may be in its twilight for certain sectors, but for many applications—heavy-duty transport, aviation, industrial power—its future remains deeply relevant. Meeting the dual imperatives of regulatory compliance and technical excellence demands more than mechanical refinement; it requires methodological evolution.

The combined application of **Functional Analysis** and **Decision Matrix** represents a mature, systematic response to this challenge. FA provides a rigorous vocabulary for describing and decomposing engine objectives. DM transforms engineering intuition into evidence-based decisions.

Together, these methodologies constitute not just a set of tools, but a new design ethos—one where complexity is mastered, trade-offs are transparent, and innovation is strategically guided. For engineering leaders navigating the next era of propulsion, mastering these techniques will be not optional but essential.