https://doi.org/10.1590/jatm.v16.1345
Preprint deposited on: Feb 05, 2024 [https://doi.org/10.1590/SciELOPreprints.8817]
ORIGINAL PAPER

A DFX Attribution Method Applied to Integrated Product Development within the Aerospace Domain

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ABSTRACT

The aerospace industry continually seeks to optimize product development processes to remain competitive. Design for Excellence (DFX) plays a crucial role in meeting customer expectations while aligning with organizational capabilities. However, the diversity of DFX technological areas and methods can make it challenging for companies to select the appropriate ones for each project. Successful DFX application, ensuring projects stay within scope, time, cost, and quality constraints without overburdening the development process, often depends on the engineering team's experience and the project phase. This work maps DFX technological areas to address the decision-making problem of selecting the most suitable ones for various projects. The objective is to evaluate, from the engineering team's perspective, whether a general approach can guide project managers in selecting key DFX areas, considering a typical aerospace organization's project portfolio and specific project phase characteristics. Starting with a literature review of DFX in aerospace, the research includes a survey along with senior product development engineers. Quantitative results are gathered using the Likert scale and analyzed through the analytic hierarchy process (AHP). The paper presents a method to guide the initial selection of DFX areas, aiding project managers and engineers in designing complex products.

Keywords: Design for excellence; Integrated product development; Product development processes; Analytical hierarchy process.

INTRODUCTION

The aerospace sector is currently experiencing substantial transformations, such as the satellite business is shifting from a period of expansion to a time of maturity (Perondi 2023). The exponential expansion and upheaval caused by the New Space era have fundamentally changed the space-based infrastructure, making it a vital necessity (Pessoa Filho 2021). Nevertheless, this swift progress has also sparked apprehensions over the sustainability of space and the need for enhanced global collaboration to tackle the pressing difficulties confronting our planet, often referred to as "Spaceship Earth" (Pessoa Filho 2021). Within this framework, the aerospace sector continually adjust its ecosystem, as elucidated in Luna-Andrade *et al.* (2021), to enhance its product development procedures and maintain competitiveness, with your contributions to Design for Excellence (DFX) assuming a pivotal role. The wide range of technological areas and procedures within DFX can pose a challenge for organizations in choosing the most suitable ones for each project, as success often depends on the specific environment. Therefore, it is necessary to conduct a thorough mapping of DFX technological areas to assist project managers in choosing the most appropriate ways for their aerospace organization's project portfolio and lifecycle stages.

Received: May 06 2024 | **Accepted:** Jul 26 2024
Peer Review History: Single Blind Peer Review.
Section editor: Alison Moraes

Integrated product development (IPD) is a collaborative approach that coordinates people, processes, and systems from the initial stages of product conception through to its final production to overcome the challenges faced by complex product development processes (PDPs). It is intended to facilitate concurrent engineering, where tasks are performed in parallel, reducing the product development costs and improving quality (Ulrich and Eppinger 2015). DFX is an IPD framework aimed at defining clear product requirements, balancing stakeholder expectations, and considering various factors impacted by the evolving customer demands on complex systems (Smith and Johnson 2020).

In the aerospace industry, for instance, managing advanced technologies, materials, testing, and certification requires strong interdependency among these aspects, making the DFX approach a valuable resource for dealing with complexity (Chiu and Kremer 2010; Gupta and Sharma 2016). It helps to identify potential issues and conflicting requirements early in the design phase, yielding improved product performance while mitigating rework and uncertainty in the PDP (Anderson and Thompson 2018; Cooper and Kleinschmidt 2016; Pinto and Slevin 1988). Notwithstanding, applying DFX methodologies and tools often requires investments in new technologies, tools, or even expensive training programs, so that companies should carefully consider the return on the investment to implement DFX techniques (Gupta and Sharma 2016).

Integrating DFX methodologies into the PDP of complex evolving technologies while ensuring compatibility with existing systems can be complex and resource-intensive (Wang and Zhang 2019). One potential consequence of using DFX methodologies incorrectly in the aerospace industry is that it can disrupt project schedules, as DFX methodologies include analyzing and implementing design changes, which can affect delivery deadlines (Chen and Wang 2017). Conversely, the aerospace industry is heavily regulated, with stringent safety standards and certifications. This means that companies' PDPs are subject to comprehensive regulatory frameworks covering various aspects including safety, performance, emissions, and noise. Failure to adopt an integrated approach may result in overlooking these important considerations. Even so, incorporating DFX techniques to comply with regulations can be challenging due to the need to change established design practices (Williams and Davis 2019). Therefore, companies must ensure their design decisions meet regulatory requirements without compromising the overall performance and quality of their PDP.

Successful DFX implementation also requires the collaboration of various stakeholders, including designers, manufacturing experts, suppliers, and regulators. Since it requires expertise in multiple areas, communication gaps, differing priorities, and lack of coordination among these stakeholders can pose significant challenges (Kim and Lee 2018). The aerospace industry itself faces the difficulty of bridging the skills from design, manufacturing, materials, and regulation, as DFX practice requires a holistic understanding of the product lifecycle and company's project portfolio (Pessôa and Trabasso 2017).

A theoretical company's project portfolio may comprise, for instance, the following kinds of projects: Competitiveness, Operational Continuity, Cost Reduction, Customer Request, and Product Reliability & Correction. Each of these project types has specific characteristics that may require a specific DFX approach. The regular PDP lifecycle follows several well-known phases, such as – but not restricted to – Pre-Development Conceptual Study (PDEC), Pre-Development Studies (PDS), Informational Design (ID), Conceptual Design (CD), Detailed Design (DD), Certification Tests and Analysis (CTA), Production Preparation (PP), and Launch and Production (LP). Each phase has specific goals, tasks, and deliverables that contribute to the overall PDP output (Cooper 1993). In the daily practice of an aerospace manufacturer, DFX methodologies' attribution and selection are based on the design needs, PDP performance, and project portfolio and phases. Given this context, companies should endeavor in-depth analyses to properly consider the project portfolio and PDP lifecycle phases, which are rarely static.

In this scenario, the problem addressed in this work is determining the suitable DFX technological areas and methodologies that can help companies to successfully address the needs of each project type and phase. The main goal herein stated is to perform a preliminary mapping of the technological areas of the DFX, according to the perspective of the engineering experts. Then, a general approach is proposed to guide project managers in selecting the main technological areas of the DFX, considering a typical aerospace organization's project portfolio as the main boundary condition.

To provide an overview of the relevance of this research, a short summary of the main recent contributions in the literature is presented in Table 1.

Table 1. Literature review: recent selected works on DFX technological areas prioritization.

Summary	References
This research highlights the integration of DFX areas such as design for manufacturability, assembly, and cost to optimize resource allocation during PDP to improve operational efficiency.	Smith *et al.* (2019)
This work proposes a strategic approach for selecting DFXs to optimize resource allocation in new product development.	Chen and Wu (2020)
This article addresses the integration of agile product development with DFX, considering DFX areas such as design for flexibility, scalability, and modularity to enhance resource efficiency in dynamic development environments.	Gupta *et al.* (2021)
This work presents a framework for resource optimization in product development using DFX principles, emphasizing design for sustainability, reliability, and serviceability to achieve effective resource utilization.	Wang *et al.* (2019)
This paper examines the maximization of resource utilization through DFX integration in a case study in the electronics industry.	Garcia *et al.* (2018)

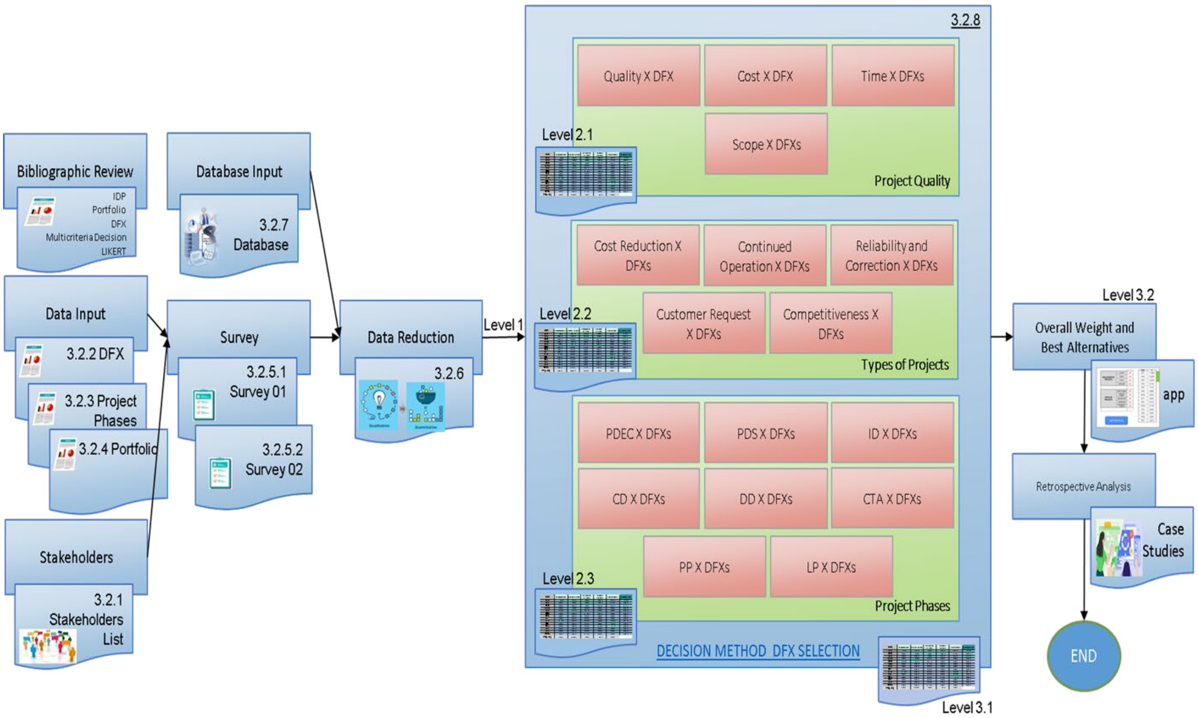
Source: Elaborated by the authors.

From these recent results, that research effort has been put on evaluating suitability and proposition of novel DFX areas to different ways of addressing optimized PDP results (Chen and Wu 2020), for instance, proposes a strategic approach for selecting DFXs to optimize resource allocation in new product development, but they did not relate typical project portfolio and design phases.

The research design detailed in this work is an approach to guide, at least initially, project managers in the aerospace domain to select the main technological areas of the DFX, given their typical organization project portfolio. The proposed approach departs from the literature review of the main technological areas of DFX used in the aerospace domain, followed by a contextual survey carried with senior engineers and product development managers from the aerospace sector. Quantitative results are gathered by means of a treatment based on the classical Likert scale (Likert 1932), which then allow to draw a hierarchization analysis based on the AHP method (Saaty 1990; 2004; 2005; 2008). Both techniques have been widely accepted in the scientific community to perform, respectively, subjective human-based and decision-making research. To the best extent of the knowledge of the authors, this can be considered an innovative contribution that can help to pave the comprehension about managing decision criteria to prioritize strategic technological areas of the DFX during the PDP in the aerospace domain.

METHODOLOGY

The resources established to carry out this work are reviewed in this section, emphasizing the review of a typical aerospace organization project portfolio, project development phases, project quality criteria and the main DFX technological areas used in the aerospace domain. The methods used through investigations are briefly reviewed, advocating the assumptions to define questionnaires and the Likert scale for the surveys as well as the AHP method steps. Departing from a base of knowledge built upon these concepts and – in addition – a relevant internal stakeholder's list and project record database of a given aerospace company, the general research approach followed in this work is depicted in Fig. 1. The core of the proposed research depicted in Fig. 1 is the definition of the multicriteria AHP matrix that allows extracting implicit knowledge evoked by expert opinions (collected by means of two specific surveys), considering the individual clustered criteria from project quality AHP, types of projects AHP, and project phases AHP. In the end, these are also crossed with the AHP Overall Weight method, which allows to design an app that issues general initial decisions on DFX selection. Performing a "retrospective analysis" considering previous selected records of real projects has been conducted to verify the method and draw results, conclusions, and recommendations.



Source: Elaborated by the authors.

Figure 1. Research approach: the output is constituted of recommendation of the DFXs.

Portfolio classification

Portfolio classification is crucial in the development and modification of aircraft for efficient and strategic management in the aerospace industry (Williams and Davis 2019). By identifying and grouping projects based on their specific objectives and characteristics, companies can gain a comprehensive view of their portfolio and make informed management decisions. Moustafaev (2019) provides insights into portfolio management across sectors, including aerospace, through specific case studies. By categorizing projects based on their goals and characteristics, companies can effectively prioritize and manage portfolios. The basic steps used to organize and define the representative example portfolio of projects are as follows:

- Identification of classification criteria: the first phase involves identifying classification criteria that help evaluate each project. Criteria may include factors such as financial return, strategic alignment, risk, complexity, and development time, among others.
- Evaluation of projects: the second phase evaluates each project based on the classification criteria identified in the first phase. This usually involves gathering information about each project, including financial, market, and competition data.
- Project classification: the third phase classifies projects based on the evaluation conducted in the previous phase. Projects are usually grouped into categories such as "high priority," "medium priority," and "low priority."
- Review and update: the last phase reviews and updates periodically the project portfolio classification. As market conditions and strategic priorities change, it is important to regularly review and update the classification to ensure that the selected projects align with the organization's objectives.

According to Moustafaev (2019), company management should observe the following points in order to classify their respective portfolios: (i) develop new product families; (ii) develop attractive products; (iii) increase revenue and profitability by developing new product families; (iv) increase market share in new markets; (v) expand the product family; (vi) expand into new geographic markets; (vii) enable higher revenue growth; and (viii) implement a rigorous project portfolio management system to prioritize projects and cut low-priority ventures.

Aerospace companies usually adopt a project classification system known as "programs" (sets of projects) or specific "development projects". They base this classification on the development stages of an aircraft and the key objectives of each project. Departing from this "aerospace commonplace knowledge" and from the main recommendations analyzed in Moustafaev (2019), the portfolio classification used in this paper is summarized in Table 2, with a reference for detailed consultation.

Table 2. Representative example portfolio used in this research.

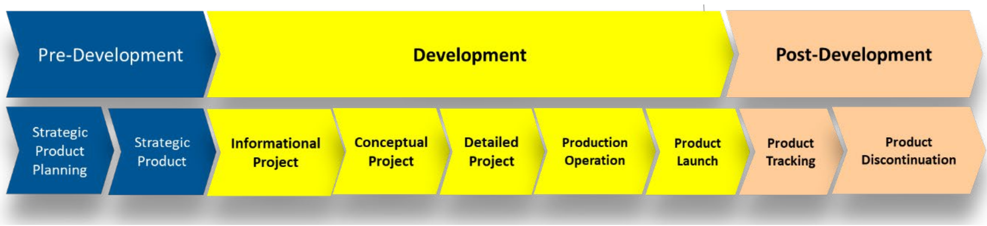
Types of projects	Brief description
Competitiveness	Improve a company's competitive position in the aerospace industry, involving research and development initiatives to enhance aircraft efficiency, increase performance, or introduce new technologies (Raymer 2012).
Customer Request	Involve customized modifications to existing aircraft (Patel 2009) driven by the specific needs of a customer or group of customers
Reliability and Correction	Increase reliability and reduce failures (Cardoso 2007) by ensuring aircraft reliability and safety, monitoring activities, performance data analysis, identification and correction of technical issues, and implementation of improvements.
Cost Reduction	Identify and implement cost reduction opportunities throughout the aircraft lifecycle, involving optimizing production processes, implementing maintenance, and repair improvements (Levine 2014).
Continued Operation	Maintain the operation and sustainability of in-service aircraft. They may involve regulatory updates, modifications to extend the aircraft's lifespan, and obsolescence management (Shtub *et al.* 2005).

Source: Elaborated by the authors.

This classification for the aerospace industry should allow companies in the sector to have a strategic view of their portfolio, facilitating project prioritization, planning, and execution. The proposed portfolio is used as the basis for the survey phase of the research, following the steps detailed bellow. If the proposed method described herein is to be used in a sector other than aerospace, the contents of Table 2 must be adapted accordingly.

Project development phases

In the dynamic realm of PDP, the journey from a nascent idea to a fully operational product involves a series of intricate phases, each marked by specific milestones and evaluations. This process is particularly nuanced in sectors like aerospace, where products are not only highly complex, but also subject to stringent safety and quality standards. Figure 2 shows the theoretical sequence of design phases in a common PDP considered in this paper.



Source: Adapted from Rozenfeld *et al.* (2006).

Figure 2. Product development phases process.

The product development lifecycle begins with PDEC where market intelligence synergizes with advanced design principles to sow the seeds for innovative products, laying the groundwork for future phases. Pre-Development Studies (PDS) follow, focusing on the critical assessment of a product's technical and economic feasibilities. As the concept solidifies, the ID takes over, setting concrete goals, objectives, and detailed plans, pivotal for the transition from idea to tangible design. Subsequently, the CD and DD further refine the product through collaborative efforts, leading to the creation of prototypes and rigorous design reviews. Post-design, the CTA stands as the crucible wherein the product is tested against the highest standards, affirming its readiness for real-world application. Table 3 summarizes some of the product development phases considered in this research.

Table 3. Product development phases considered in this work.

Phase	Description	Key references
PDEC	Identification of new product opportunities; activities include market research, competitive analysis, trend tracking, and brainstorming.	Cooper (1994), Ulrich and Eppinger (2015).
PDS	Assessment of technical and economic viability; activities include feasibility studies, cost evaluation, risk assessment, and market studies.	Blank (2013), Pahl and Beitz (2013).
ID	Submission of business plan for approval; activities include goal setting, requirements definition, in-depth analyses, and conceptual modeling.	PMI (2017), Pugh (1990).
CD	Detailed project definition: activities include creating product structures, computational models, prototypes, and conducting preliminary design reviews.	Clarkson *et al.* (2004), NASA (2018).
DD	Transformation of designs into components; activities include critical design reviews and initiation of part fabrication.	DOD (2001)
CTA	Product testing to meet requirements; activities include in-flight tests, ground assessments, system rig testing, and qualification trials.	FAA (2011)
PP	Preparation for operational debut; activities include finalizing customer support services, crew training, and maintenance.	AIA (2013)
LP	Commencement of large-scale production; activities include addressing customer demands, component obsolescence, regulatory compliance, and engineering modifications.	Pyzdek and Keller (2009), Trott (2008).

Source: Elaborated by the authors.

As the product approaches completion, the PP ensures that all ancillary systems, training, and support structures are operational, paving the way for a smooth Entry into Service (EIS). Finally, the lifecycle culminates with the LP, marking the commencement of large-scale production, with continual adaptations and improvements in response to evolving customer needs, market trends, and regulatory standards.

This comprehensive framework underscores the multifaceted nature of the PDP, highlighting the need for meticulous planning, cross-functional collaboration, and unwavering commitment to quality and innovation at every stage. A general review of quality criteria for evaluating the PDP output is presented as follows.

Project quality (performance criteria)

In the contemporary landscape of product development and project management, the quest for optimizing project outcomes necessitates a nuanced understanding of performance criteria. This paper delves into the pivotal role of DFX practices enhancing project quality across four cardinal dimensions: scope, schedule, cost, and quality. These dimensions are instrumental in evaluating a project's effectiveness and its alignment with the PDP.

These practices are integral to optimizing products and processes across various performance criteria, effectively preempting challenges throughout the product development cycle (Brissaud 2013). This paper explores how DFX practices contribute to mitigating challenges in these areas, drawing insights from scholarly literature and real-world case studies.

In the challenging field of project management, particularly within product development, the quality of the output is directly influenced by a multiple performance criteria. To address the intricacies of managing these criteria effectively, DFX practices have been increasingly with growing frequency across various industries. DFX encompasses a series of strategies aimed at enhancing various aspects of product development such as manufacturability, testability, reliability, and quality. Integrating DFX practices into project management is not only strategic but also pragmatic in overcoming common obstacles that may hinder a project's success.

Integrating DFX practices offers a strategic methodology to mitigate challenges across these dimensions, ensuring project success preemptively. The dimensions are defined as follows.

Scope pertains to the comprehensiveness of work and specifications required for a product, embodying the challenges that may necessitate rework.

Schedule addresses the temporal aspects of product delivery, where complexity necessitates adept coordination across teams.

Cost considerations highlight the financial implications of early-stage design decisions.

Quality focuses on fulfilling or surpassing stakeholder expectations.

Table 4 presents a synthesized view of key performance criteria within project quality management. Each criterion is paired with a description outlining common challenges faced during project execution. Furthermore, the table identifies specific DFX practices that are effectively utilized to address these challenges, supported by scholarly references that provide deeper insights into these methods. This alignment of challenges with DFX practices and supportive literature creates a comprehensive framework for understanding the impact of DFX on project quality. Table 4 synthesizes some insights, presenting a clear linkage between specific DFX practices and the performance criteria they predominantly influence.

Table 4. Project quality (performance criteria).

Criteria	Description	Key DFX practices	References
Scope	Challenges in project scope lead to rework. DFX practices mitigate these issues.	DFM, DFT, DFR, DFQ	Haque (2017), Kusiak (2013), Boothroyd *et al.* (2010).
Schedule	Product development complexity requires multi-team coordination, risking delays. DFX practices help keep projects on schedule.	DFM, DFQ	Azzi and Hansen (2015), Anderson (2014).
Cost	Cost overruns are common due to early-stage design flaws. DFX practices help control costs.	DFM, DFR	Rea and Schmid (2014), Smith and Bliesner (2006).
Quality	Quality affects satisfaction and costs. DFX practices ensure high standards.	DFQ, DFM	Swink *et al.* (2017), Chowdhury (2002).

Source: Elaborated by the authors.

The paper further articulates an analysis of each performance criterion, revealing the nuanced impact of DFX practices:

Scope management emphasizes the reduction of rework and delays through early consideration of manufacturability, testability, reliability, and quality. Design for Manufacturing (DFM) emerges as the most significant practice, followed by Design for Quality (DFQ), Design for Reliability (DFR), and Design for Testability (DFT), based on their potential to preempt scope-related challenges.

Schedule adherence highlights the importance of DFX in maintaining project timelines, with DFM and DFQ identified as critical in mitigating delays through improvements in manufacturability and quality.

Cost control explores how DFX practices, particularly DFM and DFR, play important roles in curbing cost overruns by incorporating cost considerations early in the design phase, thus addressing design flaws that could escalate expenses.

Quality assurance underscores the paramount importance of DFQ and DFM in fostering high-quality standards and reducing the likelihood of rework, thereby directly influencing customer satisfaction and project costs.

In conclusion, this paper suggests that the meticulous integration of DFX practices into the product development lifecycle can substantially mitigate risks associated with scope, schedule, cost, and quality. Such an integrated approach not only streamlines the product development process but also enhances overall project outcomes, underscoring the importance of DFX methodologies in achieving excellence in project management and product development. Through a collaborative and interdisciplinary approach, organizations can harness the full potential of DFX practices to navigate the complexities of modern product development, thereby securing a competitive advantage in the rapidly evolving technological landscape.

DFXs in the aerospace domain: an oriented review

Almost any technological area involved in the PDP of a complex system in an aerospace company (Ulrich and Eppinger 2015) could give rise to a DFX approach, with its own methodologies, tools, and guidelines (Gupta and Sharma 2016). This should at least be circumscribed to those areas or competences that claim some measure of improvement or quality (Huang 1996). Table 5 summarizes some pre-selected DFX techniques within aerospace PDPs, which will figure in our research in the survey phase (refer to Fig. 1).

Table 5. Main strategic areas of the DFX considered in the aerospace domain.

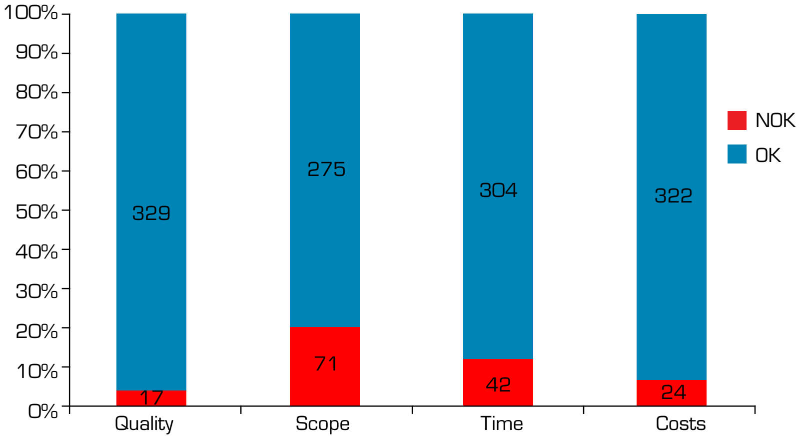
DFX area	Brief description	Main references
DFT	Designs a product to be easily tested during the manufacturing/maintenance, playing a critical role in the CTA and LP phases.	Cooper (1993), Pahl and Beitz (2013).
DFM	Designs a product in a way that facilitates and optimizes the manufacturing process. Considered in from the PDEC to the LP.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFR	Designs a product that is reliable and has an appropriate lifespan. Studies indicate that DFR is particularly important in the ID and DD phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFE	Considers minimizing environmental impacts throughout the product's lifecycle, being of great importance in the PDS and CD phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFS	Incorporates of sustainable practices in product and development. Relevant in the PDEC and PP phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFDA	Designs a product that is easy to disassembly, being relevant in the CD and DD phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFSS	Applies Six Sigma principles and methods in product design. Interesting in the CTA phase.	Antony (2014), Pahl and Beitz (2013).
DFQ	Designs products incorporating quality characteristics, being highly relevant in all development phases, especially in the ID and CTA phases.	Pahl and Beitz (2013), Ulrich and Eppinger 2015).
DFA	Designs a product that is easy to assembly, being in almost all the development phases.	Boothroyd *et al.* (2010), Pahl and Beitz (2013).
DFN	Considers the interoperability and connectivity interactions of the product in communication networks. It is relevant in the CD and CTA phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DTC	Designs a product emphasizing strictly the importance of controlling and optimizing costs throughout the entire development process.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFMt	Designs a product easy for maintenance and repair, being particularly relevant in the CTA and LP phases, minimizing product downtime.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFO	Designs a product considering its operational efficiency and effectiveness, being indicated in the ID and PP development phases.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).
DFB	Designs a product considering commercial and strategic aspects, mainly to strictly align the development with business objectives and market needs.	Pahl and Beitz (2013), Ulrich and Eppinger (2015).

Source: Elaborated by the authors. DFA = Design for Assembly; DFDA = Design for Disassembly; DFN = Design for Network.

Although not all the DFX technological areas presented above could encounter immediate resonance to manager engineers, Pahl and Beitz (2013) highlights the interesting aspect of their affinity with the phases of the product development lifecycle, which is especially important to our research goal. Table 5 gives rise to a good scenario for the survey carried in the survey phase of this work, as it is detailed in the following.

Resources – Database input (background analysis)

Following the approach depicted in Fig. 1, the first step involves defining a relevant database for a comprehensive analysis of project performance within the illustrative organizational portfolio defined in Fig. 3, encompassing 346 distinct projects. The evaluation metrics focus on four critical dimensions: quality, scope, time, and cost, with an aggregated status indicator termed "ALL OK?" to signify overall project health. Figure 3 summarizes this initial evaluation of the database.



Source: Elaborated by the authors.

Figure 3. Overview of background considering the evaluation of each performance criteria. If a project is "OK" in each criterion – scope, schedule, cost and quality –, it will be counted in blue.

An initial appraisal of the dataset reveals a bifurcation in project performance outcomes. A majority of 228 projects met the predefined criteria across all dimensions, as indicated by an "OK" status in the "ALL OK?" proposition. Conversely, 118 projects exhibit deficiencies in one or more dimensions, necessitating further scrutiny to identify and address underlying issues.

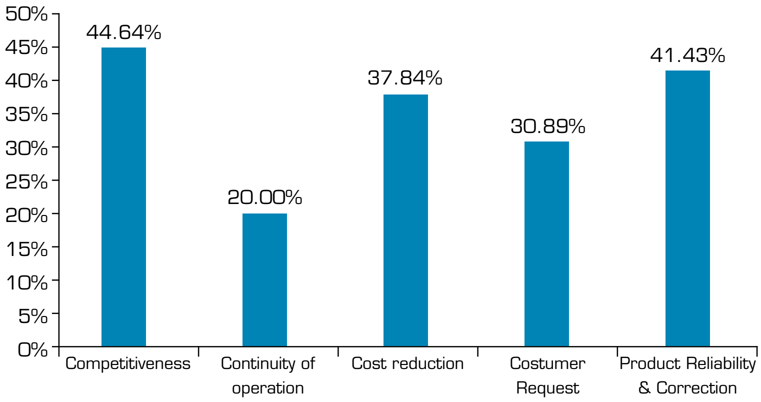
From Fig. 3, a critical analysis of individual performance categories elucidates that scope is the predominant area of concern, with 71 instances of non-compliance ("NOK"). This is followed by time, with 42 instances, suggesting a pervasive challenge in adhering to project timelines. The cost dimension, with 24 instances, and quality, with 17 instances, reflect comparatively fewer occurrences of non-conformance, though they warrant continuous monitoring and improvement efforts.

Data shown in Fig. 4 reveal that competitiveness challenges are most prevalent, affecting 44.64% of projects. This high incidence rate underscores the imperative for organizations to continually innovate and enhance their product offerings to maintain a competitive edge in the market. It suggests a dynamic environment where the pace of technological advancement and customer expectations necessitates agile and responsive project management strategies.

Following closely, Product Reliability & Correction issues impact 41.43% of projects, highlighting the critical need for robust design and quality assurance processes. This statistic emphasizes the importance of integrating reliability considerations into the product development lifecycle, thereby preempting potential defects and ensuring product integrity.

Cost reduction challenges are encountered in 37.84% of projects, reflecting the ongoing pressure to optimize resource allocation and efficiency. This dimension emphasizes the need for strategic cost management practices that do not compromise product quality or customer satisfaction, maintaining a delicate balance between cost-effectiveness and performance excellence.

Customer Request-related challenges are noted in 30.89% of projects, illustrating the significance of aligning project deliverables with client expectations. This finding reinforces the necessity for effective communication channels and flexible project scopes that can accommodate evolving customer needs.



Source: Elaborated by the authors.

Figure 4. Overview of background considering the evaluation of each Project Type considered "NOK".

Lastly, Continuity of operation challenges are observed in 20% of projects. Although the least frequent, these challenges still represent a substantial area of concern, emphasizing the importance of ensuring operational resilience and the ability to sustain business functions amidst unforeseen disruptions.

The exploratory investigation into potential correlations suggests that deficiencies in project scope may exert a cascading effect on other dimensions, particularly time/schedule. This correlation indicates that inadequate scope definition not only jeopardizes the project's timeline but also influences its competitiveness, reliability, cost-effectiveness, and responsiveness to customer requests. Such interdependencies highlight the interconnected nature of project challenges and the importance of a holistic approach to project management that considers the interplay between scope, schedule, cost, quality, and stakeholder expectations.

The analysis underscores the interconnected nature of project challenges and the imperative for a holistic management approach that addresses the intricate interplay between scope, schedule, cost, quality, and stakeholder expectations. It highlights the necessity of targeted interventions to address specific areas of concern, particularly in scope and time management, to prevent the cascading effects on other project dimensions.

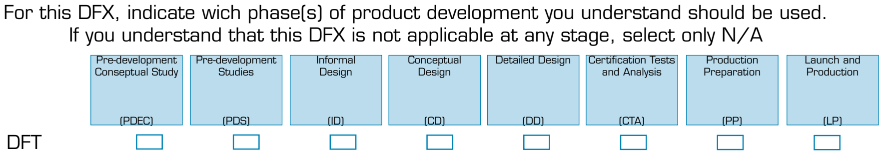
Furthermore, the prevalence of Competitiveness and Product Reliability & Correction issues accentuates the need for continuous innovation, effective communication channels, and the integration of robust quality assurance processes. Organizations must embrace agile and responsive project management strategies to navigate the dynamic technological landscape and meet evolving customer expectations.

In conclusion, this section has elucidated the critical challenges within project management and offers insights into potential strategies for enhancing project outcomes. By recognizing and addressing the root causes of deficiencies across key dimensions of project performance, organizations can better position themselves for success in the competitive technology and management arena.

Research methods – Survey and Likert psichometric scale

The assumptions to define questionnaires and the Likert scale used in the survey carried out with experts from the aerospace industry are detailed bellow. The first step involves setting up a consulting research based on a questionnaire to relate the project phases to the DFX technological areas. This aims achieve the first goal of this paper, i.e., providing expert knowledge on the suitability of each method in each situation. It was applied using Google Forms to a sample of professionals. The mapping is guided by asking the participants to rate, in terms of suitability, each of the eight predefined project phases (Table 3) with each of the DFX alternatives given in Table 5. A sample of a question could be: "For this DFX, indicate which phase(s) of product development you understand should be used", as depicted in Fig. 5.

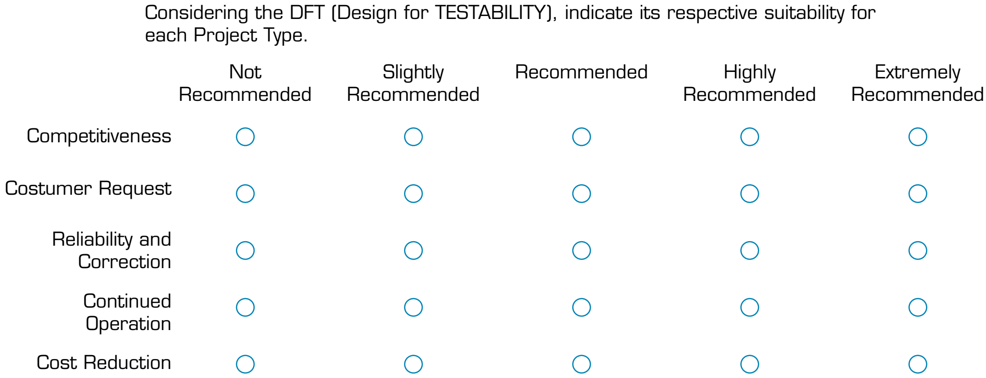
The second step is set a consulting research based on a questionnaire to relate the project portfolio to the DFX. This is to achieve the second goal of this paper, i.e., providing expert knowledge on the suitability of each method for each project type. It was applied using Google Forms to a sample of professionals. The mapping is guided asking the participants to relate each of the five predefined project types Table 2 with each of the 14 preselected technological area(s) of the DFX Table 5 in terms of suitability.



Source: Elaborated by the authors.

Figure 5. Questionnaire used in the survey 01/02 with experts from the aerospace industry to investigate DFX areas subjective importance according to project phases.

A sample of a question could be: "Considering Design for X (DFX), indicate the suitability for each project type", as shown in Fig. 6.



Source: Elaborated by the authors.

Figure 6. Questionnaire used in the survey 02/02 with experts from the aerospace industry to investigate DFX areas subjective importance according to project types.

The sample consisted of a selective and chosen audience composed solely of experienced aerospace professionals, such as senior engineers, program managers, product development managers, quality managers, and manufacturing managers. The questionnaire was submitted to 150 senior professionals, of whom 50 fully completed the forms. In addition, to concretize the step "Compilation and Results Analysis", bringing the survey from the qualitative to a quantitative basis and derating subjectivity (Likert scale). It consists of classical psychological grading scale widely recognized as a beginner, though effective, measurement technique for evaluating attitudes, opinions, and perceptions, capturing the intensity and direction of participants' opinions on the topic being researched. The scale comprises a series of statements in which participants are asked to rate on a continuum of responses ranging from "strongly disagree" to "strongly agree". In this paper, it is adapted a five-level of Likert scale, such as summarized in Table 6.

Table 6. Likert scale used in to quantize expert opinions in the survey.

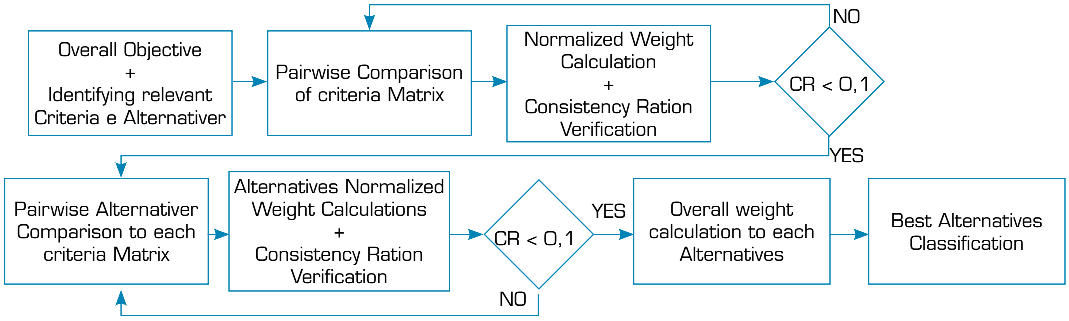
Likert scale		Paper scale (Likert scale)	
Strongly disagree	1	Not recommended	0
Disagree	2	Slightly recommended	1
Neutral	3	Recommended	2
Agree	4	Highly recommended	3
Strongly agree	5	Extremely recommended	4

Source: Elaborated by the authors.

To reach the goal of capturing the intensity and direction of participants' opinions about the DFX technological area vs. project type, the overall sum of the related grades issued by the participants is carried out. Because of that, one can notice the use of the grade 0 (and not 1) to convert the "not recommended" answer, valuing the important knowledge of the expert recording its absolute deterrence on the use of those DFX methodologies in a given specific context.

Research methods - Analytic hierarchy process (AHP)

The central focus of this study is the utilization of the AHP method to facilitate intricate decision-making processes that encompass several criteria and options. In this study, the expert knowledge acquired from the survey, as described earlier, is used to construct a universal decision workflow. This workflow prioritizes of strategic DFX technological areas based on the project type. The technique was established by Thomas L. Saaty and is extensively utilized in various domains such as management, engineering, economics, and operations research (Saaty 1990; 2004; 2005; 2008, Saaty and Vargas 2012). Figure 7 presents a flow chart that provides a concise overview of how the AHP processes are used in this study.



Source: Adapted from Krishnamoorthy (2015).

Figure 7. Flow chart of the AHP method used in this paper.

This method employs a straightforward hierarchical model comprising of three components: goals, criteria, and options. The AHP combines various preexisting concepts and approaches that were not previously connected. These include hierarchical organization, pairwise comparisons, the Eigen-vector method for determining weights, and considerations for consistency. According to Saaty (1990; 2004; 2005; 2008), AHP consists of three primary phases:

- Decomposing: the elements of the choice problem are organized in a hierarchical structure. The highest levels of the hierarchy consist of the overarching goal, followed by the criteria that directly impact the goal. The next level includes the operational sub-criteria, which are used to evaluate the decision alternatives at the lowest level of the hierarchy. It is assumed that all elements within a given level are independent of each other.
- Comparative judgements: elements of one level of a hierarchy are compared pairwise, using the hierarchical arrangement to assign relative significance (see table 8) as to the strength of their influence on an element of the next higher level.. Saaty has suggested a scale of 1 to 15 when comparing two elements, with a score of 1 representing indifference between the two elements and 15 representing the overwhelming dominance of one element over the other. These comparisons lead to dominance matrices, which are called pairwise comparison matrices.
- Synthesizing: the subsequent stage involves combining the priorities into a basic hierarchical model that assesses options based on criteria and sub-criteria related to the overall aim. The priority of all alternatives is computed in relation to each criterion. The weights for overall priority are derived from a matrix that compares pairs of elements.

Once the quantized data from the survey has been processed according to these stages, the analysis's consistency can be evaluated using a statistic known as the consistency ratio (CR). The values in the pairwise comparison matrix should be less than 0.1, suggesting that the expert's judgments/weights are fair. To calculate the CR, one must first identify the degree of consistency (CI). This can be approximated from the Eigen-value λ_{max} derived from the comparison matrices, where N represents the order of the matrix. The CI is estimated using the Eq. 1.

$$CI = (\lambda_{max} - N) / (N - 1) \tag{1}$$

The CR is determined by dividing the consistency index (CI) by the random CI (RI), as shown in Eq. 2.

$$CR = CI / RI \quad (2)$$

The RI value is acquired from Table 7, which is determined by the value of N, representing the number of alternatives being compared in the AHP context. In this study, the alternatives are related to the DFX technology domains. This work consists of 14 distinct DFX, resulting in an RI of 1.57.

Table 7. RI value according to the number of alternatives (*N*).

RI – Average random index of AHP as a function of matrix size														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.46	1.57	1.59

Source: Adapted from Saaty (1991).

Table 8. Fundamental Scale of the AHP.

Intensity of importance	Definition
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance

Source: Adapted from Krishnamoorthy (2015).

RESULTS

This section presents a discussion of the main results of the research, starting with an in-depth analysis of the answers and grades gathered from the survey, according to the procedure described in the section "Research methods – Survey and Likert psychometric scale".

Raw results from the survey

The analyses begin by converting the subjective responses into an overall sum of the related grades issued by the participants, using the Likert scale outlined (Table 6). The raw results obtained are plotted in Figs. 8 and 9.

From Figs. 8 and 9, it is evident that each project type and project phases attains some DFXs to be better methodologies to work with. From Fig. 8, one may notice some initial insights delivered by the survey, such as: for PDEC, experts issued importance on Design for Business (DFB), Design for Environment (DFE), and Design for Six Sigma (DFSS); for CD, experts seam to put relevance on DFM, Design to Cost (DTC), and Design for Sustainability (DFS); and for LP, experts issues importance to DFQ, Design for Maintainability (DFMt), and Design for Operation (DFO). These preliminary findings align with the expectations of an experienced project managers.

In Fig. 9, it is worth noticing another initial insight delivered by the second survey: for "Competitiveness Projects", experts issued importance on DFB and DFO while for "Customer Request Projects", emphasis is put on DFSS, DFQ, and DFO. "Cost Reduction Projects" issues importance on DTC, DFM, and DFA, as might be expected by experts.

Reduced data analyses – AHP results

Following the next step of the research approach, using the obtained data to apply AHP as show on Fig. 1 – part 3.2.8 – level 1, 2.1, 2.2, 2.3, 3.1, and 3.2, it has been created the different pairwise comparisons of alternatives (DFXs) per project type and per project phases. Pairwise comparisons given specific performance criteria (project quality) were also performed to evince implicit cross importance with the project type and project phases (these is discussed in detail below).

An assessment is conducted on a pair of elements based on a shared property they possess, where the smaller element is considered the unit, and one can assess the comparative significance, desirability, or likelihood, sometimes referred to as "dominance", of the other element is assigned a numerical value from the Fundamental Scale.

From Table 9, the results of the consistency check conducted using the AHP method indicate a satisfactory level of consistency (CR < 0.1 in all the cases). This allows to proceed with the final steps of the AHP method, enabling a more in-depth analysis of the relationships among each DFX and the project types and phases.

The next and final step is to populate the Table 9 with all the normalized values based on DFX and project type, DFX and project phases, and DFX and project quality indicator. Then, the calculation of the total partial normalization is performed to obtain the partial values from project type, project phases, and project quality. Finally, it is performed the last normalization calculation to obtain the final percentages corresponding to each DFX. This process enables to identify notable trends (including cross-relations), as presented in Fig. 10, which also shows the AHP overall weight and best alternatives.

The following the next steps to use AHP is to calculate the "normalized weights" and check the analysis with the CI. The results pertaining this latter aspect are summarized in Table 9.

This comprehensive analysis explores the role of DFX methodologies across various project parameters and phases, using AHP for a nuanced evaluation. The research reveals the pivotal nature of specific DFXs in influencing project success, underscoring the need for strategic application tailored to project specifics. Some key takeaways are detailed below.

Project quality analysis

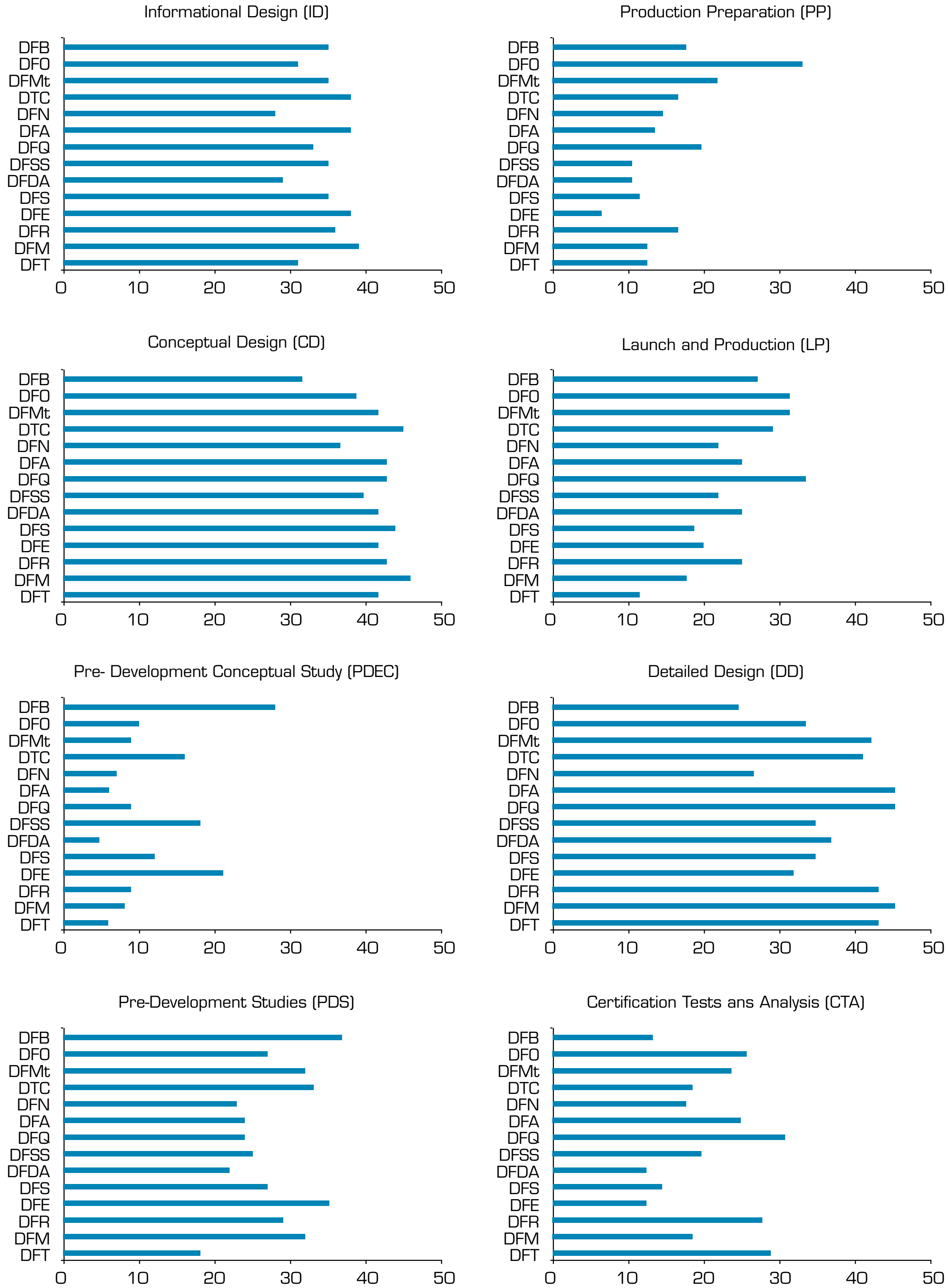
DFT emerges as a paramount strategy, particularly excelling in scope and cost parameters, an indication of its critical role in ensuring expansive project success and cost-efficiency. Notably, DFT leads with high recommendations, suggesting that easy-to-test designs could potentially reduce defects by a significant margin, streamline production, and lead to substantial long-term cost savings. DFM is not far behind, especially in the quality parameter, with strong recommendations. This persistent high ranking underscores that manufacturing considerations are pivotal throughout all project phases, potentially influencing project scope, adherence to deadlines, cost containment, and quality assurance by notable percentages.

Project phase analysis

The analysis reveals significant variation across phases for DFXs like DFE and DFB. DFE, for instance, is highly recommended during the PDEC, potentially due to growing environmental and sustainability concerns that companies can no longer afford to ignore, given the current global focus on climate change.

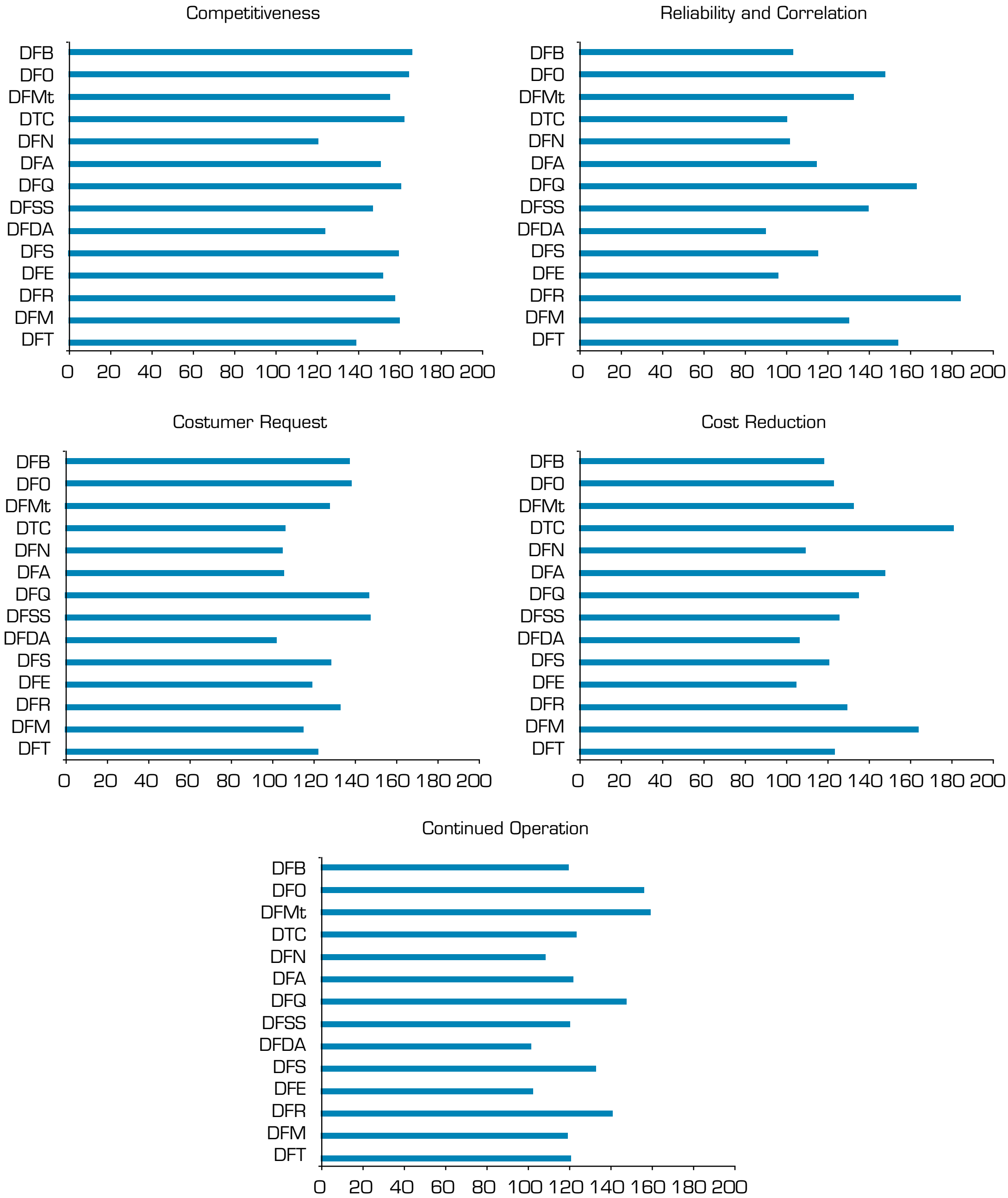
DFO stands out during the PP with an exceptional 26.25% recommendation. This peak suggests that a failure to consider operational aspects before a product goes live could result in costly post-launch modifications, potentially increasing project costs.

Project type analysis: the data provides interesting insights when dissected by project type. In projects labeled as Competitiveness, DFB, and DFO take the lead, highlighting their combined role in maintaining a competitive edge, potentially affecting market share by significant fractions. Conversely, Customer Request Projects emphasize DFSS and DFQ, underlining the critical nature of quality and six sigma principles in meeting customer expectations, which could influence customer retention rates.



Source: Elaborated by the authors.

Figure 8. Questionnaire 01/02: sum of the DFX grades rated by the participants per project phases.



Source: Elaborated by the authors.

Figure 9. Questionnaire 02/02: sum of the DFX grades rated by the participants per project type.

The analysis also shows that Reliability and Correction Projects give importance to DFR, with Continued Operation Projects focusing on DFMt and DFO, suggesting these strategies could be pivotal in reducing operational downtimes by significant percentages. For projects aimed at Cost Reduction, DTC emerges as crucial, likely due to its direct impact on the bottom line.

Table 9. Consistency check from the use of the AHP method.

Index	Competitiveness	Customer Request	Reliability and Correction	Continued Operation	Cost Reduction
CI	0.016	0.007	0.039	0.034	0.026
RI	1.570	1.570	1.570	1.570	1.570
CR (%)	1.64	0.73	3.92	3.39	2.59
Conclusion	OK	OK	OK	OK	OK

Index	PDEC	PDS	ID	CD	DD	CTA	PP	LP
CI	0.088	0.028	0.024	0.030	0.027	0.043	0.072	0.042
RI	1.570	1.570	1.570	1.570	1.570	1.570	1.570	1.570
CR (%)	5.61	1.81	1.55	1.91	1.71	2.74	4.57	2.69
Conclusion	OK	OK	OK	OK	OK	OK	OK	OK

Source: Elaborated by the authors.

DFX	Project Phases							
	Pre-Development Conceptual Study (PDEC)	Pre-Development Studies (PDS)	Informational Design (ID)	Conceptual Design (CD)	Detailed Design (DD)	Certification Tests and Analysis (CTA)	Production Preparation (PP)	Launch and Production (LP)
DFT	1.51%	1.70%	3.63%	5.75%	9.70%	17.13%	3.58%	1.21%
DFM	2.65%	8.67%	11.17%	8.99%	10.62%	3.89%	3.07%	2.33%
DFR	3.84%	6.59%	7.17%	7.19%	8.72%	11.66%	6.62%	6.24%
DFE	16.01%	11.63%	9.23%	6.21%	3.37%	1.59%	1.02%	3.14%
DFS	6.88%	5.72%	7.11%	8.85%	4.38%	2.26%	2.58%	2.85%
DFDA	1.19%	2.70%	3.25%	6.51%	5.36%	1.60%	2.19%	6.44%
DFSS	13.41%	4.20%	7.23%	5.54%	4.56%	5.16%	2.19%	4.39%
DFQ	4.01%	3.81%	5.61%	8.74%	11.82%	17.20%	11.04%	14.78%
DFA	1.65%	3.81%	10.50%	8.74%	11.82%	8.69%	4.60%	6.65%
DFN	2.32%	3.70%	3.12%	3.91%	2.22%	3.76%	5.42%	4.52%
DTC	11.23%	11.87%	10.61%	12.24%	9.60%	4.72%	7.57%	10.62%
DFMt	4.24%	10.83%	8.35%	8.06%	10.85%	8.54%	14.44%	13.71%
DFO	5.19%	6.66%	4.52%	6.38%	4.84%	11.51%	26.25%	13.71%
DFB	25.87%	18.10%	8.50%	2.91%	2.13%	2.28%	9.43%	9.42%
AHP WEIGHTING	2.13%	10.80%	17.20%	27.69%	23.42%	6.06%	3.73%	8.95%

DFX	Project Types				
	Competitiveness	Customer Request	Reliability and Correction	Continued Operation	Cost Reduction
DFT	3.82%	5.26%	9.83%	4.23%	4.65%
DFM	6.48%	4.07%	6.37%	4.02%	12.06%
DFR	6.26%	7.97%	16.70%	9.81%	5.51%
DFE	5.72%	5.54%	2.39%	3.54%	2.56%
DFS	7.28%	7.39%	4.92%	8.76%	4.46%
DFDA	2.92%	2.77%	2.13%	2.68%	2.98%
DFSS	5.55%	12.28%	8.46%	5.02%	5.86%
DFQ	8.95%	12.28%	12.98%	10.43%	8.14%
DFA	6.32%	3.48%	5.06%	6.15%	11.41%
DFN	2.75%	3.35%	3.32%	3.57%	3.73%
DTC	10.15%	3.74%	3.32%	6.85%	18.59%
DFMt	8.45%	7.84%	8.14%	14.70%	8.24%
DFO	11.99%	12.01%	12.36%	14.70%	6.41%
DFB	13.35%	12.01%	4.01%	5.54%	5.42%
AHP WEIGHTING	7.68%	43.05%	17.83%	11.04%	3.59%

DFX	Project Quality			
	Scope	Time	Cost	Quality
DFT	20.74%	21.49%	6.47%	27.10%
DFM	16.67%	19.03%	17.77%	16.21%
DFR	15.37%	13.24%	1.19%	11.84%
DFE	11.58%	11.13%	2.36%	9.41%
DFS	8.84%	8.42%	1.20%	8.14%
DFDA	7.22%	7.23%	3.73%	6.99%
DFSS	5.88%	5.41%	12.49%	5.49%
DFQ	4.76%	4.23%	8.66%	4.77%
DFA	2.69%	2.81%	2.49%	3.24%
DFN	1.62%	1.64%	5.82%	2.14%
DTC	1.39%	1.40%	24.76%	1.59%
DFMt	1.08%	1.64%	10.60%	1.03%
DFO	1.08%	1.40%	1.24%	1.03%
DFB	1.08%	0.93%	1.24%	1.03%
AHP WEIGHTING	57.95%	25.21%	9.99%	5.65%

DFX	TOTAL PARTIAL			CONCLUSION
	TOTAL PHASES	TOTAL QUALITY	TOTAL TYPES	
DFT	5.99%	19.61%	4.94%	10.18%
DFM	8.45%	17.15%	4.26%	9.95%
DFR	7.57%	13.03%	8.17%	9.59%
DFE	6.11%	10.28%	3.73%	6.71%
DFS	5.95%	7.82%	5.75%	6.51%
DFDA	4.69%	6.78%	2.20%	4.56%
DFSS	5.37%	6.33%	7.99%	6.56%
DFQ	9.43%	4.96%	9.73%	8.04%
DFA	8.74%	2.70%	3.98%	5.14%
DFN	3.42%	2.06%	2.77%	2.75%
DTC	10.51%	3.72%	4.41%	6.21%
DFMt	9.75%	3.16%	7.40%	6.44%
DFO	7.41%	1.16%	10.15%	6.24%
DFB	6.61%	1.04%	7.72%	5.12%
AHP WEIGHTING	33.33%	33.33%	33.33%	

Source: Elaborated by the authors.

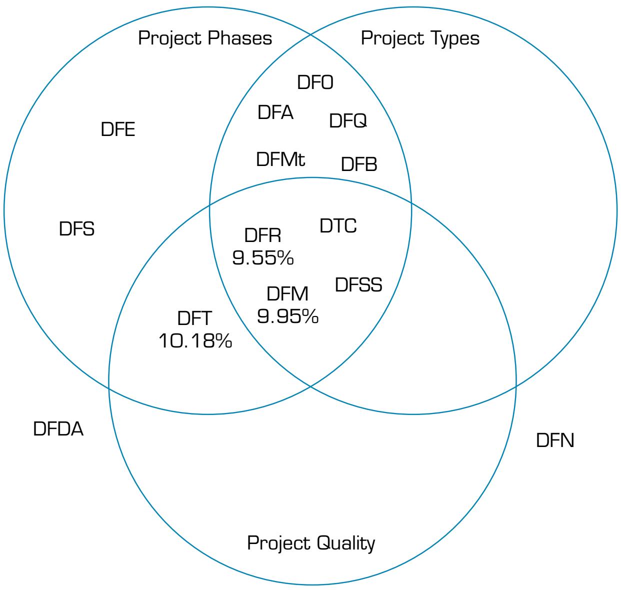
Figure 10. AHP overall weight and best alternatives analyses.

Project type analysis

The analysis offers compelling insights into the significance of various DFX criteria across different project phases, from the survey phase. It underscores the criticality of DFB, DFE, and DFS in the PDEC, with DFB, DFE, and DTC being pivotal in the PDS. The ID phase values DFM, DFA, DFE, and DTC, while the CD and DD phases highlight the importance of DFM, DTC, DFS, and DFQ, DFA, respectively. The CTA and PP phases stress DFQ, DFT, DRF, and DFO, DFMt, DFQ, with the LP phase echoing the significance of DFQ, DFMt, and DFO. Venn graphic delineates the fluctuating emphasis on DFXs, revealing DFE, DFB's varying stages of relevance, and the consistent recommendation for DFM and DFQ. The study advocates for a strategic, phase-specific application of DFXs to enhance design and development, supported by the AHP method for prioritizing DFX criteria. This approach is exemplified in the aerospace industry, indicating a nuanced strategy that prioritizes safety, reliability, and sustainability in the early stages, shifting towards quality, assembly optimization, and innovation in later phases. The findings serve as a guide for product development planning, project assessment, and education across sectors, suggesting a periodic reevaluation of DFX priorities to match evolving project needs.

Project analysis

In a comprehensive view (Fig. 11), DFT, DFM, and DFR emerge as prevalent within the highest final recommendations, each hovering just below the 10% mark. Their dominance implies that these design principles are foundational to achieving overall project success, potentially influencing project outcomes by double-digit percentages. However, it is worth noting the lower recommendations for DFN and DFDA, which indicate their more specialized roles. Their lower usage, particularly DFN with recommendations under 5%, suggests that networking considerations might not be universally applicable, but could be critical in projects specifically focused on network design.



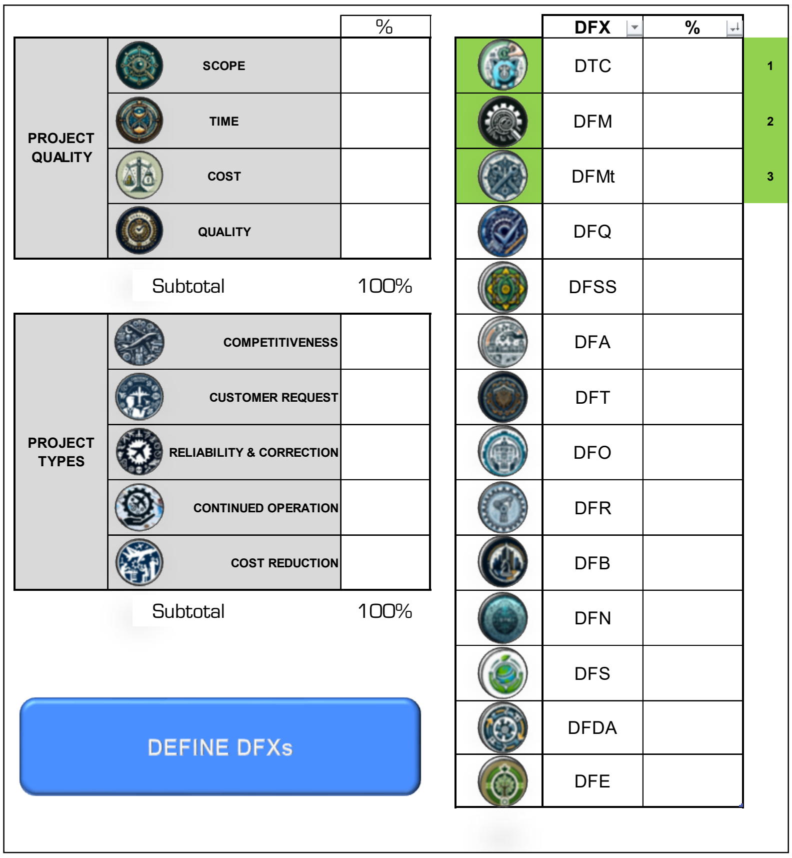
Source: Elaborated by the authors.

Figure 11. Results Venn graphic.

In essence, this detailed analysis underscores the multifaceted roles of DFXs, each holding varied significance depending on the project's quality benchmarks, operational phases, and inherent nature. The strategic application of these methodologies, informed by these numerical insights, is indispensable for achieving nuanced project objectives and overarching success. This data-driven approach not only facilitates informed decision-making but also highlights potential areas for cost savings, quality improvement, and efficiency enhancements, which are crucial for maintaining a competitive edge in today's dynamic market landscapes.

App – A DFX Attribution Method in the Aerospace Domain

To achieve the main goal of this paper, the knowledge gathered in the previous sections was used to build a tool (an Excel application – App) which is intended to help project managers in the first phase of opting for a specific DFX approach for each context. A picture of the main page of the app is shown in Fig. 12. This app is based on the data obtained and the AHP method. It is designed to output the suitability relevance (percentage) of each recommended DFX methodology, given as input, for a specific project scenario, the relative importance (%) the project manager asserts for the various project types (portfolio in Table 2), project phases (Table 3) ,and main quality criteria (Table 4). The influence of the project phase is considered, being embedded in the analyses by taking importance percentages raised in the previous section. Bellow is a step-by-step guide for using the tool is shown below, providing also some illustrative examples of applications and analyses it could support.



Source: Elaborated by the authors.

Figure 12. View of the first page of the app (A DFX Attribution Method in the Aerospace Domain).

Use of the app

The app provides tailored recommendations for DFX methodology based on user-defined project parameters. It utilizes the AHP to weight user inputs and generate a list of DFXs that best match the project's needs. The first step is to Input Project Quality Criteria Importance: input percentages for the following project quality criteria, ensuring their sum equals 100%: scope, time, cost, and quality. The app uses these inputs to understand the performance areas of the project to focus on.

Next, Input Project Types Importance (percentages) for the following project types, with their total summing up to 100%: Competitiveness, Customer Request, Reliability & Correction, Continued Operation, and Cost Reduction. These inputs help the app to gauge the strategic objectives of the project.

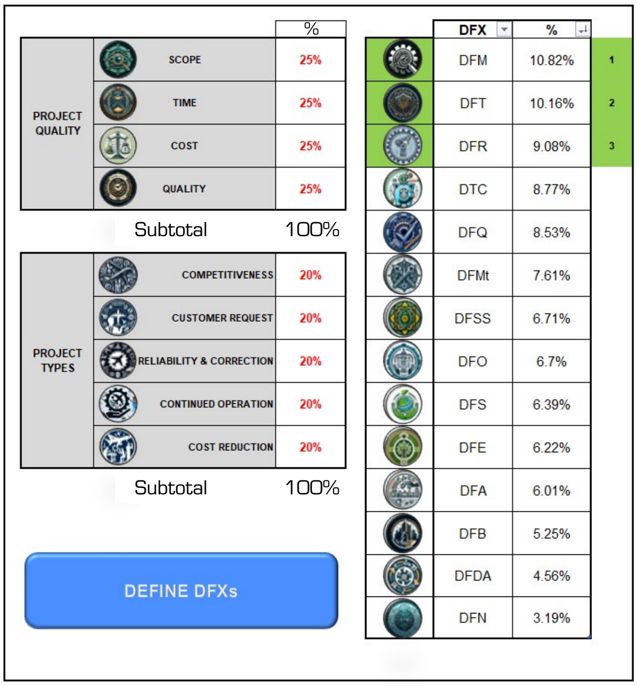
Subsequently, inputs are processed via AHP (once the user clicks “Define DFX’s”) to compare and prioritize different DFX methodologies. AHP creates a matrix based on the inputs and calculates the relative importance of each DFX. Results are then generated, ranking the DFXs based on their calculated importance scores. The app displays a list of recommended DFXs in order of their relevance to the project’s quality and type criteria. Users can use this list as a guideline for focusing their design and development efforts.

An iterative and time-to-time usage is recommended, where users can modify the inputs (percentages for project qualities and types) to see how different focus areas influence the recommended DFXs. This feature allows for exploring various scenarios and planning for diverse project requirements. This tool is a powerful resource to aid project managers, designers, and teams to align their design strategies with their project’s specific needs and objectives, aiding them in reaching optimal project outcomes.

Analyses – Illustrative scenarios

To obtain practical verification, the app tool has undergone testing in various circumstances, with the findings being compared to real-world practices. Two examples are shown below.

In the first example, each category has sub-categories with equal weightings, giving a balanced approach to evaluating project considerations. Project quality comprises scope, time, cost, and quality, each weighted at 25%, highlighting the fundamental aspects of project management. Project types encompass Competitiveness, Customer Request, Reliability & Correction, Continued Operation, and Cost Reduction, each with a 20% weight, reflecting the broader strategic objectives that projects may aim to fulfill. The output is depicted in Fig. 13.



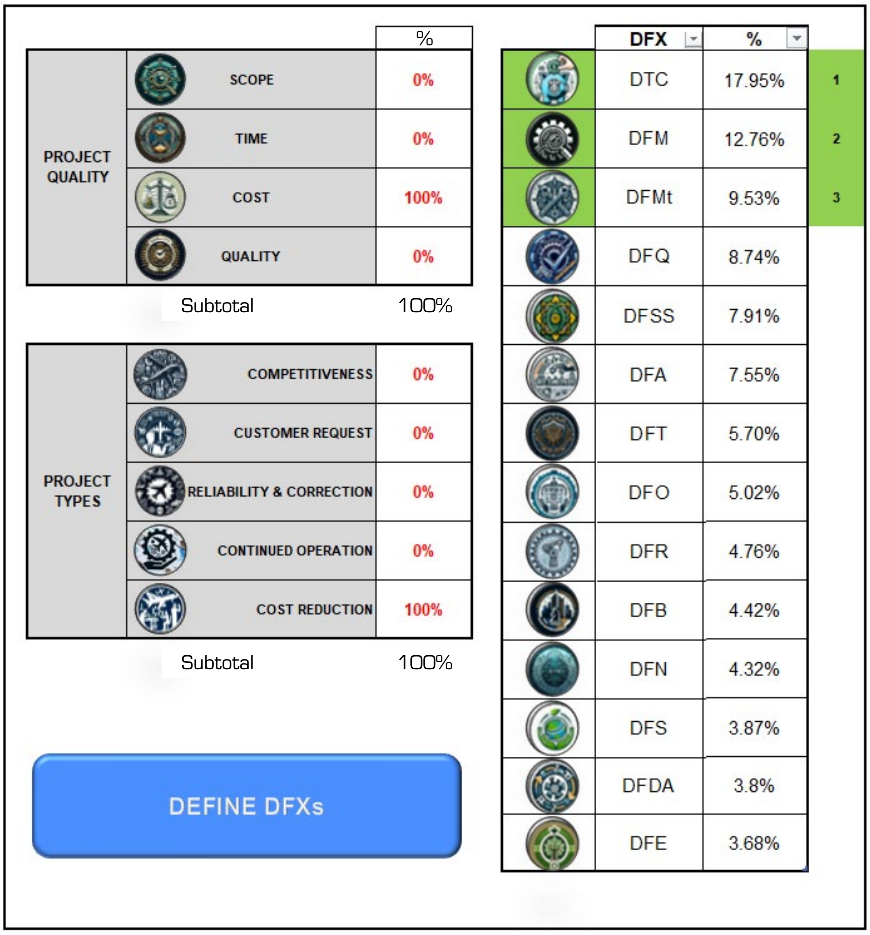
Source: Elaborated by the authors.

Figure 13. Scenario 1 – Equal importance to project types and project quality performance.

Figure 13 shows that the tool has made the following three major DFX Recommendations with nearly the same level of importance: DFM and DFT top the list, emphasizing their critical role in meeting diverse project requirements, from managing scope and cost to enhancing competitiveness and reliability. DFR and DTC follow closely, emphasizing the importance of reliability and cost-efficiency in both project quality and types.

This case exemplifies a complex multi-objective design scenario where nothing has been predetermined at all. The data suggests a need for a balanced approach in selecting DFX methodologies. While DFM and DFT emerge as broadly applicable, the importance of other DFXs should not be understated, especially in projects with specific focuses. The even distribution across project quality and types suggests that no single aspect should dominate the decision-making process. Instead, a strategic application of DFXs, tailored to the specific needs and goals of the project, is very crucial. The percentages associated with each DFX provides guidance for prioritizing various aspects depending on the project's specific objectives. Recognizing the strengths and applications of each DFX can lead to more informed decisions, enhancing the overall efficacy and success of projects.

The second example provides insights into the DFX preferences when cost considerations are paramount. The inputs were exclusively (100%) on "COST" under project quality and "COST REDUCTION" under project types. Figure 14 depicts the output for this case. DTC attained 17.95%, highlighting its primary relevance in cost-focused projects. DFM follows with 12.76%, suggesting that manufacturability is a major factor in controlling costs. DFMt holds 9.53%, indicating that ease of maintenance is important for long-term cost reduction. Products that are easier to maintain can incur lower costs over their lifecycle.



Source: Elaborated by the authors.

Figure 14. Scenario 2 – Full emphasis in cost.

This analysis reveals a strong focus on cost reduction. While this is important, exclusively prioritizing cost can overlook other critical aspects like quality, customer satisfaction, and sustainability. Even within a cost-focused strategy, the varied percentages suggest that a mix of DFX methodologies should be employed. For instance, while DTC is predominant, incorporating aspects of DFM, DFMt, and DFQ can lead to a more balanced approach, ensuring cost efficiency without compromising on other essential factors along the lifecycle.

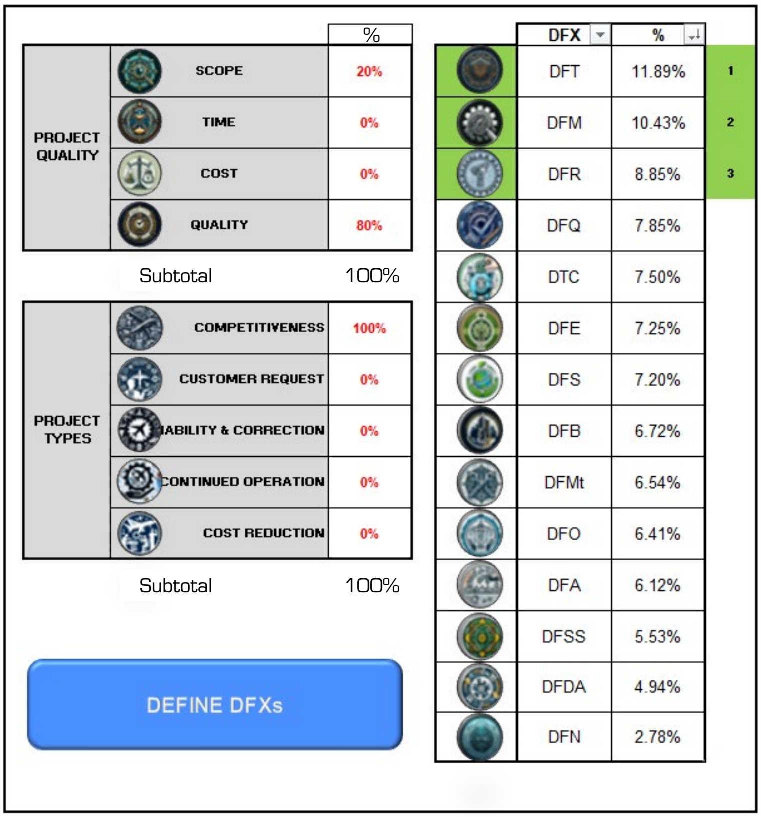
Additional verification – Retrospective analysis

In the quest for empirical substantiation of the method framework presented herein, a detailed retrospective analysis was undertaken. This analysis examined historical data from a project, hereafter referred to as "XWYZ" to maintain confidentiality. The project, conceptualized to bolster competitive advantage, due to incomplete scope comprehension, necessitating unanticipated rework.

The analytical technique adopted herein is grounded in the classical logical construct known as *modus tollens*, a form of negative reasoning in propositional logic. By applying this deductive reasoning, it is postulated that the absence of the intended outcome, namely "successful project completion as adjudicated by comprehensive quality criteria," logically infers the possibility that the method prescriptions, most notably the DFX approach as recommended by the proffered tool, were not adequately adhered to during the project's execution.

Project XWYZ faced numerous challenges from the outset, encompassing the procurement of premium quality components to navigating the intricacies inherent in sophisticated design paradigms. The project was bound by a liberal completion timeline, ostensibly within the normative industrial timeframes, with fiscal allocations strategically dispersed over the developmental trajectory. However, it is significant to note that the project team eschewed a selective DFX strategy, opting instead for a non-discriminatory emphasis on quality performance indices.

In this context, it is posited that, had the design team been furnished with the insights from the tool delineated in this exposition at the project's genesis, they would have been steered towards adopting a particularized DFX methodology, such as DFT, DFR, or DFQ. These approaches, whose salient features are encapsulated in Fig. 15, are corroborated by relevant works available in the literature.



Source: Elaborated by the authors.

Figure 15. Project XWYS_APP recording.

The retrospective analysis ventures beyond mere evaluative measures; it seeks to ascertain the contributory efficacy of DFX methodologies in circumventing the pitfalls encountered by project XWYZ. The inductive reasoning that emerges from the analysis is predicated on the hypothesis that a targeted DFX approach could have potentially obviated the need for additional rework. It would have provided a structured, criteria-based focus, facilitating a more coherent alignment with the project's objectives and quality benchmarks.

The simplification inherent in this retrospective approach should not be misconstrued as a trivialization of the complexities of causality within project management. Rather, it should be perceived as an illustration of the potential for method tools to pivot the trajectory of a project towards a more favorable outcome. The exemplification provided by the XWYZ project underscores the importance of methodical selection and application of design methods in early project stages, which could be crucial in preventing scope creep and ensuring alignment with quality parameters.

In conclusion, this retrospective analysis elucidates the implications of the methodological tool's absence, which, if present, could have been instrumental in steering the project towards a fulsome scope realization without the exigencies of rework. The discourse thus advocates for the primacy of a structured methodological approach in project design, especially one that is attuned to the nuanced demands of quality performance criteria.

CONCLUSION

The analysis of the results obtained through the AHP method provided a deeper understanding of the relationships between the DFXs and the different types of projects, DFX and project phases, DFX and project quality, providing valuable insights for project managers seeking improvements and enhancements. The analyses identified which aspects are most relevant in terms of competitiveness, customer requests, reliability, continuous operation, and cost reduction for each project phase, considering the project quality drivers. In special, it is interesting to observe the main DFX technological areas do not retains absolute, but relative importance in each project type context.

Considering the insights presented, the DFX methodology is a strategic imperative in the aerospace industry's product development landscape, transcending a one-size-fits-all approach. The complexity inherent in aerospace projects necessitates a framework like DFX, which addresses the multifaceted dimensions of product development and strategically aligns with the industry's progressive dynamics.

This research highlights the importance of a nuanced approach to employing DFX, one that demands a deep understanding of both the DFX technological areas and the unique contours of each project. The initial mapping of DFX's technological areas, as explored in this research, marks a significant stride towards this understanding, providing industry professionals with a foundational guidepost.

Particularly, DFT, DFM, and DFR emerge as cornerstone methods, especially in projects geared towards Operational Continuity and Competitiveness. These strategies, which focus on ensuring that products are efficiently manufacturable, reliably functional, and adequately testable, represent a triad of excellence in aerospace development.

Moreover, the findings emphasize the pivotal role of the engineering team's experiential knowledge in harnessing the full potential of DFX methodologies. The human element, characterized by expertise and adaptability, remains central to innovation and efficiency in this technologically driven sector.

Looking ahead, the dynamic nature of the aerospace industry, marked by rapid technological advancements and evolving regulatory standards, calls for an agile and strategic application of DFX. This agility involves not only staying abreast of technological trends but also cultivating a culture of continuous learning and adaptability among project teams.

In conclusion, the future of aerospace product development hinges on strategically curated and agile DFX applications, underpinned by a robust understanding of technological areas and an emphasis on continuous team competence development. By integrating DFT, DFM, and DFR into the initial stages, projects stand to benefit from reduced costs, enhanced quality, and streamlined processes, meeting the rigorous demands of aerospace standards. This work serves as a catalyst for further exploration and refinement in this direction, potentially paving the way for predictive and artificial intelligence (AI)-assisted decision-making frameworks in DFX application.

CONFLICT OF INTEREST

Nothing to declare

AUTHORS' CONTRIBUTION

Conceptualization: Copriva RG; **Methodology:** Copriva RG and Trabasso LG; **Validation:** Oliveira WR and Trabasso LG; **Formal analysis:** Oliveira WR and Trabasso LG; **Investigation:** Copriva RG; **Resources:** Copriva RG, Oliveira WR, and Trabasso LG; **Data Curation:** Copriva RG; **Writing - Original Draft:** Copriva RG; **Writing - Review & Editing:** Copriva RG, Oliveira WR, and Trabasso LG; **Visualization:** Copriva RG; **Supervision:** Oliveira WR and Trabasso LG; **Project administration:** Copriva RG; **Final approval:** Copriva RG.

DATA AVAILABILITY STATEMENT

The data will be available upon request.

FUNDING

Not applicable.

ACKNOWLEDGMENTS

Not applicable.

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