ISSN 1648-7788 / eISSN 1822-4180

VILNIUS TECH
Vilnius Gediminas Technical University

AVIATION

2025
Volume 29
Issue 1
Pages 30–38
https://doi.org/10.3846/aviation.2025.23175

COMPONENT DEFINITION INNOVATION PLAN AS A TOOL TO ALLOW FLIGHT SIMULATOR TRAINING DEVICE ROADMAPPING

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Article History:
- received 19 August 2024
- accepted 9 January 2025

Abstract. The use of flight simulators as a complement to pilot training offers significant advantages in reducing costs and risks associated with aircraft accidents, in addition to increasing safety and situational awareness during the practical phases of flight. However, the development of equipment to support pilot training has been carried out with an exclusive focus on this application, overlooking the exploration of alternative uses or new business opportunities that could diversify revenue streams and foster innovation. In this study, a method was developed to identify components that support the Technology Roadmapping process. The application phases are described, and each step is illustrated with a case study on developing a flight simulator training device. The results present potential markets, products, technologies, resources, and partners, forming a framework for innovation planning in aeronautical flight training. Specifically, the potential for implementing affordable full-motion flight simulators is examined, including applications in amusement parks for leisure, incentive flights for new crew, providing a passenger flight experience in the context of advanced air mobility, and, primarily, referencing flight centers to enhance airmanship skills and flight safety.

Keywords: aviation, pilot schools, planning tool, Stewart platform, technology roadmap.

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1. Introduction

Aviation can derive various advantages from using flight simulators for pilot training, such as reducing training costs associated with aircraft use (Torğul et al., 2022; Wu, 2020), enhancing pilots' situational awareness for real-life scenarios, minimizing accident risk (Grundy et al., 2016), and even optimizing training for military contexts (Källström et al., 2022; Vidakovic et al., 2021). However, the development of these devices has primarily targeted either training institutions or leisure purposes, with innovations focused on specific applications rather than exploring alternative market solutions and broader innovation opportunities (Dodgson et al., 2008). Technology roadmapping (TRM) may offer a valuable approach to optimizing innovation in flight simulator development.

TRM has been widely applied in the innovation planning of several organizations, aiming to analyse and strategically convey a business, enterprise, product, or technology (Phaal & Kerr, 2022; De Alcantara & Martens, 2019; Phaal et al., 2004). Its success is largely attributed to its simplicity, flexibility, and effectiveness (Vinayavekhin et al., 2021). Typically, the application of this tool generates a roadmap that guides efforts along paths defined by market directions for the innovative technology to be implemented (Phaal et al., 2005). When applications require analysis of both downstream and upstream elements related to TRM objectives, they become more complex, necessitating additional customization and adaptation of the tool. In the case of flight simulators, one such element is the need to align platform capabilities with flight training program requirements and, mainly, with regulatory agencies – this last requirement being a distinct characteristic of this innovation segment that influences the roadmapping process.

Understanding how to perform roadmapping in this situation is fundamental in using innovation-planning tools like TRM to develop this type of product. Adopting a flight simulator under development as a case study, the main objective of this study is to characterize and customize an innovation planning tool, especially with the application of TRM, for benefiting the aviation industry. Therefore, on the level of organizational roadmapping classification (Amer & Daim, 2010), the results of this paper present a roadmap containing some of the technologies required, possible products, target markets, the main resources, and partners.

Understanding how to implement roadmapping in this context is necessary for utilizing innovation-planning tools like TRM to develop this type of product. By adopting a developing flight simulator as a case study, the primary objective of this research is to characterize and customize an innovation-planning tool, particularly focusing on the application of TRM, to benefit the aviation industry. Consequently, at the organizational roadmapping classification level (Amer & Daim, 2010), the results of this paper present a roadmap that includes various required technologies, potential products, target markets, key resources, and partners.

2. Flight simulator training devices

Flight simulators play a fundamental role in pilot training. Given that initial flight training at aviation schools is costly (Torğul et al., 2022), flight simulator training devices (FSTDs) enable cadets to develop airmanship skills and undergo evaluation on the ground at a significantly lower cost (Wu, 2020). In addition to cost savings, virtual flight training mitigates the risk of human injury, damage to the aircraft structure, and various aeronautical accidents or incidents during practical training (Caetano, 2023; Grundy et al., 2016).

Not limited to civil aviation, FSTDs are also valuable for military training, enabling operations such as air-to-air refueling, airborne surveillance, carrier landings, landings in challenging infrastructure and difficult terrains, air-to-air combat without the expenditure of actual weapons, and team coordination akin to cockpit resource management (Borucka et al., 2024; Källström et al., 2022; Vidakovic et al., 2021).

The Federal Aviation Administration (FAA, 2024) stipulates that a minimum of 40 hours of total flight time be required to obtain a private pilot license, which is valid for both the rotorcraft category (helicopters) and single-engine airplanes. The FAA (2024) allows for a maximum of 5 hours of training credit using a full flight simulator or FSTD. According to regulations from the International Civil Aviation Organization ([ICAO], 2018), up to 50% of flight hours completed in simulators may be counted towards flight instrument rules training, as shown in Table 1.

Table 1 highlights the basic role that flight training devices play in flight training, particularly in reducing costs associated with flight time onboard an aircraft. It also demonstrates that flight simulators can be utilized even during initial flight training (PPL), underscoring the effectiveness and reliability of these devices in pilot qualifications, especially in preparing new pilots to refine their situational awareness in real-world scenarios (Vidakovic et al., 2021).

Given their extensive applicability in flight training, it is reasonable to invest effort in creating conditions that are more realistic and scenarios to deliver simulations that are increasingly indistinguishable from reality (Chertopolokhov et al., 2023). To achieve such improvements, motion platforms – designed to mimic natural movements through acceleration perception across all six degrees of freedom – can be a distinctive feature for equipping an FSTD. The most common model is the Stewart platform, also known as the hexapod (Vidakovic et al., 2021), which equips the FSTD used in this study case and has become a trend in flight simulator development in recent years (Wei et al., 2022). Figure 1 presents a general schematic diagram of a hexapod (Song et al., 2022), while Figure 2 displays a 3-D view of this equipment (Markou et al., 2021).

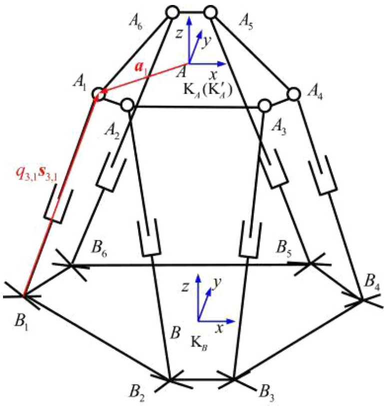

Figure 1. Diagram of a hexapod or Stewart platform (source: Song et al., 2022)

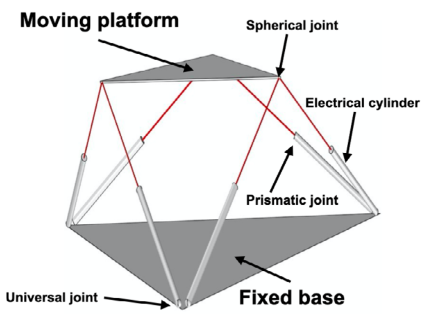

Figure 2. Stewart platform with universal and spherical joints (source: adapted from Markou et al., 2021)

Table 1. Personnel licensing requirements (source: ICAO, 2018)

Qualification	Airplane			Helicopter		
	Total hours	Simulation hours	Saving (%)	Total hours	Simulation hours	Saving (%)
Private Pilot License (PPL)	40	5	12.5	45	5	11.1
Commercial Pilot License (CPL)	200	50	25	150	30	20
Instrument Flight Rules (IFR) rating	40	20	50	40	20	50
Airline Transport Pilot (ATP) license	1500	100	6.7	1,500	100	6.7

As described in Figure 1, the Stewart platform comprises six actuators, numbered i = 1, 2... 6, along with various types of joints (universal, spherical, and prismatic). The notation A_i represents a spherical joint, while B_i denotes a universal joint. The relationships detailed in Equations (1) by Song et al. (2022) outline the primary interactions among the key components.

$$\begin{cases} s_{1,i} \perp s_{2,i}, s_{2,i} \perp s_{3,i}, s_{3,i} = s_{4,i} \\ s_{4,i} \perp s_{5,i}, s_{5,i} \perp s_{6,i} \\ i = 1, 2, \dots, 6 \end{cases}, \quad (1)$$

where $s_{j,i}$ represents the unit vector of the joint axis j in limb i.

Equation (1) demonstrates the orthogonal requirement for the $s_{j,I}$ vector, indicating that their dot product must equal zero. This implies that the axis cannot twist around its axis. Additionally, Figure 2 illustrates the main components of a hexapod and reinforces the notion that complex technological products, particularly in the aeronautical field, are assembled from various technologies sourced from different locations and manufacturers. An FSTD equipped with this type of structure is classified as a full-flight simulator (FFS). Figure 3 provides an example of an FFS, highlighting the development focused on effectively simulating motion cues.

According to Figure 3, flight simulator training represents a complex human-machine system that integrates technologies from different research areas. Figure 3 also illustrates the interaction between the product and the user (the pilot), who provides inputs and receives outputs (cues) in an interactive and continuous process.

As motion platforms are quite expensive (Wu, 2020), even considering their distinguished contribution to pilot training (Grundy et al., 2016), it is essential to achieve the best possible integration of a simulator's subsystems, such as maneuver controls, command responses, virtual reality, and internal sound, as well as their respective technologies. This can be accomplished through integrated innovation planning during the product development phase, utilizing concepts proposed in the literature, such as technology roadmapping.

Maintaining a technology roadmap that combines various solutions can optimize innovation efforts. Technological objectives, deliverables, and strategies can be clearly defined for each component, and technology routes to these objectives can be synergistically mapped. This approach enables the use of deliverables to introduce multiple innovative products to the market through a unified and integrative development program.

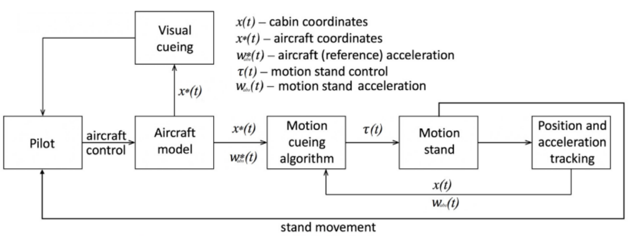

Figure 3. Motion cueing diagram (source: Chertopolokhov et al., 2023)

3. Technology roadmapping

The application of technology roadmapping (TRM) involves creating a strategic and flexible action plan that aligns with an organization's goals (Caetano & Amaral, 2011). The TRM serves as a framework that mobilizes efforts to achieve these objectives, often implemented through workshops with experts in the relevant field. Information and decisions gathered from these workshops are subsequently analysed and projected onto a roadmap, outlining potential technology pathways to guide the innovation process (Nazarenko et al., 2022; Vinayavekhin et al., 2021).

Typically, the general framework for constructing a roadmap for dynamic systems is organized in layers and arranged chronologically along a horizontal timeline (Phaal & Muller, 2009). The strategic directions highlight the technological phases of current and future objectives, as well as the present situation that the development team is considering and the efforts required to achieve the desired technological advancements. As a project becomes more complex, the roadmap will contain more information, making a structured framework essential for proper organization.

One attribute of TRM is its objectivity and impartiality, which are fundamental to avoiding limitations on its effectiveness, thereby preventing technically unfounded decision-making (Viola et al., 2022) and non-technically justified choices (Aleina et al., 2018). Utilizing technical methods or artificial intelligence techniques for data collection and processing can help ensure that the document is as free from personal bias as possible (Nazarenko et al., 2022). Often unconscious, some biases stem from personal misjudgments, which may be exacerbated by a false sense of expertise on the part of the roadmap builder. Nazarenko et al. (2022) emphasize that eliminating bias is one of the primary challenges to ensure the success of TRM.

The tangible characteristics of TRM include its visual and flexible representation (Vinayavekhin et al., 2021), which enhances the objectivity of the method, facilitates adjustments, and improves the reporting of desired information. Kerr et al. (2019) argue that adapting TRM to a specific context and benefiting from feedback information requires ongoing testing for its enhancement. Sensitivity analysis or post-optimality assessments should be conducted periodically, especially when strategic targets are redefined or environmental conditions change. One of the fundamental challenges in implementing TRM is maintaining its consistency, flexibility, and currency, as highlighted by Phaal and Kerr (2022). A proposal addressing this issue, which incorporates the principles of agile project management, is presented by Carlos et al. (2018) in Figure 4.

According to Figure 4, the definition of strategy routes (SRs) must be established by considering both market

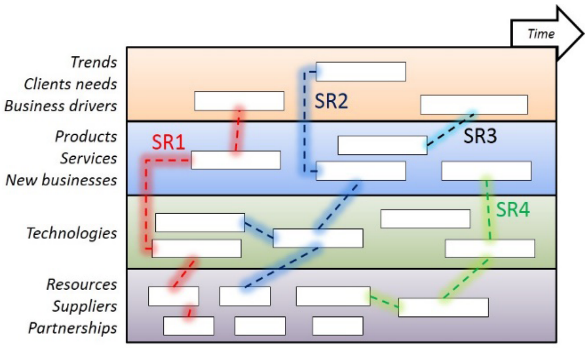

Figure 4. Technology roadmap (source: Carlos et al., 2018)

needs (demand-pull) and technological capabilities (technology-push) (Hötte, 2023). Key elements related to complex projects, particularly in aviation, include adherence to national and international regulations and ensuring operational safety (Yadav & Nikraz, 2014). This necessitates that the definition of the technologies to be developed and their associated resources align fully with the standards set by regulators.

TRM applications in aviation can be traced back to the early 1960s in organizations such as Boeing, Lockheed Corporation, General Electric (GE), Rockwell, and the United States Air Force (USAF) (Phaal & Kerr, 2020). However, TRMs that specifically address demand and trends related to professional development, such as flight training, are scarce in the scientific literature due to the challenges of identifying technological pathways for the intermediate elements in their conception.

Additionally, the application of TRM in the aerospace industry is evident in the studies by Aleina et al. (2018) and Viola et al. (2022), which highlight various characteristics specific to this sector, including numerous technical and operational requirements that must be met to enable the use of technology and enhance reliability. In the case of Viola et al. (2022), the authors incorporate the technology readiness level (TRL) into the TRM process and the construction of a roadmap, including methods for quantifying other indicators of maturity and technology availability. TRL is a scale that ranges from 1 to 9, representing the maturity level of a new technology in relation to its potential application and use in real-world situations (Mankins, 2004).

In the aerospace literature, there are proposals for planning technological advancements. However, a gap exists regarding the human factor in analysing products designed for flight training. This type of product requires robust user approval before market launch, which should be integrated into the TRM to ensure the product's success. Additionally, roadmapping for an engineering-to-order (ETO) strategy product differs from that for a make-to-order (MTO) strategy, which is more applicable to flight simulator projects. Consequently, a theoretical gap identified in the literature is the absence of a roadmap framework that incorporates training on the innovative technology or product being launched and its compatibility with MTO manufacturing. The application of TRM in aviation can enhance the aeronautical sector by providing a more transparent and scrutinized training program that effectively considers novel technologies. A pertinent example illustrating this necessity is the two Boeing 737 MAX 8 accidents, where a major contributing factor was Boeing's negligence regarding the training on the Maneuvering Characteristics Augmentation System (MCAS) Standard Operating Procedure (SOP) for failure scenarios (Jamieson et al., 2022). The relevance of this topic is underscored by the Safety Recommendations Report issued by the National Transportation Safety Board [NTSB] (2019), which, following the aforementioned accidents, recommended reevaluating assumptions about pilot training and responses to safety-significant failure conditions as part of the project certification process.

Furthermore, flight simulators are complex products whose development involves a technological package with many distinct technologies. They are also not the primary focus of the companies that commercialize them; rather, they are part of a larger development program that represents the company's main focus. How can a roadmap be utilized to address these cases? Aleina et al. (2018), in their study, applied to the aerospace sector, provide a relevant suggestion: the authors propose additional phases before the application of TRM, during which the mission and the product are defined, with the latter using functional modeling. Similarly, Viola et al. (2022) advocate for the use of a Product Breakdown Structure.

Neither of these solutions can be directly applied here. Given that flight simulators comprise a package of distinct technologies, identifying functions would become overly abstract. While Viola et al.'s (2022) proposal is more aligned with this study's objective, the focus here is on components rather than products, systems, and subsystems. Therefore, is it possible to develop a method for identifying components that could be beneficial for flight simulators? This has been explored in this study through a case study approach.

4. Case study

To optimize the development of a flight simulator device through the application of technology roadmapping, a case study was conducted with an ongoing project named EB#2. This flight simulator training device has been developed for research purposes in the field of human factors in aviation. Lemes et al. (2018) report the development stages, while some of the results obtained from its use are described in Macedo et al. (2020). Notably, its interior is adaptable for various aircraft categories, and its software supports the dynamics of different types of aircraft, ranging from the Cessna C152 to the Boeing B777-200. Table 2 presents the main components of the research protocol for the case study, following the procedures proposed by Yin (2018).

Table 2. Case study research protocol (source: adapted from Yin, 2018)

Component	Description
Case study overview	
Objective	Improve de innovation planning of an FSTD.
Research question	FSTD innovation development optimized by TRM.
Context	The project started in 2015, with an estimated cost of US$ 50,000, developed by professors, undergraduate and graduate students, currently in the prototype stage on TRL 5.
Data collection and reporting	
Procedures for interview and observation	Document analysis, semi-structured interviews with the project coordinator and team, as well as the physical prototype analysis.
Results format presentation	Reports, verbal communication, and scientific papers.
Schedule and deadlines	A total of 210 hours, distributed in twelve months, beginning in August 2022.
Cross-checking	Combine information from interviews with the project team and in-loco analysis.

Figure 5. External view of the prototype (source: the authors)

Figure 6. Interior view of the prototype (source: Lemes et al., 2018)

Both the equipment and the laboratory team responsible for its development – comprising five members, including professors and graduate students – were monitored through action research (Coughlan & Coghlan, 2002) to identify the main factors associated with the analyzed flight simulator that could be improved by TRM.

Due to its flexibility and adaptability, the EB#2 cannot be certified as a B772 FFS-type equipment, as it does not meet the requirements for an enclosed full-scale (1:1) replica of the original cockpit, including switches, knobs, throttle quadrants, and other components. However, because the EB#2 is equipped with motion cues, it is more effective for ab initio cadets (Vinayavekhin et al., 2021).

The primary goal of this case study is to establish a roadmap to guide the process of transferring this expertise for building more affordable hexapods to the market, adapting the simulated aircraft to a single-engine airplane, such as the Cessna C152. In other words, the aim is to facilitate the innovative process that will create the potential for this FSTD to eventually serve as the basis for an academic entrepreneurial model in the future. Figures 6 and 7 present the external and internal views of the prototype, respectively.

Figure 5 presents the FSTD from the outside, showcasing the base plate that connects the cockpit with the platform, as well as the joints and actuators (legs). Additionally, Figure 6 provides an interior view of the simulator, specifically highlighting the pedestal, rudder pedals, and side stick. Therefore, it is believed that the identification of both technological and market opportunities for this product can effectively leverage TRM.

5. Results

For the innovation planning of the flight simulator analysed in this case study, the subsystems – including the computer module, the Stewart platform, and the cabin – were initially identified, as illustrated in Figure 7, which demonstrates their interaction with the user. The pilot in training provides input parameters for the maneuvers, which are transferred via mouse commands to audio and visual outputs, as well as the movements executed by the platform. These inputs then return to the user through auditory cues (e.g., engine spooling up or shutting down), visual feedback (e.g., pitch changes), and acceleration sensations (e.g., yaw, vibration, g-force, etc.). The latter is processed by the flight simulator software and sent to the servo actuators, controlled by a MATLAB program and washout filters.

After identifying the systems and their subsystems, the next step involved technology roadmapping with the project development team, along with in-situ data collection. The constructed roadmap and its main elements are presented in Figure 8.

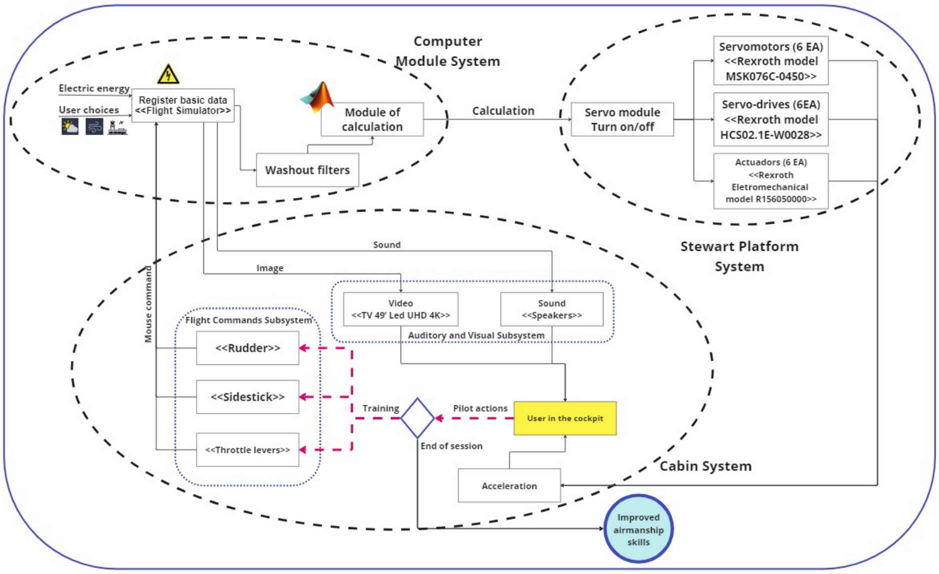

Figure 7. FSTD equipped with motion cues system (source: the authors)

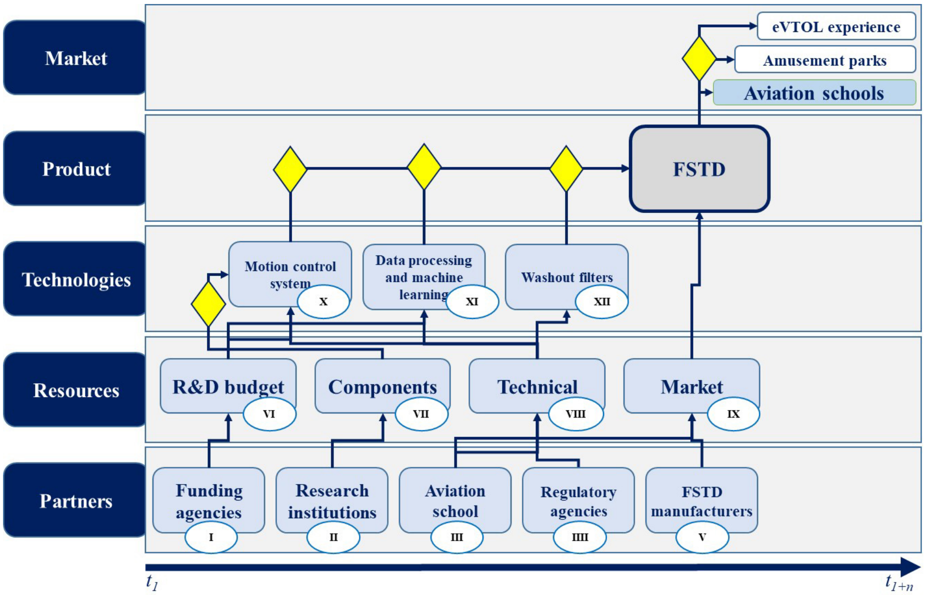

Figure 8. TRM on FSTD conceptual model (source: the authors)

The main elements described in Figure 8 include obtaining financial support from development agencies (I) to secure the necessary resources for the R&D budget (IV). Additionally, it highlights the necessary investment in the development of technologies associated with the motion control system (X) and creating mathematical models and algorithms for big data processing using artificial intelligence (XI).

Collaboration with partners such as research institutions (II) can provide essential knowledge or components (VII) used in the various subsystems. Engagement with aviation schools (III), regulatory agencies (IIII), and FSTD manufacturers (V) is also crucial, as they can offer support with technical (VIII) and marketing (IX) information and resources applicable to the development of the subsystems (X, XI, and XII). These integrated elements will ultimately be incorporated into the flight simulator for market introduction.

The potential new products can be targeted toward various markets, including aviation schools, incentive flights, amusement parks, and even providing flight experiences for passengers in advanced air mobility (AAM) settings. For instance, simulators could be used for public demonstrations of autonomous electric vertical take-off and landing (eVTOL) vehicles to foster user acceptance (Kiesewetter et al., 2023), especially given the anticipated significant demand for advanced air mobility (Justin et al., 2022).

In particular, item III suggests partnering with aviation schools to gain insights into the market and user needs. Given their close ties to the aviation industry, these schools can provide valuable perspectives on industry requirements and technology needs (Wei et al., 2022). Including aviation schools in the TRM process ensures that flight simulators are designed to meet the specific demands of the aviation sector. Furthermore, these schools could gain access to cutting-edge technology and offer students training on state-of-the-art flight simulators that accurately reflect the technology used in real-world aviation operations. This approach could lead to a more realistic and effective training experience, enhancing the functionality of the Stewart platform to simulate, for instance, eVTOL movements for prospective users of advanced air mobility (AAM).

Overall, the integration of all these technologies contributes to the proof of concept established by the simulator developers, alongside market and budget considerations. This framework will guide the innovation process and the training program, acting as a bridge between the new products developed from this prototype and its successful entry into the market.

Identifying the relevant regulations is essential, as a comprehensive set of requirements governs the registration of flight simulators. The five diamonds, or decisive moments, depicted in Figure 8, are strategically placed along the transition arrows to serve as certification gates. These gates were established during the roadmapping phase to ensure compliance with all requirements. Subsequently, regulatory agencies (IIII) can validate the technology and certify the product for aeronautical use.

Documentation of all necessary steps, tests, and actions taken is crucial throughout the entire predevelopment and development phases. The EB#2-simulator project has encountered challenges in this regard, complicating the assessment of its continuous improvements and evolution for potential investors.

Identification of various development timelines for the FSTD will depend on which alternative applications are considered, such as incentive flights, amusement parks, or eVTOL flight demonstrations. This determination can be guided by marketing parameters for prioritization, including market size and anticipated revenue (Ginieis et al., 2020), and the use of quantitative methodologies identified by Phaal and Kerr (2022) regarding when updates should be performed. Therefore, having possible metrics that reflect the efficiency of the TRM can enhance its credibility and sustainability within organizations, tackling one of the concerns raised by Petrescu et al. (2021) and Vatananan and Gerdsri (2012).

6. Conclusions

This study identified the key elements for innovation planning in the development of a flight simulator training device through technology roadmapping. It highlights potential markets for the simulator, including various applications for pilot training, incentive flights for aspiring crew members, entertainment, and flight experiences for new urban air mobility users. Additionally, it addresses the technologies required for each subsystem, the necessary resources, and possible development partners, all of which play a crucial role in guiding both research and product development while facilitating successful market entry.

The primary theoretical contributions include optimizing flight simulator development by leveraging this tool to identify diverse application opportunities, technologies, and partners, thereby enhancing the innovation process and recognizing market potential. Furthermore, the study contributes to the emerging landscape of advanced air mobility by recommending the planning of new products that offer flight experiences to potential urban air mobility passengers.

The practical application of component analysis in supporting the technology roadmapping process can also be instrumental in identifying the aviation industry's technology requirements, ensuring that flight simulators are designed to meet these needs. Engaging with industry stakeholders as part of an open innovation process can help developers better understand the technology demands and requirements of the aviation sector, ultimately leading to a more realistic and effective training experience for users.

The process of breaking down a new product project using technology roadmapping offers developers several advantages, including enhanced market insight and a clearer understanding of regulatory practices. This approach helps mitigate the risk of unexpected noncompliance with regulations. Furthermore, it facilitates the identification of potential risks and the estimation of the time required to complete the overall project. Given that the launch of complex innovative products relies on a set of deliverables that comprise a complete technological package, this type of planning provides valuable support for decision-makers and investors.

Future research opportunities in this field include evaluating the extent to which a full motion platform enhances flight training effectiveness compared to its associated costs. The objective would be to validate whether applying technology roadmapping could lead to a new business case and provide investors with estimated costs for new product development projects.

Acknowledgements

We would like to thank to National Council for Scientific and Technological Development – CNPq for supporting this research, both in the research productivity and scientific initiation modality. We would like to thank the reviewers and editor for their fundamental contributions to improving the study.

Funding

National Council for Scientific and Technological Development – CNPq.

Author contributions

GS, MC and DA conceived the study and were responsible for the design and development of the data analysis. GS, MC, DA and JB were responsible for data collection and analysis. All the Authors worked on the final version.

Disclosure statement

The Authors declare no conflict of interest.

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