Applying the Industry 4.0 Maturity Models to the Aerospace Sector

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Abstract

The aerospace industry is a sector with primary demand for mastering cutting-edge technologies and innovations. It has the potential to pull other sectors to previously unattainable levels. Its current transformations and emerging new vectors are of key importance for a wide range of areas in the economy and society. Currently, companies in this sector are faced with the challenges of mastering Industry 4.0 technologies. The article examines the main trends and technological achievements in the global aerospace industry. Based on the presented picture, the authors propose an adapted model for assessing the technological maturity of the aerospace sector, tested on the example of Brazil. Pilot testing of the companies included in it, using this model, showed that for most of the aspects considered, the level of technological readiness does not exceed the second (with a scale of five levels), and this is despite the fact that the products of the Brazilian aerospace sector are in high demand in many countries, including developed ones. The presented model can be adapted to assess the technological maturity of other sectors of the economy.

Keywords: global value chain transformation; innovation; aerospace industry; technological transformation; Industry 4.0; manufacturing technologies; technological maturity; national sectoral innovation systems

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Introduction

The aerospace sector a priori applies to those strategic, high-tech industries which, on the one hand, are drivers of scientific and technological progress, and on the other hand, make a significant contribution to increasing the mobility of society. The industry consists of three main industrial segments: the aviation industry (produces airplanes and helicopters), the space industry (creates space platforms, spacecraft, provides related services), and the defense industry (produces missiles, combat aircraft and works with other aviation and space technologies related to the military sphere). Its most characteristic feature is that the technologies, products, and processes are highly complex, while the military segment is usually ahead of the civilian segment in terms of the level of innovation (Bravo-Mosquera et al., 2022).

In recent years, this area has been developing dynamically, the developing market opens many opportunities that both investors and professionals respond to. There is an increased interest in the development of companies specializing in satellite technologies. The main focus is on the production of compact devices that can comprehensively analyze the Earth's surface, provide communications between highly protected servers, the operation of the global Internet of Things, and broadband communications for civil and military purposes.[1] Digital technologies are radically transforming production and industry models, changing the ways of providing services.

According to a Deloitte study on Industry 4.0, 84% of aerospace and defense executives are considering the new generation of digital technologies as one of the significant forces for achieving competitive advantages.[2] To study their transformation potential and the industry's readiness to master them, we apply a tool – an assessment of technological maturity (*technology maturity)*.

Based on this, we set out to explore existing methods for assessing technological maturity in the context of Industry 4.0. Using the example of the Brazilian aerospace sector, we demonstrate the model we have developed – the process of its formation, structure, and content. Current maturity models are poorly suited to a rapidly changing and increasingly complex context, as they are primarily theoretically focused, making them inflexible and unable to offer effective solutions to the problems at hand (Barata, Cunha, 2017).

After a comprehensive overview of technological trends in the global aerospace sector, we move on to describe the Brazilian context and then present a technological maturity model.

The Soft Transformation of the Global Aerospace Industry

To describe the evolution in the sector under consideration, we can use the term soft transformation, which, of course, does not exclude high levels of complexity and stress. A favorable, dynamic climate results from a successful combination of various factors: past developments, constant and growing demand for services and products, and orders for innovations. Large-scale investments (both public and private) are concentrated here, high standards of personnel, products and services training are observed, and innovations are continuously introduced and are aimed at increasing the efficiency of the sector, both in the production of products and in its management.

The aforementioned aspects, on the one hand, determine the relative well-being of the industry and increase its potential, and on the other hand, "make it feasible" only for a few countries.[3] Largely due to research and development (R&D), which, by definition, requires both a historical and competence-based background, namely, a solid scientific base. However, this does not mean that the industry does not face serious challenges.

The aerospace industry is becoming increasingly knowledge-intensive, with rising costs for specialization (Gkotsis, Vezzani, 2022). Patents, know-how, and new knowledge are driving the transformation of the sector, increasing the competitiveness of its companies. According to Deloitte, in 2023, the aerospace industry saw continued strong demand for products, particularly for new aircraft, due to the increase in transportation (Deloitte, 2024). In comparison to many sectors, the aerospace industry showed sustained positive dynamics (World Bank, 2020). The value of aerospace intermediate good exports grew by about 6% per year, increasing over the period from $272 billion in 2007 to about $536 billion in 2018. (Caliari et al., 2023).

The composition of the exported goods has also changed as the importance of intermediate production phases (particularly pre-assembly) has grown relative to the final goods. This trend reflects the fact that countries other than those where the main contractors are located are increasingly involved in aerospace value chains and can use their innovation and manufacturing capabilities to get closer to final markets.

Companies are able to maintain their leading positions by relying on economies of scale and intensive investments in R&D . Table 1 lists the main players in the aerospace industry according to their turnover.

Most of the companies are based in the US and Europe, with some of their activities related to the defense sec-

[1] https://www.boyden.com/media/aerospace-and-defense-industry-outlook-perspectives-on-future-6979750/, accessed 21.05.2024.

[2] https://www2.deloitte.com/th/en/pages/financial-services/articles/the-industry-4-paradoxes-the-challenge-of-digital-transformation-en.html, accessed 18.06.2024.

[3] The key players in the aerospace industry are related, first of all, to G7 countries (USA, Japan, Germany, France, United Kingdom, Canada, Italy) as well as China and Russia..

Table 1. **Major Players in the Global Aerospace Industry in 2020**

Company	Country	Annual turnover (million dollars)	Number of employees	Investments in R&D (million dollars)	R&D intensity (%)***
Lockheed Martin Corp.	USA	65 398.0	114 000	1157.2	1.8
Airbus	EU	61 409.0	131 349	3491.0	5.7
Boeing Company	USA	58 656.0	141 000	2674.9	4.6
Raytheon Technologies Corp.	USA	56,587.0	181 000	2683.8	4.7
General Dynamics Corp.	USA	37 925.0	100 700	414.8	1.1
China ASIC Limited **	China	37 075.2	–	–	–
Northrop Grumman Corp.	USA	36 799.0	97 000	–	–
Honeywell International Inc	USA	32 637.0	103 000	–	–
Bae Systems Plc	United Kingdom	26 161.0	81 000	283.8	1.1
Safran	France	21 635.0	78 892	1171.0	5.4
Thales	France	20 908.5	80 702	918.6	4.4
Leonardo SPA	Italy	17 060.4	49 882	1496.0	8.8
Rolls-Royce Holdings Plc	United Kingdom	15 867.8	48 200	1305.8	8.2
Bombardier Inc	Canada	15 462.0	16 000	387.2	2.5
Parker Hannifin Corp.*	USA	14 347.6	54 640	–	–
Avic Airborne System Co. Ltd.**	China	13 496.0	–	137.7	1.0
Textron Inc	USA	11 651.0	33 000	575.9	4.9
L3 Technologies Inc **	USA	10 244.0	31 000	–	–
Almaz-Antey**	Russia	9657.0	–	–	–
Huntington Ingalls Industries **	USA	8899.0	–	–	–

Note: Due to data availability, turnover figures may refer to 2021 (*) or 2019 (**). *** - R&D Intensity calculates as share of R&D investments in total annual turnover.

Source: authors, adapted from (Caliari et al., 2023).

tor. Airbus, Boeing, and Raytheon Technologies Corporation significantly exceed $2 billion in annual R&D investments. The national innovation system is an important asset in developing productsion capacities in this industry (Alberti, Pizzurno, 2015). Improving national capabilities is often seen as a government-oriented strategy, with governments committed to science and innovation (Lee, Yoon, 2015) and using industrial policies based on subsidies and public procurement (McGuire, 2014). The intellectual property factor is of high importance for the formation of national production as well as scientific and technological potential. The previously noted positive industry dynamics are reflected in the increase in the number of patents filed. Thus, during the period under review, according to statistics from the US Patent Office (US Patents and Trademarks Office) it grew fourfold (from 2,225 to 9,494). At the same time, the number of patent applications increased by about 20%, and the number of countries of origin of the applicants increased from 36 to 63 (Caliari et al., 2023).

Despite the described positive dynamics of demand, it is becoming increasingly difficult to meet it. One of the limiting factors is the shortage of highly qualified specialists capable of working with great complexity, both in the technological and managerial dimensions. Therefore, aerospace companies are in fierce competition with other industries for valuable personnel.

Another factor is the increasing complexity and vulnerability of supply chains.

The Changing Nature of the Aerospace Supply Chain

The aerospace industry is a high value-added sector, characterized by the strong role of national governments, linked to issues of sovereignty and efforts to implement strategies to promote industrial and technological capabilities. This is complicated by the fact that many different technologies contribute to the final products (Landoni, Ogilvie, 2019). The different stages of production in the aerospace industry are usually characterized by a multi-tiered supply chain structure.

Moving down the value chain, products exhibit a higher degree of technological content, become more industry-specific, and require greater innovation capabilities as well as closer relationships with leading companies. From a relatively low level of complexity to an intermediate level, which consists of integrating different components into subsystems, which in turn are used by primary contractors to produce the final products.

The relationship between countries' competitiveness and innovation systems depends largely on the product, but innovation capabilities generally become increasingly important as one moves along the value chain from basic components to final products embodying different technologies. The positioning of countries along the value chain is more closely related to the strength of the innovation system. There is a positive relationship between qualitative advantages in the innovation system and participation in the most sophisticated and valuable segments of the aerospace value chain. Countries that are better positioned to export products at the lower end of the supply chain (closer to the market) also have more developed and high-quality IP.

In terms of challenges for all industry segments, the most unifying one is the unprecedentedly complex and turbulent reconfiguration of global supply chains, making the implementation of diversification and transparency in the chain extremely problematic, but necessary.

These are points of vulnerability where delays in the delivery of necessary resources, slowdowns in production, higher prices for materials, and so on can potentially occur. Turbulence is observed at all stages of the chain - from raw material suppliers to manufacturers of equipment, semiconductors, microelectronics, and other key components. The search for raw materials, especially for rare earth minerals - a key component of electronics, is a unique problem, since their reserves are concentrated in only a few countries. There is no short-term alternative to them, most likely, this will only become possible in the distant future. Thus, enterprises are required to be especially insightful, inventive, and flexible in order to combine current developments with emerging ones, build up a strategic resource base for the production of critical products, and participate in the creation of new supply chain options. Recently, a new model of cross-border production relations has emerged – friendshoring.[4] In such conditions, companies can take an advantageous position in the supply chain, provided that they maintain strategic reserves of raw materials, ensure bulk purchases of goods with long lead times, and explore alternative supply channels.

Participation in global alliances provides opportunities for large aerospace companies to reduce production costs, fully utilize partners' technologies, and optimally allocate resources in favor of focusing on high-value-added production segments such as aircraft design, assembly, and marketing (Bamber et al., 2016; Niosi, Zhegu, 2005; 2010). The authors of the article (Caliari et al., 2023) analyzed the participation of countries at different stages of the value chain using data on the exports of products of different levels of complexity, as well as the effectiveness of their innovation systems, based on statistics about patents registered in the United States. Data on 38 countries for the period 2007–2018 were analyzed. A close relationship was found between the strength and sophistication of the innovation system and involvement in supply chains, and patterns of specialization of countries at different stages were traced. At the stages with high added value in the chains, there are countries whose innovation systems rely on the diversity and high quality of products, rather than on production intensity and quantitative indicators. Therefore, to maintain competitiveness, countries must make a greater contribution to the modernization of supply chains by improving their innovation systems, integrating different actors into it, and diversifying the knowledge base.

Key contractors are increasingly focusing on their core competencies, delegating *greater* responsibility to large suppliers to share risks with corresponding revenue distribution. The bulk of secondary functions are delegated to participants at lower levels of the supply chain, producing less complex products. Such a management structure allows for the organic linking of different stages in order of ascending added value. Key contractors operate at all stages of the chain, from R&D and design to providing high-level after-sales service.

"Low complexity" companies design parts for after-sales replacement, while "high complexity" manufacturing plants located closer to the end user place orders for them (Caliari et al., 2022).

The more complex the level of production, the greater is the contribution of the company to the creation of added value. This is also an indicator of the changed nature of aerospace value chains, where the traditional vertically integrated and geographically localized structures are being replaced by a specialization model with a translocal hierarchical structure, distributed along the links of the supply chain (Turkina et al., 2016).

The relationship between innovation and participation in value chains has two main characteristics: the importance of differentiated intellectual property (diversification among actors and technologies) and the role of prime contractors (Niosi, Zhegu, 2010). The industry relies on a system of scientific and technological organizations with different and complementary capabilities, as well as on the leadership of prime contractors, with traditionally key contributions from nation states.

The most successful countries tend to combine prime contractors and a strong innovation system, with strong public policy support. The United States, France, and Germany combine prime contractors and a large number of companies operating at high complexity levels (Landoni, Ogilvie, 2019; Robinson, Mazzucato, 2019). A counter-example is Brazil, which, despite having a world-class prime contractor (Embraer), has failed to use economies of scale and scope to develop a network of globally competitive local suppliers and strengthen its innovation system (Caliari, Ferreira, 2022). For countries specializing in sub-assemblies, the options for entering more complex global value chain (GVC) segments may be different. When the development of an innovation system is too complex, the capabilities offered to suppliers from GVCs can be decisive (Cooke, Ehret, 2009; Rebolledo, Nollet, 2011). However, the risk of lock-in at low GVC stages should be avoided. Mexico, Morocco, and the Philippines have managed

[4] Friendshoring is the practice of limiting the reach of supply chain networks to allies and friendly countries in order to minimize potential threats to business processes.

to achieve a relevant international position at the subassembly stage, but they have not developed technological capabilities at the same pace; this hinders their further improvement (Bamber et al., 2016).

Singapore has built competitive advantages in both components and subassemblies, coupled with significant growth in its industry-specific technological capabilities, putting the country in a stronger position in the aerospace sector.

It appears that the real challenge for developing countries that have established themselves in the production of low-complexity products through the fragmentation of aerospace value chains is to improve their technological capabilities to enter more complex stages of the value chain. Government policies should both guarantee access to the potential offered by participation in the chains and improve local capabilities. This, in turn, may impact IP through local suppliers' demand for an improved system (Lema et al ., 2019). The hierarchical governance structure of this industry is dominated by leading companies that maintain stable control over the value chain and its knowledge flows.

Technologies and Materials

Technologies. Among the industry's digital management technologies, digital twins are becoming increasingly popular, making processes occurring in supply chains as transparent and predictable as possible. This, in turn, optimizes production at all stages, increasing efficiency and quality standards. Digital twins can also be used to track the operation of parts and mechanisms throughout their entire service life.

Other important areas are the creation of engines that run on alternative fuels as well as supersonic and hypersonic aircraft. To solve these problems, it is extremely important to develop new materials that will reduce the weight of aircraft, which will reduce fuel consumption and increase overall strength.

In the defense segment, new geopolitical challenges and the task of modernizing the technical base have driven demand for next-generation innovations. For example, the United States is developing new-generation fighters based on adaptive engine technology. The possibilities of ensuring silent flight at supersonic speeds by reducing the intensity of the sonic boom are being studied. However, so far, these developments are only at an early stage. In addition to supersonic aircraft, the demand for defensive hypersonic technologies is growing. Due to the accelerating digitalization of the entire industry, cybersecurity issues are becoming increasingly relevant.

Materials. Aerospace product design today is dominated by high-strength composites and alloys of titanium, aluminum, steel, and carbon-reinforced polymers. These materials have advanced the industry in many ways. Their use allows aircraft to be lighter, save fuel, and carry more passengers and cargo, reduce noise and vibration, and improve thermal insulation. Modern composite materials are at the forefront of aerospace innovation. Research in this area is aimed at creating new composites with improved properties that promise super-strength, flexibility, and resistance to extreme conditions.

Additive manufacturing (3D printing) has become a radical innovation that facilitates the production of parts of particularly complex shapes compared to traditional technologies. At the same time, the total time and number of iterations of the production process are reduced many times over, and resources are saved.[5]

Another transformative direction for the sector is the use of "smart" materials. Their production actively uses bio-imitation principles, that is, the reproduction of the properties of various natural structures. They have the potential for self-healing, adaptation to changing weather conditions and increased functionality. Numerous sensors are built into them, allowing for the monitoring of structural integrity, stress, temperature, and other critical parameters of aircraft components in real time.

New technologies are paving the way for the industry to reach a new level. The fusion of smart materials and breakthrough technologies is taking the aerospace industry into areas of innovation previously thought unachievable. Artificial intelligence (AI) and machine learning have penetrated deep into the aerospace industry, analyzing massive amounts of data and running complex simulations to identify the most efficient design options.

Thus, it can be said that the industry in question has made significant progress in recent decades, largely due to progress and innovation in the field of structural and engine materials.

Space Business

The picture would not be complete without mentioning the main areas in the aerospace industry, where new companies are most actively created. More than 60,000 patents, over 10,000 implemented R&D grant projects[6], and high investment activity is noted. The largest investors are Fidelity, Geely, and BlackRock. Companies are developing reusable launch vehicles to further reduce the cost of launching rockets. An increase in space travel is expected, in connection with which the relevance of space traffic management systems and the development of clearing services in near-Earth space will increase. For example, a joint project Slingshot is being implemented in this area. The Defense Advanced Research Projects Agency (DARPA) is devel-

[5] For example, the General Electric plant in Brazil has managed to reduce the manufacturing process for some parts from two months to one day.

[6] https://www.startus-insights.com/innovators-guide/spacetech-startups/, accessed 16.07.2024.

oping a new system for detecting anomalous satellites.[7] Its task will be to serve several large satellite constellations of more than 10,000 spacecraft being formed by international government and commercial space operators. The system will be built on machine learning technologies based on more than 60 years of data. The system is highly adaptable and scalable, which gives it a wide range of potential applications outside the space industry, such as genomics, biomedicine, agriculture, and utility management. New space communication systems based on laser and quantum technologies are also being developed, providing higher data rates and better data security compared to traditional radio frequency systems.

Aerospace Industry in Brazil

Brazil is one of the few countries with a developed aerospace industry with strong potential, which is of strategic importance to the national economy. It creates jobs, stimulates R&D, and generates export earnings, which significantly contributes to economic growth and strengthens national security. This sector catalyzes innovation and high-value-added production, increasing Brazil's competitiveness in the global aerospace sector.

Leading national aerospace company Embraer (Empresa Brazil de Aeronáutica) is one of the world's leading manufacturers of regional aircraft, producing a variety of commercial, military, and utility aircraft, including the popular E-Jet series. Military aircraft (the AMX fighter and the super turboprop aircraft Tucano) are exported even to developed countries.[8] The national space program focuses on satellite development, space research, remote sensing, and telecommunications.

The Brazilian aerospace science and technology complex plays a decisive role in the development of the sector. The innovative ecosystem formed around it includes the following actors: the government, the army, the defense industry, funding and educational institutions, and accreditation bodies (Reis et al., 2021).

For example, in 2023, the Brazilian Ministry of Science, Technology and Innovation allocated BRL 1B from the National Fund for Scientific and Technological Development for five priority innovative initiatives to develop new satellites, with the participation of local universities and research institutes.[9]

It is planned build the Aerospace Technology Park to stimulate the innovative industry system. It will operate in four key areas: space, defense, aeromobility, and commercial aeronautics. In particular, the following sub-areas will be implemented: advanced flight and air traffic control systems, aerospace engineering systems, new energy and propulsion technologies, and aerospace cybersecurity.[10]

Close partnerships at two levels contribute to the development of innovation: nationally – between universities, research institutes, and industry, and internationally – in inter-country aerospace programs.

Brazil has managed to build a robust supply chain to support its aerospace industry, including the production of components and systems, which will allow it to fully exploit its potential in the coming years, in particular in expanding its market share in regional aircraft, leveraging its expertise in military aviation and exploring advances in space technology.

Development of a Technological Maturity Model

The presented literature review contains a sufficient knowledge base for the development of a technological maturity model in Industry 4.0 and its adaptation to the Brazilian aerospace sector.[11] The concept of "maturity" is characterized by a quantitative assessment and the assignment of a certain status in the development of a particular technology in terms of its applicability in the sector under consideration and the degree of integration into the industry strategy (Figure 1).[12]

In Figure 2, the relationship between the Industry 4.0 concept, maturity models, and the aerospace sector is reflected. The overlapping circles are the location of the proposed method, reflecting its synthetic nature. The stages of creating the proposed model are illustrated in Figure 3. Part of it was the development of a realistic and reliable questionnaire, therefore, in addition to studying the literature, a survey was conducted with the aim of obtaining reverse communications from specialists (from the scientific field and business).

Different maturity models presented in the literature were compared. Their key attributes were studied and those that the proposed model should consist of were identified, including the completeness and meaningfulness of the assessment questions, applicability to the specifics of the sector under consideration, and ease of use.

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[7] https://www.slingshot.space/news/slingshot-darpa-agatha-ai, accessed 07.08.2024.

[8] https://latamfdi.com/aerospace-industry-in-brazil/, accessed 12.08.2024.

[9] https://www.gov.br/aeb/pt-br/assuntos/noticias/empresas-brasileiras-celebram-investimento-de-r-1-bilhao-para-inovacao-no-setor-espacial, accessed 24.09.2024.

[10] https://gizmodo.uol.com.br/brasil-vai-ganhar-novo-parque-aeroespacial-veja-o-que-ja-se-sabe/l, accessed 24.09.2024.

[11] According to the Web of Science database on January 1, 2023, with the keywords "Industry 4.0" AND "maturity", 409 results were obtained. The publications started in 2015 with four publications, increasing over time, and in 2022, 116 papers were published. In comparison with the keyword "Industry 4.0", which has approximately 26,000 published works (only 1.6% of the total number of Industry 4.0 publications), leading to the conclusion that there are few publications on maturity in Industry 4.0.

[12] https://www.industria40.ind.br/artigo/19931-maturidade-para-industria-40-avaliacao-quantitativa-e-qualitativa-do-nivel-de-tecnologia-gestao-e-pessoas-para-implantacao-da-digitalizacao, accessed 24.09.2024.

At the initial stage of the model creation, existing approaches were analyzed, taking into account concepts related to aerospace sector. A total of 36 dimensions were identified. Similarities between them and the possibilities were identified. Synthesis within the questionnaire was ensured in such a way as to optimize the time spent by respondents on filling it out and at the same time not omit key aspects. It turned out that most existing models are dominated by issues of strategic planning and human resource management. For this reason, the first of the two basic dimensions of our model was "Strategy and People". The strategic component is vital for any organization or project, establishing the potential for long-term success, since it allows for the coordinated management of a diversity of available resources, processes, tools, practices, and behavioral models, which contributes to the achievement of the fundamental goal (Heerkens, 2007). The human component is important, since with changing market needs and technological developments, the requirements for competencies will change (Bonilla et al., 2019).

The second basic dimension of the model was the "Intelligent Factory" as a specific attribute of Industry 4.0. Smart factories are defined as the collection of machines, systems, and processes across the supply chain that form an interconnected ecosystem based on advanced technologies such as: AI, machine learning, big data analytics, Internet of Things, robotics, and automation.

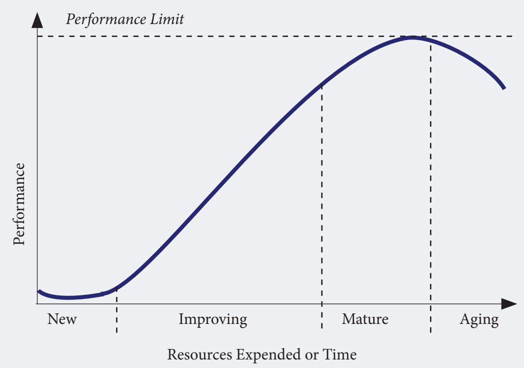
The block of questions for the first dimension contains 19 questions and the second is comprised of 16 (see Appendix).

We then moved on to defining the evaluation criteria. To convert the answers into a quantitative point assessment in maturity models, the Likert[13] scale is used most often. A five-point version of the scale was adopted, with the following levels of technology proficiency identified: 1 - "beginner", 2 - "learner", 3 - "intermediate", 4 - "specialist", and 5 - "top specialist". The company's maturity level is calculated as the average of these values (Figure 4).

In the "Strategies and People" block, calculations are based on 19 questions, and in the "Smart Factory" block, they are basedon 16. We implemented the maturity model in the form of online tools - a questionnaire with questions on two dimensions ("Strategies and People" and "Smart Factory"), a calculator, a dashboard, and monitoring.

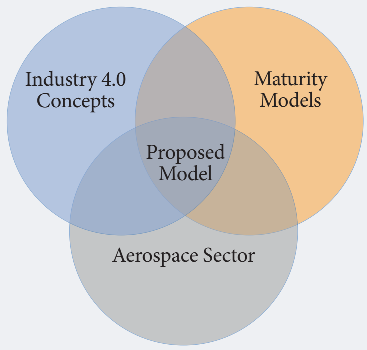
An adapted scenario was created for analyzing the survey responses and their targeting as well as receiving feedback (an example is given in Table 2). Then a panel was formed for tools, which was designed to display all the key indicators obtained from the analysis of questionnaires on one screen (Few, 2006). At the beginning,

Figure 1. **Technology Maturity**



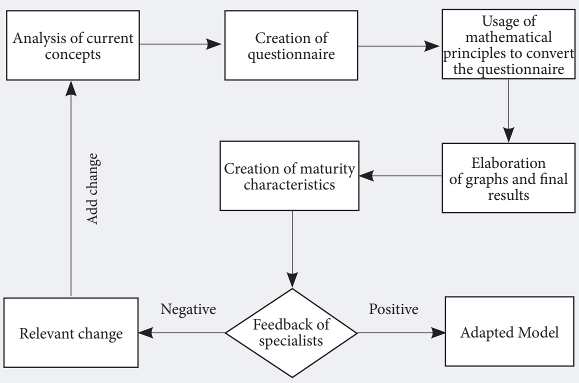
Source: compiled by the authors

Figure 2. **Venn Diagram**



Source: compiled by the authors

Figure 3. **Steps in the Model Building Process**



Source: compiled by the authors

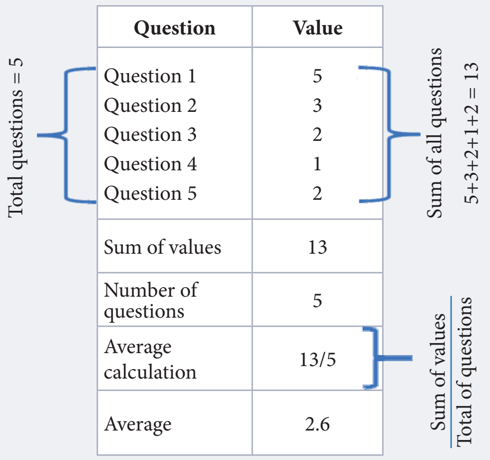
[13] See, for example, the works (Schumacher et al., 2016; Xavier et al., 2020), dedicated to the Business Intelligence Maturity Model, adopted by Hewlett - Packard.

Table 2. Examples of Questionnaire Prompts with Answer Options

Question	Answer options
9 – Have you created a roadmap with objectives related to Industry 4.0 at the organization?	A. No. B. There are studies underway to implement this. C. It is currently being implemented D. It is used in some projects. E. Yes
10 – Has the organization's decisions been based on data?	A. No. B. A few decisions C. Half of the decisions D. More than half of the decisions E. All the decisions

Source: compiled by the authors

Figure 4. Calculation of the Average Level



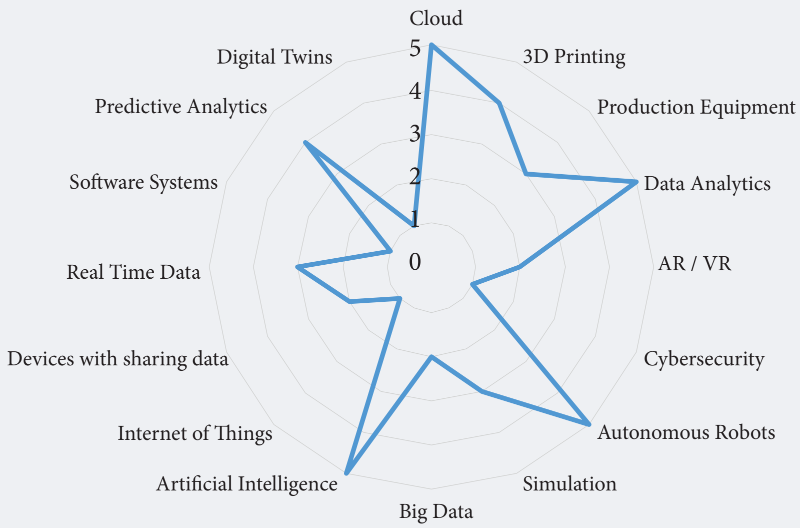
Source: compiled by the authors

Table 3. Survey Results

Components	Meaning	Proficiency level
Strategy and People		
Strategy Implementation	2.3	Learner
Partners	2.2	Learner
Investments	2.7	Learner
Data analysis	2.3	Learner
Employee skills	2.5	Learner
Development Areas	2.3	Learner
Indicators	2.2	Learner
Roadmap	2.7	Learner
Decisions using data	2.7	Learner
Agile methodologies	2.5	Learner
Multidisciplinary teams	2.7	Learner
Continuous improvement	2.3	Learner
Innovation management	2.3	Learner
Zero paper	2.3	Learner
Technology watch	1.5	Beginner
Leadership	2.3	Learner
Smart Factory		
Cloud	2.5	Learner
Data analytics	2.3	Learner
Cybersecurity	2.5	Learner
Simulation	2.2	Learner
Artificial intelligence	1.5	Beginner
Data sharing	2.4	Learner
Predictive analysis	1.5	Beginner
3D printing	2.4	Learner
Equipment	1.5	Learner
Virtual / augment reality	2.7	Learner
Autonomous robots	2	Beginner
Internet of things	2	Learner
Real time analysis	2.5	Learner
Software	2	Learner
Digital twins	1.5	Beginner
Average of both dimensions	2.23	LEARNER

Source: compiled by the authors

Figure 5. Smart Level Radar Chart



Source: compiled by the authors

one of five levels of proficiency in a particular technology is displayed (from beginner to top specialist).

The second part of the dashboard contains a variety of visualizations (in the form of radars, tree structures, and bar and pie charts). They reflect the current picture of the organization's level of mastery of certain technologies (Figure 5).

Tree maps provide an opportunity to study and select the most optimal option for managing these assets from a variety of available methodologies (for example, Scrum, lean manufacturing, Kanban, Crystal Family, hybrid methods). In general, the data panel can be flexibly configured and display the level of maturity of the company, both in general and in individual aspects. A "traffic light gradation" is provided when visualizing the assessment indicators, showing which aspects need more attention. To implement the presented tool in the Brazilian aerospace sector, invitations were sent to its constituent companies for pilot testing. Responses were received from 20% of those organizations. The results are presented in Table 3. It can be seen that in none of the aspects, according to the questionnaire prompts, did the companies achieve even an average level of competence. The lowest level (beginner) is observed in relation to technological monitoring, autonomous robots, AI, predictive analysis, and digital twins (all of which are included in the dimension «Smart Factory»).

Conclusion

Like most sectors, the aerospace industry is transforming and modernizing through the adoption of new production technologies and management methods. Given the sector's primary need for advanced technologies to ensure the maximum quality and safety of its products, all companies have found themselves among the first to face the challenges of mastering Industry 4.0 technologies. Technological maturity assessment models are being created to effectively manage these processes. The objective of this study was to develop such a tool, applicable to the specifics of the Brazilian aerospace sector, and to pilot it among relevant organizations. According to 2019 data, only 4% of the national economy's sectors could be considered to have adapted to Industry 4.0 (FIESP, 2019). In terms of the sector in question, our pilot survey of companies showed that they could be considered "learners" in most respects (average level - 2.23). In some aspects, mainly concerning Industry 4.0 technologies, only a starting level of maturity has been established, therefore, there is an urgent need to improve upon performance. There is sufficient potential for this, since Brazil ranks second in terms of the number of publications on maturity in Industry 4.0, and also it has the largest number of start-ups among all Latin American countries. Based on the above, it can be concluded that the country is moving quite dynamically toward the development of Industry 4.0, however, it is necessary that certain tools be employed to facilitate an increase in the country's technological maturity.

Our research can only be considered as initial contribution to understanding the maturity level of the Brazilian aerospace sector in relation to Industry 4.0 technologies and the prospects for its improvement. In this direction, continuous and in-depth expert work is required, taking into account the latest scientific and technological achievements. The interest in the process of assessing technological maturity in Brazil is growing, including from companies and universities related to the sector in question, which determines the relevance of the model we have developed.

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Appendix 1. **Questionnaire Contents***

1. The Strategy and People dimension

1- How would you describe the status of implementation of the industry 4.0 strategy in the organization?
2 – Does the organization have partners encouraging development in industry 4.0?
3 – Are these technologies being invested in the organization?
4 – In which dimensions do employees have skills for industry 4.0?
5 – How important is the use of data analysis in the organization?
6 – How many % does the organization need development work in relation to industry 4.0?
7 – Is there any action to obtain the missing skills (abilities)? (updates, seminars, courses, etc.)
8 – Are indicators and schedules being used for the implementation of industry 4.0?
9 – Was a roadmap created with objectives related to industry 4.0 in the organization?
10 – Does the organization make decisions based on data orientation?
11 – Does the organization use any agile methodology?
12 – Are the organization's teams multidisciplinary?
13 – Is any continuous improvement methodology being used in the project?
14 – Are innovation management tools used in the organization?
15 – Does the organization operate using the concept of zero paper – for documentation, data, etc?
16 – Is the organization familiar with the concept – technology watch?
17 – Is there collaboration (universities, companies, agencies, etc.) to prepare the project?
18 – On a scale of 1 to 5, which grade would you choose in relation to leadership of your organization (data-driven decisive – disruption driver – talent champion and social super)
19 – Do employees have the autonomy and freedom to manage their tasks, give opinions and change something?

2. Smart Factory dimension

1 – What is the level of use of 3d printers in the organization?
2 – Does the organization use cloud services?
3 – How advanced is the digitalization of your production equipment (sensors, iot connection, digital monitoring, control, optimization and automation?)
4 – Is data analytics (autonomous data examination) used in the organization?
5 – Are virtual reality and/or augmented reality used in the organization?
6 – Which of the following services does your organization use in relation to cyber security?
7 – Are autonomous robots used in the organization?
8 – Is adaptive robotic simulation used in the organization?
9 – Is data management and analysis done in real time?
10 – Is artificial intelligence (autonomous and flexible processes – pattern recognition) used in the organization?
11 – Is the internet of things (IoT) used in the organization?
12 – Can machines provide data and send it to computers in real time, which employees can communicate and connect with the devices?
13 – Is there integration of information sharing between departments in the organization?
14 – Does the organization use these systems for management? (example: PPS- production planning system, CAD – computer-aided design, PLM – product lifecycle management)
15 – The organization performs forecasting by analyzing different variables (predictive analysis)
16 – Does the organization use the concept of digital twins?

* Respondents have the opportunity to choose several answer options.
Source: compiled by the authors