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Abstract

This paper examines the role of small technology-based firms (TBF) in aeronautics industrialization processes. In particular, given the susceptibility of these firms to the changing nature of industrial production, it focuses on the integration and growth of small TBFs in aeronautics supply chains. We use the case study of Embraer, the Brazilian firm that leads the regional aircraft segment, to uncover processes through which small TBFs can integrate its supply chain, creating value and enhancing regional technological capabilities. This case is of particular relevance since Embraer pioneered the introduction of risk-sharing partnership for product development in aeronautics, followed by other aircraft manufacturers, which led to significant changes in the supply chains structures.

Based on 100 semi-structured interviews with leading experts in Brazil and Portugal, our research shows that aeronautics inherent specificities impose several challenges to the integration and growth of small TBFs into the aeronautics supply chain. We identify 11 main challenges for the integration and growth of small TBF suppliers in aeronautics, and 5 major reasons why despite these challenges, some of these firms make the strategic decision of entering this sector. In addition, we argue that small TBFs should be promoted through regulatory frameworks that take into account the aircraft development process.

JEL Classification: O14, O32, L52, L62

Keywords: *small technology-based firms, aeronautics, industrial dynamics, global supply chains, aircraft development*

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1. Introduction

Industrial landscape is being modelled and changed very rapidly by the increasingly fast pace of technology introduction as well as the intense competition in industries. Those challenges have forced companies to rely on a wide set of different actors, in order to compress their product development cycles (Fine, 1998). In addition, such unstable industrial environment have encouraged several countries around the world to adopt public policies aimed at attracting industrial investments with the ultimate goal of fostering and diversifying their technological basis (e.g., Baldwin, 2013). Research on industrial production has noted that developing countries have used offset agreements and other public incentives to accelerate growth, catch-up with major technological advances and quality standards, as well as to integrate local suppliers in global supply chains (Baldwin, 2013; Caves, 1974; MacPherson and Pritchard, 2003). More recently, advanced economies, seeking to strengthen their domestic manufacturing sector, have developed re-shoring policy initiatives (Bailey and Propris, 2014).

In specific sectors such as aeronautics, with stratified and hierarchical supply chains, the trend has been for manufacturers to outsource the development and production of several important parts (Niosi and Zhegu, 2005). Additionally, attempts to reduce steep development costs of new products in aeronautics resulted in the establishment of risk-sharing partnerships with suppliers of major modules, such as aerostructures, landing gears, and avionics (Ferreira et al., 2011; Figueiredo et al., 2008). These contractual modalities allow risk suppliers/partners to participate more actively in product development, sharing the financial risks of the launch of a new aircraft, thereby acquiring rights to their future sales income. Consequently, aircraft manufacturers (often called Original Equipment Manufacturers – OEMs) have become more specialized in systems integration and coordination. This global decentralisation of aircraft production has significant implications in the regional industrial structure, including effects on employment (MacPherson and Pritchard, 2003). In most cases, the decentralisation led to the disappearance of local capabilities that reduced the accumulation of knowledge, depriving the industrial ecosystem of new learning, which ultimately shrinks the potential for future innovation (Berger and MIT Task Force on Production in the Innovation Economy, 2013). These decentralisation processes affect differently the various stakeholders, and in this paper, we look specifically at the role of small technology-based firms (TBFs) in the development of industrial capacity in aeronautics, by addressing the question: how can small TBFs integrate aeronautics supply chains, creating value and fostering the development of regional technological capabilities?

Although a handful of studies focused on aeronautics industrial dynamics (e.g., MacPherson and Pritchard, 2003), less attention has been paid to small TBFs. Small TBFs in lower levels of the aeronautics supply chain are more susceptible to the changing nature of industrial production because they supply firms in upper levels of the supply chain, which shift their production to the most cost-effective locations. Thus, it is necessary to understand the opportunities for the integration and growth of small TBFs in aeronautics supply chains.

We use a case study of Embraer's supply chain to uncover processes through which small TBFs integrate and enhance the aircraft development process. Embraer provides an interesting case study because the company transformed their supply chain configuration with the introduction of risk-sharing partnerships in aeronautics in early 1990s. Our analysis focuses on Brazil and Portugal as these countries present distinct examples on the development of technological capabilities in aeronautics. On one hand, Brazil is the home of Embraer and several other firms that supply low value added components for this aircraft manufacturer.

On the other hand, the decision to establish two Embraer manufacturing facilities in Portugal in 2008, triggered firms' interest to integrate the aeronautics industry. Consequently, both countries are trying to ramp up their industrial systems, creating, developing, and accumulating technological capability in aeronautics. For this reason, these countries offer useful panoramas for understanding how to promote and develop small TBFs capable of fostering regional technological capabilities.

Drawing on 100 semi-structured interviews that were conducted with faculty and firm executives in Brazil and Portugal, our research results identifies twelve main challenges for the integration and growth of small TBF suppliers in aeronautics and for their transition towards higher value-added activities, namely: investment capacity, certification, business diversification, long cycles, low volumes, companies dimension, previous experience, no new big projects, liability, specialized knowledge, and parts dimension. In addition, our analysis shows that despite these challenges, some companies make the strategic decision of entering this sector due to five major reasons: master technological niches, acquire expertise, value creation for the firms, take advantage of spillovers effects, and for obtaining higher profit.

We argue that small TBFs play an important role in seeding aeronautics capacity in an uncertain industrial environment and should be promoted through regulatory frameworks that take into account the aircraft development process. To take full advantage on this role, aeronautics industrial policy should be aimed at the promotion of phases in which small TBFs are more likely to benefit from the changing nature of industrial production, namely: research and development (R&D), project development, project detail and specifications, and prototype. Furthermore, this work provides evidence on three strategies that small TBFs can use to move towards higher value-added activities in aeronautics: (i) establish join-venture partnerships with other companies, (ii) collaborate with research and technology organizations in the development of knowledge and technological competences, and (iii) participate in technological demonstrator projects that enable the integration and test of new technologies in real conditions.

The paper is structured as follows. Next section provides a global overview on aeronautics innovation dynamics, and the role of small TBFs in the industrial transformation process. Section 3 describes the methodological approach followed in this research. Section 4 contains our research findings, namely the key challenges and opportunities for the integration of small TBFs in aeronautics. Section 5 focuses on capacity building in aeronautics, more specifically on the integration of small TBFs in the aircraft development process, ending up with strategies that these firms can use to move towards higher value-added activities in this sector. Finally, Section 5 provides some final remarks on our analysis.

2. Theoretical Background

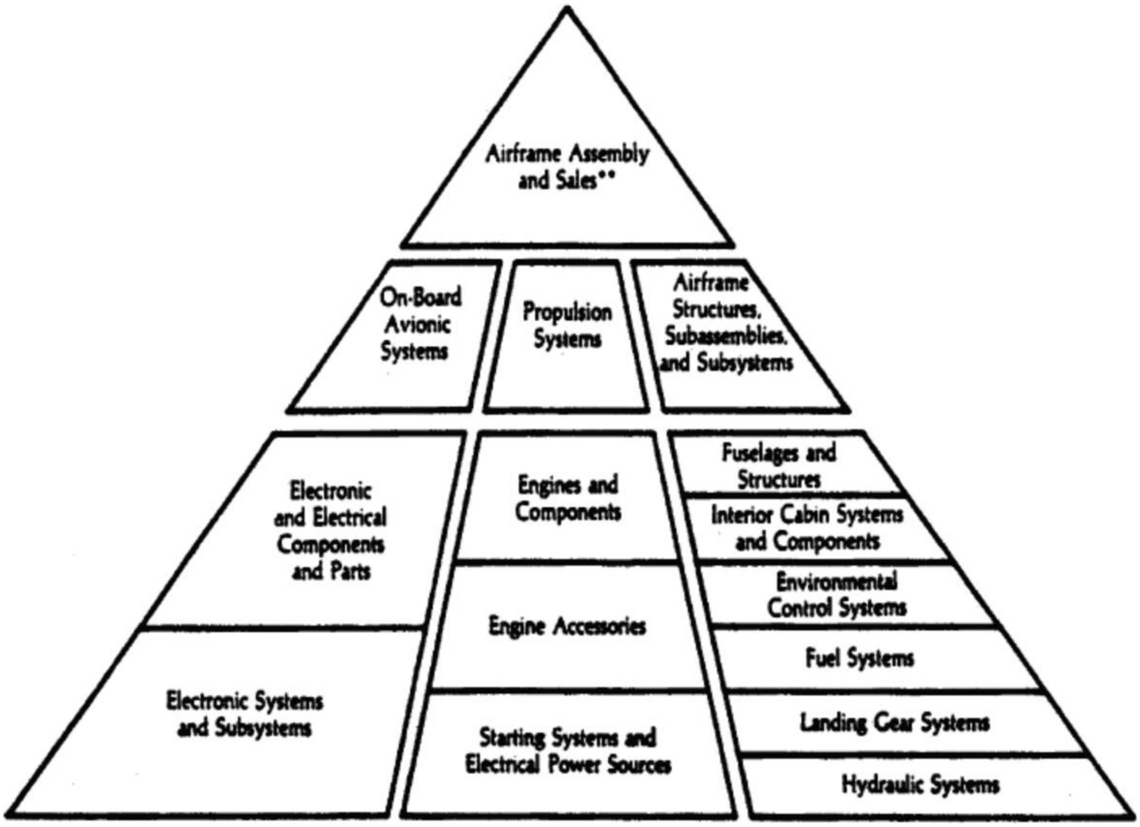
The changing nature of industrial production in aeronautics has been extensively studied in the literature from the viewpoint of incumbents (Hickie, 2006; MacPherson and Pritchard, 2003), and latecomers (Hira and Oliveira, 2007; McKendrick, 1992). Such a focus neglects small TBFs in lower levels of the supply chain. This paper examines how small TBFs can integrate the aeronautics supply chain, creating value and fostering regional technological capabilities. Thus, this section provides some background on aeronautics innovation dynamics, and on the role of small TBFs in the industrial transformation process.

2.1. Aeronautics Innovation Dynamics

In this research we focus our analysis on aeronautics, a knowledge intensive sector that represents an important case of industrialization. In fact, aeronautics has been considered of strategic importance for nations due to its potential at industrial dynamics, innovation, human capital development, enhancement and maintenance of national security systems and socioeconomic development in general (e.g., MacPherson and Pritchard, 2003). It has been, for example, the most important industry to the US economy in terms of skilled production employment, and exports (Pinelli, 1997).

The aeronautics industry has the particularity of being extremely globalized and centred in a small number of big corporations, following a stratified and hierarchically organizational model structured by “Tiers” (Niosi and Zhegu, 2005), as shown in Figure 1. At the top of the pyramid are aircraft manufacturers, who are responsible for the aircraft development and supply-chain management. These companies own the project and select major modules from 1st Tier suppliers, such as avionics systems, propulsion system, and airframe structures. At the subsequent levels one identifies a very concentrated group of small and medium-sized enterprises (SME), which provide parts and components to 1st Tiers, and sometimes even to aircraft manufactures. Building an aircraft is a complex process. For instance, the Boeing 787 Dreamliner has about 2.3 million parts that are designed and manufactured all over the world, and must be assembled together to build an aircraft (Boeing, 2016). Unsurprisingly, the ability to coordinate a global supply chain as this one involves a high degree of risk since when something goes wrong it impacts the whole aircraft production, and may result in major losses for companies (Simangunsong et al., 2012). For example, Boeing’s decision to outsource the design and manufacturing of major sections of the 787 Dreamliner resulted in defective aircraft components, major product delivery delays, and ultimately colossal losses for Boeing (Hult et al., 2010).

Figure 1 – Aircraft manufacturer’s pyramid



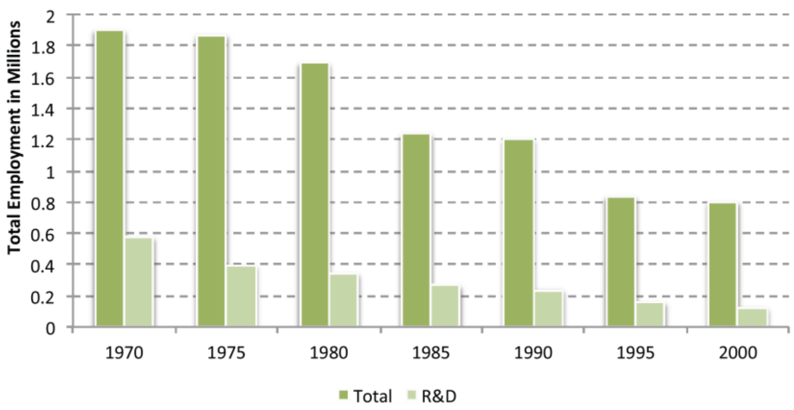
Source: Niosi and Zhegu, 2005

The increasing complexity and heterogeneity of emerging technologies, associated with high development costs of launching a new aircraft program makes this industry highly risky. For instance, Embraer, entered into an agreement with Argentina to produce a 19-seat passenger plane in 1987, and despite the programme technological advances, the project was a business disaster, accumulating losses of $280 million by 1990 (Hira and Oliveira, 2007). To avoid such results, secure the future of the company, and finance the development of a new programme, the ERJ 145 programme, Embraer pioneered the introduction of risk-sharing partnerships in aeronautics in early 1990s (Cassiolato et al., 2002). According to this contractual modality, risk suppliers help to finance the launch of a new aircraft programme, and in exchange acquire rights over its future sales income. At the time, four international companies became risk partners in the development of the ERJ 145 programme, financing more than $ 100 million from the $300 million needed to fund the project: Gamesa from Spain, Enaer from Chile, Sonaca from Belgium, and C&D Interiors form the US (Montoro and Migon, 2009).

Following this experience, and as aircraft manufacturers learned how to integrate geographically dispersed operations efficiently, they started to outsource the development of entire modules and systems to 1st Tier suppliers. Consequently, the number of 1st Tier suppliers has been decreasing over the years. For instance, Embraer counted just 38 suppliers (16 of which risk-sharing suppliers) for its EMB 170/190 model in 2000s, compared with 350 (4 of which risk-sharing partners) for its ERJ 145 in 1990s (Birchler et al., 2015). This drop in the number of 1st Tier suppliers enabled aircraft manufacturers to better manage them, reduce costs, and improve product quality by collaborating with the best companies in the sector. By following this strategy, Embraer was able to reduce its effort on development of some modules, focus on systems integration and on the development and coordination of its global supply chain (Ferreira et al., 2011).

These changes in the supply chain configuration impact mostly lower tiers of the supply chain, which usually supply less sophisticated products and are not able to evolve along with these changes. These shifts of industrial production favour geographic dispersion of manufacturers, which have implications in terms of the regional employment structure. In fact, the shutdown of a plant and its relocation abroad has important consequences in terms of regional employment, as it comes along with a boost of unemployment (Cowie, 2001). In Figure 2, we can see that US employment in commercial aircraft production has decreased substantially over the last decades.

Figure 2 – US employment in commercial aircraft production



Authors' elaboration based on data from MacPherson and Pritchard (2003)

Weber et al., (1991) shows that the criteria most often present in the outsourcing literature are: price, delivery, quality, production capacity, and location amongst qualified suppliers. Nevertheless, the reason for relocation of production in aeronautics is not exclusively shaped by cost, quality or logistic aspects, but also by industrial offset agreements (MacPherson and Pritchard, 2007). These agreements, in which aircraft manufacturers promise to purchase work and/or provide technology to firms within the buyer's home country in exchange for a sale, are widely spread practice in aeronautics. For instance, in 1997, the South Korean Asiana aircraft carrier was only given government approval to buy new aircrafts from Airbus and Boeing after their agreement to attribute additional manufacturing work to South Korean firms (Bowen, 2007).

Industrial offset agreements instigate the transference of scientific and technical knowledge to foreign firms. As a result, foreign firms get access to novel information and technologies, which allow them to develop internal capabilities. As foreign firms incrementally develop technological know-how and acquire production competences, they become capable of manufacturing more sophisticated components, which allows them to move up to higher levels of the supply chain. Therefore, over the years, aircraft manufacturers have become more and more dependent on outsourcing. For example, in the case of Boeing's exposure to foreign content, we observe that in the 1960s the foreign content of a Boeing 727 was only around 2%, increasing to 30% in the 1990s with the production of the Boeing 777 (MacPherson and Pritchard, 2003), while the Boeing 787 maintained an analogous ration of foreign content (Kavilanz, 2013), as shown in Table 1. The unprecedented difference of this programme was that almost 90% of the engineering, manufacturing, and integration of the aircraft was outsourced to supply partners, including the detailed design (Lamba and Elahi, 2012). Although more recent re-shoring policy initiatives in the US can lead to a decrease in these numbers and reverse part of this production migration, the rise of specialization and industrial segmentation within aeronautics makes aircraft manufacturers more and more reliant on outsourced work.

Table 1 – Foreign content in U.S. commercial aircraft production

	Boeing 727 (1960s)	Boeing 777 (1990s)	Boeing 787 (2010s)
Foreign Content	2%	30%	30%

Author's elaboration based on data from MacPherson and Pritchard (2007) and (Kavilanz, 2013)

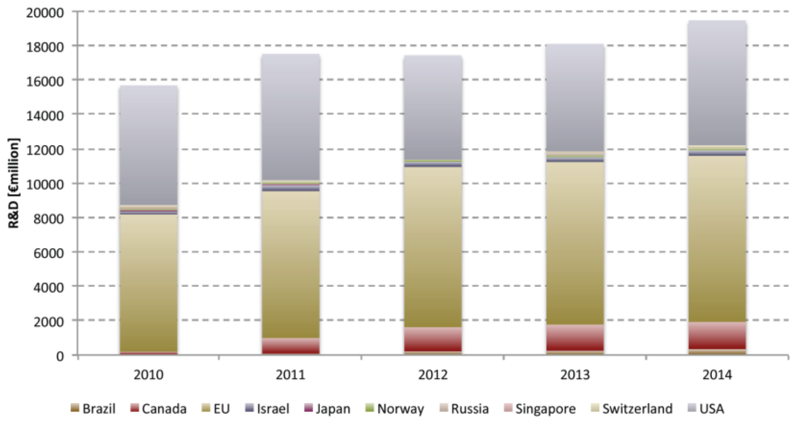
With low transport and communication costs, it is more cost effective to relocate certain production segments in low-wage economies. Global supply chains help structural transformation process by segmenting industrial production, and facilitating its relocation to other parts of the world. However, the industrialization process becomes "easier and faster", but at the same time locally "less meaningful" as firms in these countries can connect with international production networks, drawing on the technological and marketing expertise of leading firms in these supply chains (Baldwin, 2013).

In addition, research indicates that developing industrial capacity in aeronautics takes several years of continued investment. According to Hickie (2006), for example, it took more than half a century of continuous government policy to grow and develop an indigenous aircraft manufacturing industry in Toulouse, Seattle, and in the northwest of England. In the case of Japanese aeronautics firms, they were able to upgrade their supplier status within aeronautics' value chains by leveraging on their integration on Boeing's global supply chain (Kimura, 2007). This process was possible due to industrial policy, which allowed firms to have access to appropriate capital resources to fund this learning period. As a result, the firms had the support to acquire technological capabilities and the knowledge (Kimura, 2007). This is a good example of the role of policy in the integration of firms in aeronautics global value chains, and the effectiveness governments' incentives and targeted policies in the development of an aeronautics industry (Hickie, 2006).

The level of impact the delocalization has on regions also depends on their R&D intensity. Niosi and Zhegu (2010) showed that large firms in aeronautics can produce knowledge externalities in the region where they are located if they are intensive in R&D activities. Literature on economic growth advocates that investments in R&D and education play a crucial role in the knowledge creation and commercialization (Aghion and Howitt, 1998; Romer, 1990). As a result, several countries worldwide have made significant R&D investments with the goal of advancing national production (Mendonça and Heitor, 2016). In addition, Cabrer-Borrás and Serrano-Domingo (2007) noted that innovation in a region depends on its R&D efforts, its innovative tradition and its human capital endowments, and that the composition of economic activity has a positive effect on innovation. Thus, the more specialized regions are, the more innovative activity they have (Cabrer-Borrás and Serrano-Domingo, 2007).

Figure 3 shows the evolution of R&D investments of the top 1000 world companies in the aerospace and defence sector from 2010-2014. Despite the shift in industrial production, companies that invest more heavily in the aerospace and defence sector are extremely concentrated in the US, and some EU countries, such as The Netherlands, France, UK, and Italy, as well as in Canada, indicating that the geographic distribution of suppliers has not affected the distribution of knowledge production in the sector.

Figure 3 – R&D investments of the top 1000 world companies in the aerospace and defence



Authors' elaboration based on data from IRI (2016).

Aeronautics is widely recognized as a leading sector regarding technology and innovation (e.g., Hickie, 2006; Mowery and Rosenberg, 1981; Vértesy, 2011), driven by the need to reduce weight and costs, as well as meet strict regulations. Indeed, current aircraft configurations, such as the 787 represent great efforts to expand design and manufacturing capabilities (Slayton and Spinardi, 2016). The usage of carbon composites along with other technological advances in the 787 enabled Boeing to produce a more light weighted and efficient aircraft (Lamba and Elahi, 2012). In this context, and given OEMs' needs, aeronautics 1st Tiers suppliers are becoming more involved in R&D activities, making increased investments in R&D, and acquiring capacities from external companies. This trend allows suppliers to expand their engineering competences to further develop complex modules based on their internal knowledge. Consequently, suppliers' responsibilities shifted towards built to specification requests, which means they can design and manufacture modules based on specific operation parameters demanded by OEMs. Therefore, the relation between aircraft manufacturers and suppliers is transitioning from *build to print* to *build to specification* (Birchler et al., 2015). Aircraft manufacturers reinforced this trend by setting more complex specifications with stringent quality requirements and intellectual property transfer clauses. By doing this, the responsibility and liability concerning the part quality and design lies directly on the supplier. This displacement of manufacturing activities creates new windows of opportunities for small TBFs within the aeronautics sector.

2.2. The Role of Small Technology-based Firms

The literature shows that economic activity in manufacturing industries has been moving away from large companies to small enterprises since the 1970s (Acs and Audretsch, 1993; Carlsson, 1992; Carree, 2002; Loveman and Sengenberger, 1991). Several researchers contributed to our understanding of the reasons following this shift towards smaller businesses. For example, Loveman and Sengenberger (1991) highlighted the importance of two industrial trends: the decentralization and vertical disintegration of large companies, as well as the formation of new small business communities. These authors also stressed the role of public and private policies supporting small businesses. Carlsson (1992) argued that this shift towards small firms has been essentially driven by technological progress arising from flexible automation in combination with an intensification of global competition around the world. Nevertheless, the extent and timing of this shift differs across countries. Audretsch et al. (2002) find empirical evidence for 17 European countries over the period of 1990-1994 that the economic growth consequences of not moving the industrial structure away from large businesses towards smaller ones have been relatively large. Similarly, Carree (2002) use the case of five economies (France, German, Japan, United Kingdom, and the United States) to show that industries that underwent little downsizing in the 1977–1990 period also experienced less subsequent growth when compared internationally.

Small firms that have a technology focus are seen as an important source of innovative as they can act as agents of technological change, influencing the industrial transformation process, and are commonly referred in the literature as small technology-based (Audretsch, 2001). The environment and characteristics of small firms contribute to foster key product innovations as they are more freely structured and not yet locked into rigid hierarchical organizations (Abernathy and Utterback, 1979). As firms increase in size, the relations amongst employees become more structured and hierarchical organized, which tends to constrain the open and interactive flow of ideas. Small TBFs are especially prone to introduce innovations into the marketplace, which leads large firms to take different actions to protect their market share, improve their old technology, and acquire state of the art technologies (Bollinger et al., 1983). Research also suggests that despite being a massive investment commitment for small businesses, these firms appear to be better positioned to capitalize on new technologies. For instance, Meredith (1987) discusses the way small firms are leveraging on new manufacturing technologies, such as numerically controlled machine tools and computer-aided software, to develop a competitive advantage over other in the market. Cohen and Klepper (1992) discuss the firm size trade-off in the pursuit of technological progress, and explain that, if on one hand, the existence of small firms assures diversity of innovative approaches, on the other hand, large firms are able to make massive investments and take advantage of scale economies. However, even though large firms devote larger financial resources to innovation activities, small TBFs produced a remarkable share of key innovations (Audretsch, 2003).

Small TBFs, predominantly new ones, are an important source of new jobs and provide a crucial stimulus to national economies (Audretsch, 1995). For example, Feldman and Audretsch (1999) show that knowledge creation and knowledge spillovers are essential elements in stimulating economic development, and small TBFs act as a key element of technological change and regional competitiveness. Therefore, factors that drive their performances have increasingly attracted the attention of scholars, practitioners, and policy makers. For example, Venkataraman (2004) shows that the formation of Silicon Valley, currently one of the most dynamic regions in the world in terms of growth and innovation, was propelled mainly by new technology and the creation of start-ups over 40 years, which was only possible due to a set of conditions that came together, including: new ideas, creative people, and a culture of risk taking. The entrepreneurial ability has also been fundamental to the success of newly industrialized economics, such as Korea and Taiwan (Nelson and Pack, 1999). Moreover, Ács and Naudé (2012) argue that the development of small TBFs is dependent of the existent economic structure, and of their integration within productive chains.

Overall, the literature shows that small TBFs can act as engines of economic and technological change, but does not reveal strategies for their long-term development and contribution for the development of industrial capacity (Licht and Nerlinger, 1998). Thus, our research asks how small TBFs can integrate aeronautics supply chains, creating value and fostering regional technological capabilities.

3. Methodology

The present research used grounded theory-building methods (Eisenhardt, 1989; Yin, 2009) to unravel processes by which small TBFs benefit from their integration in the aeronautics supply chain, creating value and fostering regional technological capabilities. We conducted a case study of Embraer's supply chain in Portugal and Brazil. This case is of particular relevance not only because both countries have small aeronautical supply chains excluding Embraer, but also because Embraer pioneered the introduction of the risk-sharing partnership concept in aeronautics, which led to significant changes in the structure of their supply chain (Cassiolato et al., 2002; Figueiredo et al., 2008).

The region of São José dos Campos, in Brazil, is perhaps best known as the home of Embraer, the market leader in terms of regional jet deliveries (Vértesy, 2017). Apart from Embraer, this region has over 100 other companies [5] that play some role in aeronautics production and services, varying from the small and indigenous companies (e.g., Winnstal, a stamping company) to aerospace subsidiaries of major companies supplying Embraer (e.g., Aernnova, which assembles major modules and provides engineering services). However, despite Embraer's success as a regional aircraft manufacturer, many other Brazilian companies remained relatively small and confined to the provision of less sophisticated products and services, such as machining, stamping, and tooling. As found by Montoro and Migon (2009), these firms are characterized by knowledge deficits at the economic, financial, technological, managerial and market levels. In addition, Montoro and Migon (2009) noted that engineering firms are amongst the ones with the highest revenue due to the high technological value of their services.

Portugal is small and peripheral country of Europe that faces a singular moment in its aeronautics history due to the establishment of two Embraer manufacturing facilities in Évora, Portugal, in 2010. This event triggered the attention of many Portuguese firms to aeronautics (Mendonça and Heitor, 2016). Given the small number of companies working in the aeronautics sector in Portugal at the time, a supplier development program in cooperation with Embraer was put in place to qualify suppliers. In addition, the Portuguese Government allocated EUR 20.8 million until the end of 2017 to ensure the Portuguese participation the Embraer KC-390 program (Carregueiro, 2016), more specifically in the sponson, elevator, and central fuselage development (AICEP, 2013). Overall, the Embraer KC-390 accounts with participation of 13 Portuguese companies (Talixa, 2016).

As major OEMs become more specialized in systems integration, as well as in developing and coordinating their supply chains, they become increasingly dependent upon linkages between many different institutions and sources of knowledge (MacPherson and Pritchard, 2003). The increasing outsourcing of aircraft technology brings new challenges and opportunities for small TBFs. On one hand, by devolving R&D tasks without internalizing value chain activities inside the home country, the competitiveness of the local supply chain becomes strongly dependent on external factors (Luz and Salles-Filho, 2011). On the other hand, new technologies and aircraft architectures allow newcomers to enter this

[5] In 2016, the Brazilian Aerospace Cluster accounted with 111 members (Prefeitura de S. José dos Campos, 2016).

sector and become part of the supply chain. Thus, how can small TBFs integrate the aeronautics supply chain, creating value and fostering regional technological capabilities?

In order to address this issue, the research process conducted herein triangulated participant observation, qualitative interview data and archival data to provide a holistic view of the forces driving small TBFs integration in aeronautics (Jick, 1979). Results draw primarily from 100 semi-structured interviews with Embraer representatives, supplier managers, university professors, researchers and other experts who were somehow engaged in Embraer's supply chain, as summarised in Table 2.

The interview protocol used contained four main sections. The first part contained background and human resources questions. The second part was composed by questions about the main technological trends in the sector. The third part concerned suppliers' integration in aeronautics industry value chain, namely questions such as: is there a real opportunity to create a value chain for aeronautics, what are the main difficulties to develop technological capacity aeronautics, and how relevant is policy in this process. Finally, there was part about how beneficial were regional/local conditions to establish a local aeronautics industry. These semi-structured interviews allowed us to collect open-ended narrative data that preserved important details about the context of the firms.

Table 2 – Interviews overview

	Number of Interviews	Location
Embraer	32	Brazil & Portugal
Suppliers	24	Brazil & Portugal
Potential Suppliers	15	Portugal
Industry Associations	5	Brazil & Portugal
Research & Technology Organizations	10	Brazil & Portugal
Other	14	Brazil & Portugal

We identified key stakeholders through a snowball effect based on names mentioned in early interviews (Fuchs, 2010), as well as references in documents such as the catalogue of Brazilian aerospace suppliers, published by CECOMPI, a Brazilian entity that supports the local aerospace and defence industrial production (CECOMPI, 2014) and the directory of organizations that contribute to the aerospace sector in Portugal (Reis, 2011). Overall, we conducted the interviews to ensure that they included the different perspectives of OEM, suppliers, potential suppliers, academia, industrial associations, research and technology organizations, and other experts from the aeronautical industry. All interviews were conducted between January 2014 and July 2016.

In our research, and following the definition of Klofsten (1994), we considered a TBF a firm "whose strength and competitive edge derived from engineering know-how of people who are integral to the firm, and upon the subsequent transformation of this know-how into products or services for a market". Given that a central aspect of our research was role of small TBFs in aeronautics supply chain, our study focused specifically on suppliers and potential suppliers that fitted the standard definition of small TBF, which employ fewer than 500 employees (Audretsch, 2001). In Table 1, we categorised our sample of TBFs into different type of activities: design; electric equipment; engineering services; engineering services and assembly; engineering services and parts production; machinery production; metallic moulds production; metal treatment and coating; maintenance, repair and overhaul (MRO) services; parts production; and tooling.

Table 3 – Type of activities performed by the focal small TBFs

Type of Activity	No. Interviews	Size Class (No. Employees)
Design	1	10-49
Electric Equipment	1	50-249
Engineering Services	2	1-9
	5	10-49
	4	50-249
	1	250-499
Engineering Services & Assembly	1	50-249
Engineering Services & Parts Production	2	10-49
	1	50-249
Machinery Production	1	50-249
Metallic Moulds Production	2	10-49
	3	50-249
Metal Treatment & Coating	1	50-249
Parts Production	2	10-49
	10	50-249
	1	250-499
Tooling	1	250-499

We also conducted twelve participant observations throughout the course of the research to gather insights into the specificities of the aeronautics industry and supplier's role in technological development. For example, we were able to observe sessions of Embraer suppliers development program. These observations provided us rigorous and systematic insights on aeronautics supply chain's operation model. Examples of these events were the *2nd Universities, Information and Communication Technologies (ICT), and Business Cooperation Meeting*, the *1st Brazil-Sweden Aeronautics and Defence Workshop*, and the Aeronautics Innovation Roundtables in Portugal. We also attended a *Workshop on Additive Manufacturing* aimed at exploring technical and regulatory issues associated with the development and adoption of metallic additive manufacturing in aircraft engines and airframes that took place in Washington DC, US (Bonnín Roca et al., 2017). These events were aimed at exchanging ideas between industry, academia, experts and policy makers on critical issues to foster innovation in aeronautics, and were used to complement our interview data.

Table 4 – Overview of participant observations

Date	Event	Location
14.10.2014	2nd Universities, ICT and Business Cooperation Meeting	São José dos Campos, Brazil
21.10.2014	Participatory Planning Workshop	São José dos Campos, Brazil
07.11.2014	Session of Embraer Supplier Development Program	São José dos Campos, Brazil
13.11.2014	1st Brazil-Sweden Aeronautics and Defence Workshop	São José dos Campos, Brazil
17.11.2014	Session of Embraer Supplier Development Program	São José dos Campos, Brazil
21.11.2014	Meeting with Embraer Technology Development Team	São José dos Campos, Brazil
16.01.2015	Fostering Global Supply Networks – the case of Portugal	Porto, Portugal
24.02.2015	Challenges in engineering design for complex engineering systems in Aeronautics: looking at case studies	Lisbon, Portugal
19.06.2015	Workshop on Additive Manufacturing	Washington DC, US
22.09.2015	Meeting with Embraer Technology Development Team	São José dos Campos, Brazil
04-05.02.2016	Meeting with Embraer PT	Évora, Portugal
24.06.2017	Airbus Conference: *Building the Future of Flight*	Le Bourget, France

Finally, we were able to draw on archival data available through the *Instituto Tecnológico de Aeronáutica* (ITA) libraries. Moreover, a host of information about both Embraer and suppliers initiatives can be found in popular press and in industry trade journals. We used this material to document the processes through which TBFs can integrate the aeronautics supply chain, creating value and fostering the development of regional technological capabilities. In Table 5, we group our archival data into different categories: reports, magazines, and Internet.

All the recorded interviews were carefully transcribed on from July 2015 to August 2016, and field notes from interviews and from participant observations were transcribed mostly within 24 hours after the event. At this stage, we wrote an overview of the supplier selection process using the interviews, observational, and archival data (Eisenhardt, 1989; Yin, 2009). The use of different data sources allows for data triangulation, thus improving the robustness of research (Jick, 1979). We then used coding techniques to look for the most noticeable constructs and themes across the collected data (Corbin and Strauss, 2008; Miles and Huberman, 1994). We performed an open coding of the interviews and participant observations, which generated 79 different codes that proved to be extremely useful to structure the findings and discussion chapters that follow. We continued with a first and second level coding to aggregate the previous codes in more general themes (Miles and Huberman, 1994), which resulted in the emergence of challenges and opportunities that small TBFs face when integrating aeronautics (see Appendix A for coding structure and sample interview transcripts). To provide more insight about the research findings frequency analysis was also employed. From the emerging constructs and themes, we developed a tentative theoretical framework for capacity building in aeronautics through the integration and growth of small TBFs. The literature was consulted frequently to appraise consistence between the findings and extant theories (Miles and Huberman, 1994).

Table 5 – Summary of archival research sources used in this research

Archival Research Category	Documents	Reference
Embraer	Quality Requirements for Suppliers Investors Relations	(Embraer, 2010) (Embraer, 2016).
Reports	International Civil Aviation Organization, European Commission, Brazilian Industrial Development Agency	(ICAO, 2007),(ECORYS, 2009), (ABDI, 2014)
Books	Brazilian Aeronautics Production Chain - Opportunities and Challenges	(Montoro and Migon, 2009)
Thesis	Massachusetts Institute of Technology	(Chang, 2009)
Magazines & Newspaper Articles	Portugal Global, Exame, Aviation Week & Space Technology, Financial Times, Jakarta Post	(AICEP, 2012), (Coutinho, 2010), (Flottau and Norris, 2014), (Weitzman and Done, 2009), (Oliveira and Bigarelli, 2017), (Sapiie, 2016)
Internet	Richard Aboulafia, Airmod, ITA, Brazilian Funding Authority for Studies and Projects, Airbus, AeroWeb, International Organization for Standardization, SAE International, Boeing, Airway, Global Security, TEDxAlAin	Aboulafia (2015), (Airmod, 2016), (ITA, 2016), (FINEP, 2013), (Airbus, 2013), (AeroWeb, 2017), (ISO, 2017), (SAE International, 2017), (Boeing, 2017), (Vinholes, 2017), (Global Security, 2015), (TEDxAlAin, 2011)

4. Overview of the Supplier Selection Process

Introducing a new aircraft into the market is a long process. It takes around 10 years to design an aircraft that is produced for 20 to 30 years (ICAO, 2007). The massive development costs, as well as the long payback periods make this industry extremely risky. For instance, the development cost estimates for the A380 reached US$ 15 billion in 2004 (ECORYS, 2009). Once an aircraft manufacturer partners up with a supplier, the partnership usually lasts for the entire lifetime of that particular aircraft program, which stays in service for 30-50 years. Therefore, if a company misses out the window of opportunity to partner up with an aircraft manufacturer at the start of a new program, it is extremely difficult to enter the programme later on. For this reason, firms must be qualified as a supplier before the beginning of a new development cycle.

Potential suppliers are evaluated based on different criteria, including: commercial offerings, ability, capacity, integrity, financial health, geographic location, performance, reliability, quality, on-time delivery, and customer-supplier relations, and a fundamental aspect is the supplier’s proven ability to manage its own suppliers (AeroWeb, 2017). Given that OEMs must ensure the integrity and flight safety of all products received from its suppliers, suppliers are required to be certified ISO 9001 and AS 9100 at minimum (Airbus, 2013). While ISO 9001 is an international standard of quality management that is intended for companies and organizations within different industrial settings meet their costumer’s requirements (ISO, 2017), AS 9100 is a quality management systems developed for use within the aerospace industry (SAE International, 2017). Although different countries release the standards under their conventions (in Europe the standard is released as EN 9100 and in the US as SAE AS 9100), the versions of the standards should be similar in content, and thus the standard is recognized worldwide (Boeing, 2017). Additional requirements on quality and processes might be required on a commodity basis (Airbus, 2013).

Likewise, Embraer's suppliers have to comply with a series of requirements that are published in the Embraer Quality Requirements for Suppliers, which adhere to the aerospace standard (AS 9100) as a quality management system basic requirement (Embraer, 2010). Depending on the type commodity to be supplied, suppliers may also have to comply with an additional set of requirements. If the supplier does not comply with a specific requirement, a waiver may be requested and negotiated with Embraer. After complying with the agreed set of requirements to be fulfilled, the supplier is included in the list of qualified suppliers.

Although Embraer's supplier selection process is centralized in Brazil, different units within the company deal with international and Brazilian suppliers. Both suppliers' selection processes encompass a risk assessment analysis of the potential suppliers according to different criteria, such as financial capacity, compliance with environmental legislation, possibility of strikes, as well as operational capabilities of the potential supplier (Contract Administrator, 2014). The overall score of a supplier is calculated using a multi-criteria model, in which Embraer assign a weight coefficient to each criterion, and assess a value score for that criterion (Contract Administrator, 2014). The criteria that account with the highest weight coefficients are the operational and financial performance of the suppliers (Contract Administrator, 2014), and the appraisal of suppliers according to each criterion is made according to the SAE J4000 standards (Supply Chain Analyst, 2014). This standard is used to identify and measure best practises in the implementation of lean operation. The resulting overall score is used to classify the supplier into different risk categories. For instance, a supplier that is classified as a high-risk supplier has to take some actions in order to lower its risk-level. Otherwise, Embraer will initiate the phase-out process of that supplier, which means that Embraer starts transitioning the all parts numbers (PNs) provided by the supplier in the phase-out process to other suppliers that present a lower risk level.

Hence, once Embraer is looking for suppliers for a specific PN, it asks all the qualified suppliers to provide that PN and that are not blocked from bidding to quote that PN. Potential suppliers receive requests for quotes according to their production capabilities and if they are interested in supplying that PN, they submit a bid. Afterwards, Embraer appraises the quotes and selects the supplier for that PN. In addition, there are particular situations in which Embraer is interested in qualifying new suppliers for specific PNs (Product Development Engineer, 2014). For example, if Embraer identifies a supplier of a particular technology with great potential for the development of the aircraft, it is not uncommon to help the supplier to get qualified. Other situation occurs when Embraer aims at reducing its dependency of a particular supplier, and fosters the development of alternative suppliers.

We also observed that Embraer played a role in fostering the development of Brazilian small TBFs through their supplier development program. As Embraer focused on coordinating a global supply chain, it started outsourcing its low value-added activities from Brazilian small TBFs. Following this production shift, Embraer developed a program to aid these firms to improve their production and quality processes in order to increase productivity and reduce costs.

Similarly, when Embraer announced the investments in Portugal in 2008, there were a small number of companies working in aeronautics, and it was considered critical to develop a network of local suppliers. Therefore, in 2009, within a joint effort between Embraer and the Portuguese Government, and with the support of industry associations (Pool.net and PEMAS), several Portuguese companies participated in awareness sessions aimed at disseminating the path to become a qualified supplier for aeronautics, with visits to OEMs in Belgium, Brazil, Spain, and Portugal (AICEP, 2012).

Additionally, a group of companies was selected to participate in a supplier development program intended for qualify companies as Embraer suppliers. Within this qualification process, Embraer disseminated amongst the potential suppliers all the general and special process standards that suppliers must comply with. In addition, people from Embraer's commercial, manufacturing, and quality departments went to the sites of potential supplier to help them develop an action plan, which contains the steps required to get qualified and the correspondent timeline (Product Development Engineer, 2014). Within this process, firms were required to produce a *tryout* part according to the drawings received from Embraer, and prepared a bid for it. Despite having to support all expenses, including the expenses related with Brazilian technicians, the firms enrolled in this qualification process benefited from the interaction between Portuguese and Brazilian experts, especially considering that the supplier selection process is centralized at Embraer headquarters in São José dos Campos, Brazil (Coutinho, 2010). In particular, the 12 firms that got qualified as suppliers of Embraer over a four years period (President, 2016).

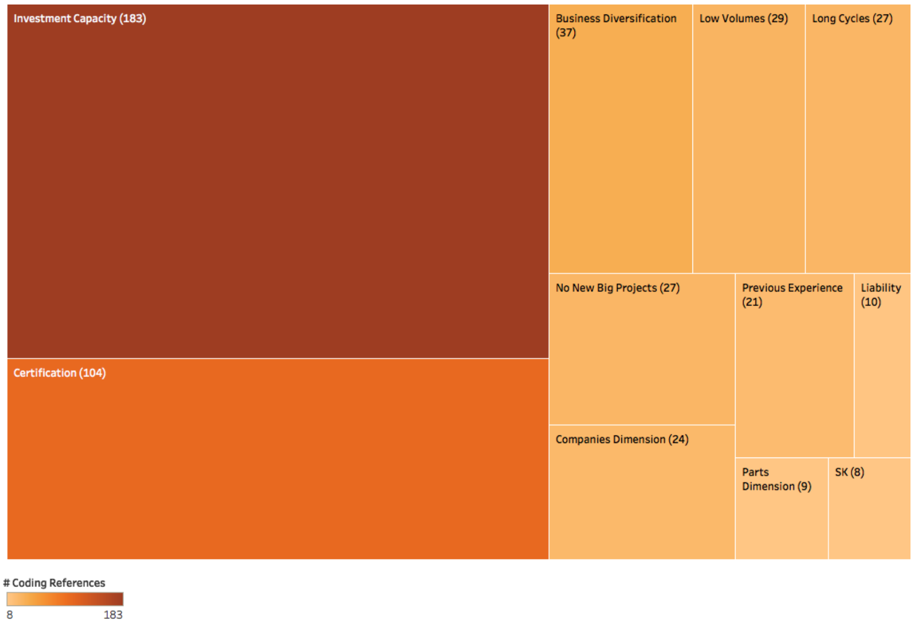
5. Integration and Growth of Small Technology-based Firms in Aeronautics

Our research addresses the question: how can TBFs integrate the aeronautics supply chain, creating value and fostering regional technological capabilities? In this section, we present the main challenges and opportunities for the integration of small TBFs in aeronautics identified from our data collection. These challenges and opportunities were identified through open coding of the interviews and participant observations, and validated through archival research. The challenges and opportunities that emerged throughout the coding process are presented bellow in the form of treemaps. These treemaps represent the coding frequency of each specific challenge in Figure 4, and of each particular opportunity in Figure 5. Therefore, each cell represents a specific challenge/opportunity that was identified through the coding process, and its size reflects the number of times a certain challenge/opportunity was coded. Counting code frequencies is a suitable way to identify the main challenges/opportunities for the integration of small TBFs in aeronautics, as well as for their transition towards higher value-added activities.

5.1. Challenges

Our results have led us to identify 11 main challenges to the integration and growth of small TBFs in aeronautics supply chains: investment capacity, certification, business diversification, long cycles, low volumes, companies dimension, previous experience, no new big projects, liability, specialized knowledge (SK), and parts dimension, as can be seen in Figure 4.

Figure 4 – Challenges to the integration of small TBFs in aeronautics (coding frequency in parenthesis)



Our results revealed that small TBF are typically deprived of the massive financial resources required to invest in human resources recruitment and training, software, machinery, and certification to enter this sector. This issue was mentioned 183 times in our interviews and participant observations as it is extremely challenging for these firms to integrate aeronautics supply chains, and they have to support all the costs related with the qualification process beforehand. Many times, even when small TBFs get qualified as a supplier, they have no warranty of a contract with aircraft manufacturers or major suppliers. For instance, a small TBF in Brazil invested heavily in state-of-the-art machinery expecting to supply high value-added components to Embraer, but at the end this firm was not able to secure a contract, which consequently resulted in the bankruptcy of the firm. In fact, according to Meredith (1987), small TBF's major disadvantage when compared with large firms is having the resource base to resort in case of technology implementation problems. For this reason, many small TBFs are reluctant to make the required investments to become a qualified supplier for aeronautics or to transition towards higher value-added activities within this sector without having a business prospect in medium/long term. This is even more relevant when considering the difficulty of small TBFs to access credit lines to fund industrial projects in this sector (Montoro and Migon, 2009).

Embraer, like other aircraft manufacturers, requires compliance to the norm AS 9100 as a pre-requisite to become qualified as a supplier (Airbus, 2013; Boeing, 2017; Embraer, 2010). This standard confirms a firm's ability to execute the proposed services and operations in accordance with the established requirements. Nevertheless, as noted 104 times in our interviews and participatory observations, the investment required to obtain this certification is challenging for many small TBF. Furthermore, there are additional standards that aeronautics suppliers have to comply with, depending on the type of commodity to be supplied (Embraer, 2010), and in order to establish these procedures, firms need to be able to make effective use of technological specificities of the sector and the aircraft manufacturer, such the decision-making procedures, bidding logic, technical standards, and cycles of approvals. Our research indicates that such knowledge about the sector does not happen overnight, and is typically embedded in the human resources of the firm. Therefore, integration and growth of small TBF suppliers in aeronautics is dependent on making heavy investments in processes and certifications that this industry requires, which require additional access to specialized human resources.

Our evidence suggests that small TBFs in aeronautics are many times dependent on aircraft manufacturers or major suppliers. For instance, most of the small TBFs in Brazil are completely dependent on Embraer business (Montoro and Migon, 2009). This dependency is particularly risky because if Embraer aircraft orders are cancelled or go down, the suppliers can be left without business. Thus, as discussed 37 times in our interviews and participatory observations, it is important for small TBFs to diversify their client's portfolio to growth their businesses, which can be done inside the aeronautics sector or into other sectors. Our evidence suggests that diversifying into the same sector is easier as the standards and processes are similar between aircraft manufacturers. Moreover, aeronautics inherent specificities, such as production and quality procedures, provide additional challenges for diversifying into other sectors. Given that these production and quality control procedures are expensive, and that other sectors like the automotive do not require such strict requirements, it is not competitive to supply components to others sectors were margins are smaller. Furthermore, the aeronautics industry demands machinery exclusivity (Participant Observation, 2014). As such, diversifying into other markets would require small TBF to acquire new machinery, which is an investment that these firms may not be able to make.

Our analysis indicates that small TBFs also struggle with the low levels of production required from aircraft manufacturers. As highlighted 29 times our interviews and participatory observations, the issue is that without a minimum production volume, it is not worthy to invest in this industry, especially considering the investments in terms of personnel training and certification. For example, in 2015 Embraer delivered 101 E-jets aircraft, and 120 executive aircrafts (Embraer, 2016). As a result, small TBFs that are dependent on these programmes have difficulties to sustain and grow their businesses with such levels of production.

The development of a new aircraft program takes around 10 years, and that aircraft can stay in service for 25 to 40 years (ICAO, 2007). Given the high development costs, high-risk investments, and long payback periods, the ability to sustain the process for a long time is a crucial feature of a firm's success, as well as having a long-term plan (ECORYS, 2009). Nevertheless, small TBFs that lack the financial stability this sector requires are not able to guarantee they will remain active through the aircraft life cycle. Therefore, as reported 27 times in our interviews and participatory observations, small TBFs have the added difficulty of assuring they endure for such a long period.

Aircraft manufacturers adopt similar technological solutions in order to mitigate risk, which functions as an obstacle to innovation and deters the adoption of relatively unproven technologies (ECORYS, 2009). For this reason, technological evolution in this sector has been incremental. As a consequence, small TBFs, many times without internal R&D activities, struggle to innovate and introduce new products and processes into this sector. Although big projects have the potential of providing a common denominator for aeronautics firms, especially for small ones without a research agenda, our data suggests that there are no new big aircraft projects.

Our evidence shows that small TBFs need an industrial dimension that allows them to compete with other incumbent firms already established in the sector, especially large ones. This issue was reported 24 times in our interviews and participatory observations. Many small TBFs need to resort on competences that they do not have in-house in order to deliver a finished product, which increases their production costs and lead times. For instance, a small TBF that supplies machined aluminium parts has to deliver them after the required surface treatments, such as anodising and powder coating. Nevertheless, the number of firms in Portugal and Brazil that have these types of processes in-house is very small, and have to subcontract these services from others in other to supply the finished part, thus decreasing their ability to supply parts at a competitive level. As a result, small TBFs struggle to compete with incumbent firms within the industry. In addition, we observe that firms that provide more sophisticated products or complex modules have a critical dimension that allows them to make strategic investments in state-of-the art machinery and technology, which in turn helps them to remain competitive in the long run.

As highlighted in our research, aircraft manufacturers and major suppliers reduce the risk level associated with the supplier selection by requiring firm's market proofs of their capabilities. Moreover, companies in this sector partner for a relatively long time (Cagli et al., 2012). Therefore, small TBFs find it particularly challenging to integrate and grow in this industry, as mentioned 21 times in our interviews and participatory observations. As such, we detected that small TBFs need to assure the survival of their business for a long period of time with scarce financial resources, while looking to acquire the trust of potential clients.

Traceability is a fundamental issue in aeronautics since there are lives at risk, and an aircraft manufacturer remains accountable for lifetime of the aircraft. For instance, Embraer is still liable for its first plane, *Bandeirante*, which flown for the first time in 1968 (Participant Observation, 2016). Evidence from our interviews and participatory observations reported 10 times that the responsibility and liability associated with the production of each PN adds extra pressure for small TBFs to set all the procedures that guarantee that every PN can be traceable. The scarce human resources within a small TBF have to be capable of trace the movement of a PN since the raw material enters a production facility until it levels, documenting accordingly every step.

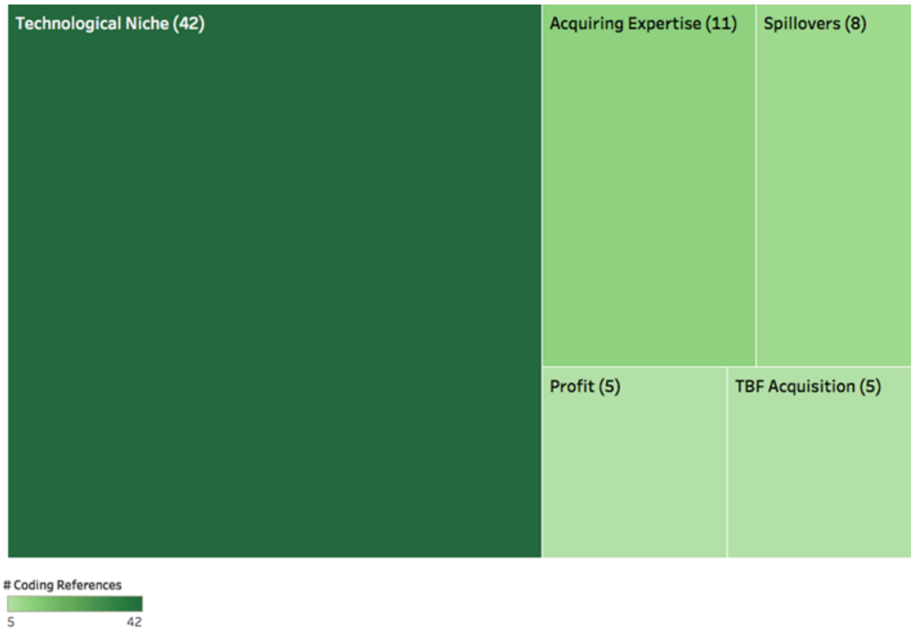
It was referred 9 times in our interviews and participatory observations the added difficulty of dealing with large aircraft parts. As the part size part dimension increases, a number of additional considerations must be taken into account. For example, to machine large aeronautics materials with thin-walled structures, using 7000 series aluminium alloys, firms need to have a good knowledge about the mechanics of materials given that this type of aluminium alloys deform a lot, and even about how vibrations affect the surface finish. Therefore, small TBFs that aspire to integrate the aeronautics supply chain must be able to control these effects, which is challenging due to the limited number of financial and human resources these firms have.

Aeronautics is a very specialized high-tech industry that demands a high degree of knowledge (ECORYS, 2009). Designing and producing an aircraft entails the domain of many fields of expertise that need to be developed concurrently to each other by multi-disciplinary teams with knowledge in a variety of scientific areas, such as aerodynamics, materials, propulsion, and avionics, amongst many others. It is not uncommon for firms in aeronautics to bring key personnel with the necessary knowledge and expertise to support the integration and growth of firms in this industry (Global Security, 2015; Sapiie, 2016; TEDxAlAin, 2011). As discussed 8 times in our interviews and participatory observations, despite the need of deepening knowledge of the field, small TBFs lack the financial recourses to attract this kind of specialized personnel to their firms.

5.2. Opportunities

Our results show that there are five key opportunities for the integration and growth of small TBFs in aeronautics supply chain, which are presented in Figure 5.

Figure 5 – Opportunities to the integration of small TBFs in aeronautics, and their respective coding frequency in parenthesis



Our evidence suggests that OEMs are interested in developing supplier redundancy, which can be beneficial for small TBFs. This happens not only to diminish suppliers' bargaining position, but also to decrease the risk of depending on sole suppliers. Supplier's production and design problems impact significantly the whole supply chain, delaying the introduction of the new aircrafts into the market. Therefore, many times OEMs acquire suppliers to strength their supply chain capabilities (Weitzman and Done, 2009).

Our analysis shows that interviewees were aware of the difficulty to enter technological areas where aircrafts manufacturers have established suppliers. Therefore, as mentioned 42 times in our interviews and participant observations, small TBFs are much more eager to invest in technological niche areas where they can leverage on their existing competences to bring more value added for their firm. Nevertheless, developing novel knowledge within a specific domain is not immediate and entails several years of continued investment (Hickie, 2006). As such, small TBFs, which many times have difficulties to get access to credit lines, must be willing to invest in a particular technological path well adapted to their industrial context despite its risk.

Examples from our interviews show that collaborative research and development projects can promote the accumulation of technological capabilities, especially when aircraft manufacturers partner up with small TBFs providing them guidance on how to integrate novel technologies within new aircraft programmes. As discussed 11 times in our interviews and participant observations, these collaboration projects speed up technological developments as small TBFs acquire crucial knowledge and experience in which they leverage to obtain new contracts in aeronautics global supply chains. These findings corroborate previous research from Cagli et al., (2012), which argues that early involvement from suppliers in the aircraft development process fosters the delegation of responsibility to them, and promotes a more solid relationship with the aircraft manufacturer.

Additionally, our interviews and participant observations report on the importance of technological spillover effects from aeronautics activities to other business segments of small TBFs. Indeed, small TBF reported benefits of getting qualified for aeronautics. The knowledge developed to put in place the required production and quality procedures function as an attractive for getting other clients not only from aeronautics, but also from different sectors. Another example of technological spillover effects results from small TBF making use of their technological knowledge in aeronautics to develop products and processes to other business sectors (Full Professor, 2014a).

As highlighted 5 times in our interviews and participant observations, small TBFs that aspire to integrate aeronautics global supply chains look into this sector as a profitable one. Despite being characterized by long payback periods (ECORYS, 2009), our evidence suggest that small TBFs only invest in this industry if it looks profitable in the long run, by either getting the return from the supplied products or by acquiring the knowledge and expertise necessary to the company's long-term strategy.

Our analysis also revealed that it is not unusual for small TBFs to be acquired by a larger company. Indeed, small TBF acquisition was mentioned as a natural exit strategy of many of these firms. While small TBFs are looking for ways to leverage on their developed intellectual property, larger firms look for obtaining technological competitive advantages from the acquisition process. As reported by the CEO of a small TBF in Portugal, a possible exit strategy is to get acquired by an incumbent firm that already posses the knowledge of the sector, the required procedures in place, and the necessary investment capacity to take its technology to the market (CEO, 2014a).

6. Capacity Building in Aeronautics

In this section, we detail the aircraft development process, discussing the integration of small TBFs in this process with the analysis of our results. In addition, we provide evidence on three strategies that small TBFs can use to move towards higher value-added activities in aeronautics.

Our findings suggest that opportunities for the integration and growth of small TBF in aeronautics are scarce when compared to the challenges that these firms need to overcome. Evidence obtained in previous studies indicates that the aircraft development process goes through different phases (Chang, 2009; Figueiredo et al., 2008). According to Figueiredo et al. (2008), Embraer's product development phases comprises four phases: preliminary studies, contact and selection of partners, joint definition phase, and development. Our data shows that Embraer not only follows these development phases, but also has additional ones in place. Figure 6 shows the aircraft development process phases: R&D, Pre-project, Project Development, Project Detail and Specifications, Prototype, Certification and Production. These aircraft development phases were discussed in detail with several experts, and are consistent with the product development phases at Embraer described by Figueiredo et al. (2008). Despite focusing on Embraer's case, this breakdown can be generalized to other different aeronautics contexts.

Figure 6 – Aircraft development process

R&D plays a leading role in product development since architectural decisions are made during early phases of the innovation process (Ulrich, 1995). Aircraft development is no exception since it provides the ability to develop knowledge and technologies in lower technological readiness levels (TRLs). For instance, R&D partnerships are established to study new concepts and designs, as well as new technologies, which later on can be integrated in new aircraft programs. These partnerships are increasingly important due to the long R&D cycles and the growing costs of aircraft development, as well as the large level of uncertainty about the return on investments (Bernardes, 2000).

The Pre-Project phase takes into account the market trends and potential buyers in order to perform preliminary studies about new programs. Thus, in this phase, several trade-offs are discussed and agreed in order to establish aircraft parameters, such as the range, consumption and weight. The process is highly iterative until it is somewhat locked with a business plan, which consists in the culmination of several decisions, such as make or buy, location of the plants that will manufacture major modules, as well as main technologies to be used in the aircraft. Generally, these decisions are strongly interconnected with the OEM internal capabilities, as well as with the goals and financial situation of each program (Ferreira et al., 2011). According to Figueiredo et al. (2008), it is during this phase that the OEM assesses potential advantages and disadvantages of making partnerships, joint ventures or even keeping it in-house. Hence, some projects might be abandoned at the end of this phase. According to Paulo Cesar de Souza e Silva, the CEO of Embraer, this phase takes on average three years (Oliveira and Bigarelli, 2017).

Project development is where the execution of the program receives the green light to go forward. Module suppliers are also contacted to discuss the performance requisites of the aircraft systems, as well as the requirements of functional and physical integration of each aircraft module. As a result a complete electronic mock-up, specifying structural, manufacturing, systemic and quality aspects of the program is produced (Figueiredo et al., 2008). Suppliers who meet the technical and commercial requisites are invited to bid for work that will be developed in-house. Particularly tooling, because drawings have to contain the production instructions of how the parts will be manufactured when released. Therefore, tooling has to be developed previously.

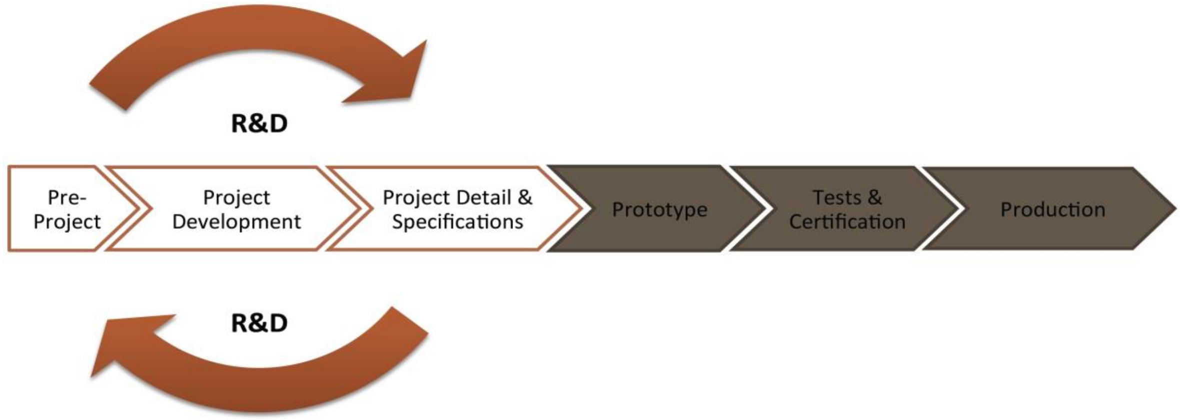
After specifying the main requirements of the program, project detail and specifications take place and the final definition of the aircraft is concluded. For instance, while the number of ribs might have been specified during the project development stage, their exact configuration, thickness, weight, spacing, use of fasteners, amongst other specifications are determined at this stage (Chang, 2009). Following this development phase, the construction of a functional prototype using parts provided by qualified suppliers takes place. The prototype frequently undergoes a complex, rigorous flight test and certification processes that go from a series of functional and reliability static tests to a flight-test campaign (Vinholes, 2017).

Static tests are designed to access how the aircraft structure acts under stress over long periods of time and during different states of operation, while flight-testing examines general handling qualities, operational performance, airfield noise emission and systems operation in normal mode, failure scenarios and extreme conditions (e.g., heat and cold). The culmination of the tests phases is the achievement of airworthiness certification by responsible authorities. It is only after this extensive process that the aircraft reaches production in series. From project development until the point the aircraft reaches production it takes on average six years, according to Paulo Cesar de Souza e Silva, the CEO of Embraer (Oliveira and Bigarelli, 2017). The OEM is responsible for all the activities required to develop and manufacture an aircraft, risk-sharing partners carry out all the activities with the exception of the pre-project as this phase is internal to the OEM, and small TBFs might participate in R&D, project development, project detail and specifications, prototype and production phases. This participation of small TBFs in the aircraft development process require they already are qualified suppliers with all the necessary production and quality procedures in place, which can be challenging for many of these firms as evident from Figure 4.

Given that Embraer's technology development team surveys the aerospace technology landscape, analyses specific technologies that Embraer plans to develop, and therefore proposes recommendations on the use of novel technologies or improved processes, the aircraft development process is not strictly linear and there are interactions between these phases. In this context, Embraer have established in collaboration with other Brazilian entities a development fund to identify and invest in the most promising small TBFs in Brazil (Fundo Aeroespacial, 2016). Thus, Embraer can purchase small TBFs that have already mastered novel technological developments, and introduce them in the market, as noted in our results (see Figure 5). This evidence indicates that R&D activities support the pre-project, project development, and project detail and specifications phases, as shown in Figure 7. As a Process Development Engineer (2015) told us:

> *At the prototype phase everything is already developed, there are no more changes. A supplier that wants to introduce a new technology or an improved process has to communicate that intention to the technology development team to understand whether the OEM is interested in pursue that.*

Figure 7 – Validated aircraft development process



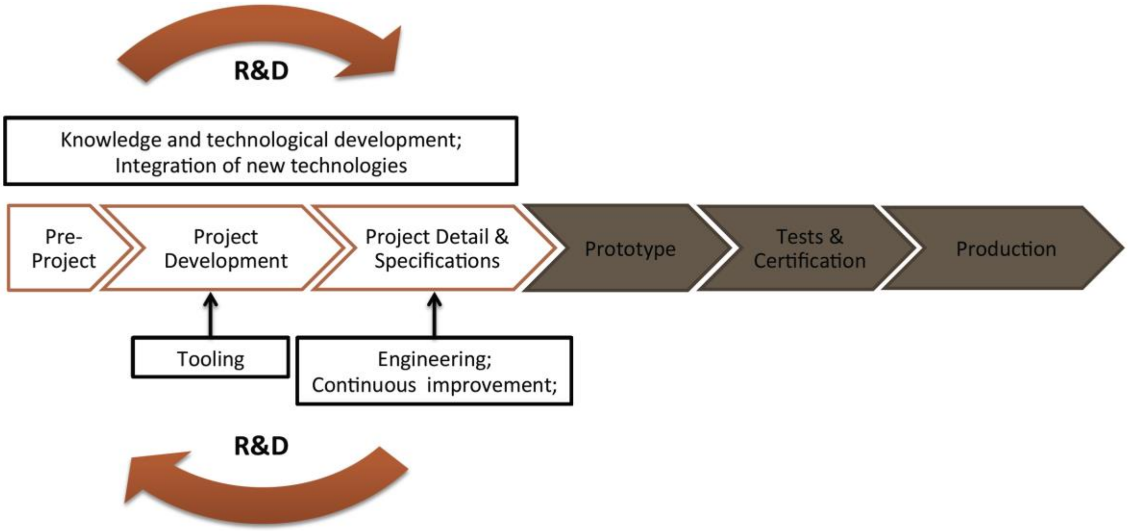
Therefore, as soon as the aircraft prototype phase is reached the design of the aircraft is completely frozen, and alterations to the design would mean a new certification process. If a supplier develops a new product or an improved process that complies with all the requirements at a lower price, the OEM cannot simple incorporate or change it. The OEM might even do that, but it has to go through the certification process again (Director, 2014).

Aircraft manufacturers are continuously looking for new technologies that would provide a better and more sustainable performance, as well as ways to improve the production processes, which provides an opportunity for small TBFs to enter technological niche areas as discussed in our findings (see Figure 5). Moreover, current aircrafts backlogs are huge, and aircraft manufacturers are considering to ramp up production in the next few years to reduce backlogs (Flottau and Norris, 2014). Therefore, the demand for components and structures is growing, and OEMs and major suppliers are looking for additional suppliers to be able to satisfy such demand. Nonetheless, it is important to take into account that orders are not as definite as they might appear since they are cancelled sometimes. As explained by Aboulafia (2015), supplier firms are being asked to make massive investments, as well as lower their prices, and if orders are cancelled suppliers risk to be stuck with overcapacity and higher fixed costs. As shown in Figure 4, the investment capacity of small TBFs constitutes a main challenge for their integration and growth within aeronautics supply chains.

Our results suggest that small TBFs integrated in early phases of the aircraft development process have the power to influence the product so that by the time a particular part reaches production the design trade-offs related with product performance, manufacturability, and tooling have been taking care off. In addition, integrating small TBFs in R&D activities provides them with more precise information for assessing technology introduction in the aircraft, while understanding prototype, tests and certification, as well as production phases. As can be observed in Figure 5, acquiring this experience was mentioned in our interviews and participatory observations as a critical opportunity to help small TBFs to better position themselves as aeronautics suppliers. Based on the knowledge gained from our data collection, we identified activities in early phases of the aircraft development process in which small TBFs are involved, namely: knowledge and technological development, integration of new technologies, tooling, engineering, and continuous improvement services. These activities are recognised as more valuable for firms as they allow firms to expand their competences in aeronautics. Figure 8 presents activities from which small TBFs can benefit more by participating in the aircraft development.

As such, small TBFs that are involved in earlier phases of development are more likely to take advantage of novel scientific knowledge and emerging technologies. As explained by the Head of Engineering and Quality of a Brazilian firm, *it is important to participate with partners in preliminary development phases since in this away we are able to react more quickly*. Additionally, value added activities can be carried out by a small TBF in the project development by developing some aircraft tooling equipment or in project detail and specifications phase, such as detail drawing and structural analysis. Despite small TBF's involvement in the prototype phase or even in the production, both these phases are known for aggregating less value since product and process design are finalized and engineering plays a smaller role. Therefore, small TBFs that only participate in later phases of aircraft development are known for handling "built to print" projects. In other words, these firms manufacture products, equipment or components according to the OEM's exact specifications, which can nonetheless comprise profit opportunities for small TBFs in aeronautics, as detailed in Figure 5. Most Embraer suppliers located in São José dos Campos do not develop R&D activities, and therefore, do not participate in the product design. In fact, most of these small TBFs receive raw materials from Embraer to manufacture the demanded components according to the required specifications, and subsequently Embraer collects the produced components for later assembly. Indeed, small TBFs considered a key challenge for their integration and growth in aeronautics, the diversification of their business activities, see Figure 4. Thus, it is extremely challenging for small TBFs that are strongly dependent on Embraer's business to move up towards high-value added activities.

Figure 8 – Activities from which small TBFs can benefit by participating in the aircraft development



Our evidence also suggests that transitioning from low value-added activities towards more value-added activities can be challenging. Indeed, our interviews indicate that most of the small TBF located in São José dos Campos, Brazil, provide low value-added services to Embraer, and despite some efforts to move towards more value-added activities they have not yet been successful. A Brazilian researcher succinctly described the current state of Brazilian aeronautics supply chain as follows:

Brazilian companies are mainly SMEs, which receive built to print projects. There are a very narrow number of 1st and 2nd tier suppliers in Brazil, and even the number of firms that provide engineering capabilities is very low. Therefore, Embraer ends up getting the largest part of their aircraft modules from large international firms, with a relatively small value of national incorporation. Additionally, Embraer is not particularly interested in developing 1st tier suppliers in Brazil since selecting international 1st suppliers helps boosting their sales to those countries (Researcher, 2014).

Aeronautics industry's competitiveness resides in the increasingly capacity to access and use knowledge and technologies in distributed knowledge bases, spread through a wide network of institutions (Reis et al., 2016). Our results show that the specialized knowledge this industry entails a main challenge for the integration of small TBFs in aeronautics, as shown in Figure 4. One of the main reasons for that is the set of complementary capabilities that companies can draw on to supplement their resources, which ultimately reduces the risk associated with innovation and enhances the likelihood of emerging technologies come to life (Berger and MIT Task Force on Production in the Innovation Economy, 2013). In the light of the foregoing, several Brazilian industry associations (e.g., ABDI and CECOMPI) have been working to leverage local capabilities and establish 1st and 2nd tier suppliers in Brazil. An initiative launched within this context was the AAG Aerospace, which consists on a joint-venture agreement between three companies: Airmod, Aernnova and Globo Usinagem. Airmod brings their expertise on program management, Aernnova provides local engineering capabilities, and Globo Usinagem provides machined parts. Each of these companies bring their particular expertise to the table, joining efforts under the AAG Aerospace to become a 1st tier supplier specialized in design engineering and manufacturing of aerostructures for the Swedish SAAB (Airmod, 2016).

Furthermore, research and technology organizations like the Competence Center in Manufacturing (CCM), located close to the Embraer's headquarters, play a significant role in the development of new knowledge and technology competences for aeronautics. This centre bridges the gap between industry and academia, developing projects with an industrial application. An example of an industrial project developed with Embraer was the AME project, which consisted on the automation of fuselage sections assembly. The automation process required the development of the fuselage sections riveting process in a single stage (one up assembly). Embraer is using both levelling and riveting processes since 2012, allowing a high degree of precision and flexibility for the aircraft assembly process (ITA, 2016). This project resulted in several scientific research work, and in the first patent of ITA, shared with Embraer, filed in 6 different countries (ITA, 2016). Some additional spin-offs are the *snake robot*, a flexible robot used for operations of difficult access for humans; a robotic effector for sanding and polishing aircraft surfaces; and reconfigurable tooling with robotic drive rods (FINEP, 2013). These examples corroborate our findings on opportunities arising from technological spillover effects from aeronautics, as exemplified in Figure 5.

Moreover, interviewees suggested that without a "common big project" it is difficult for small TBFs to recognise opportunities to better position themselves in aeronautics global supply chains, as indicated in Figure 4. Technological demonstrators are a widely used support mechanism in aeronautics early-stage research that fill this gap by enabling the integration and test of complex and new technologies in real conditions, which ultimately accelerates the progression from science to marketable proven concepts (ABDI, 2014). For instance, the US government was able to support the development of social networks necessary for initiating new technology directions in early-stage research key to national sovereignty through agencies such as the Defense Advanced Research Projects Agency – DARPA (Fuchs, 2010). Therefore, small TBFs can benefit from participating in these technological demonstrators, which are generally in line with a long-term strategy for the sector evolution, such as mitigation of environmental impacts, reduction of operation costs, and increase of flight safety.

Our analysis contributes to the literature on industrial policy by providing evidence on the integration and growth of small TBFs in aeronautics, particularly in lower levels of the supply chains. The identification of challenges and opportunities for the integration and growth of small TBFs in aeronautics is useful for formulating public policies aimed at fostering the development of regional technological capabilities in this sector. Several governments around the world have sought to build local aeronautics capabilities with the purpose of fostering economic growth (Hickie, 2006; Hira and Oliveira, 2007; McKendrick, 1992). As the result of such policies, many aeronautics manufacturers were created, triggering the establishment component and systems producers nearby, fostering job creation, capacity building and economic growth (Niosi and Zhegu, 2005). However, endeavours to reduce high development costs of new products led to a global decentralisation of aircraft production (Ferreira et al., 2011; MacPherson and Pritchard, 2003). Consequently, aircraft manufacturers are constantly looking for new technologies and suppliers that would provide them leverage over their competition, opening windows of opportunities for small TBFs integration and growth in aeronautics. Small TBFs act as catalysts of technological and change and regional competitiveness Feldman and Audretsch (1999). Our research argues that small TBFs can use three main strategies to take advantage of their role in the aircraft development process: (i) establish join-venture partnerships with other companies, (ii) collaborate with research and technology organizations in the development of knowledge and technological competences, and (iii) participate in technological demonstrator projects that enable the integration and test of new technologies in real conditions.

7. Concluding remarks and policy implications

Despite the global increase of outsourcing trends, different countries with different technology appropriation levels operate in different segments of the value chain, leading to different export patterns and reflecting different industrial policies. In this study, we examined the extent to which small TBFs can be integrated in aeronautics supply chains, creating value and fostering regional technological capabilities. In particular, we focused our attention into Embraer's supply chain in Portugal and Brazil.

We found that the aeronautics industry inherent specificities, such as long development cycles and stringent safety requirements, impose investment and certification challenges to the integration and growth of small TBFs in aeronautics. For this reason, many companies are unwilling to invest to enter this market, which can only be fruitful on a long-term basis. In this sense, understanding the challenges and opportunities that lie ahead is useful when considering entering this industry. Moreover, small TBFs gain a deep understanding of aeronautics production and quality standards by participating in the qualification process. Thus, these firms may want to initiate this process not only to gain detailed insight on key process changes needed to meet the OEM requirements and aeronautics regulations, but also to decide whether investments to comply with these changes are in agreement with the company's business strategy.

Our results confirm that the benefits coming from small TBF, which accommodate collaborative activities in early phases, outweigh those that just participate in the production phase. This study therefore identifies the activities from which small TBF can benefit more by participating in the aircraft development. Most notably, this is the first study to our knowledge to investigate ways for TBF move towards higher value- added activities in aeronautics. Our findings provide compelling evidence that collaborative projects can nurture and enhance TBF development in aeronautics, especially in aircraft development phases preceding production. Early collaboration with partners provides valuable feedback on future technological trends that firms can use in subsequent aircraft development phases. This is particularly important in aeronautics since the aircraft is completely frozen when the prototype phase starts.

The finding that firm size is positively related to ascendant moves within the aeronautics supply chain brings additional challenges for countries like Portugal that are mainly composed by SMEs. SMEs may not have the opportunity to participate in collaborative R&D activities with OEMs. Therefore, policy should be oriented towards the support of collaborative R&D projects as means of developing the accumulation of capabilities on emerging technologies with greatest potential, such as additive manufacturing, speeding up new technological developments, as well as shortening the time to market.

Finally, our investigation has limitations that unveiled possible directions for future research. Although we conducted a large number of interviews in different industrial contexts that yield more robust and generalizable findings, our research is limited to Embraer's supply chain in Brazil and Portugal. As a result, we do not take into consideration other regions of primary importance in the aeronautics global market.

Therefore, our data could benefit from being extended to other aeronautics supply chains in different regions of the world to validate the generalizability of our findings.

Appendix A: Evidence from First and Second Level Coding

Table 6 – Coding structure and sample interview transcripts

2nd level Codes	1st level Codes	Sample interview transcripts
Challenges for the Integration of Small TBF in Aeronautics	Investment Capacity	*The Brazilian firms do not have the financial capacity to sustain the investment in aeronautics. (Full Professor, 2014a)* *It is a problem of money. Why do I say that it is a problem of money? Because in order to launch a firm in this area, it has to be a company of high capital investment, therefore it will be an engineering company that needs to invest in software and machinery, advanced machinery. The existent capital in Portugal is not available for this type of companies. (CEO, 2015a)*
Challenges for the Integration of Small TBF in Aeronautics	Certification	*One of the barriers to entry for firms is having all the required certifications. (CEO, 2015b)* *The certification is determinant for the integration of new technologies. Clearly not only the certification, but also beforehand the technology maturation process... Aeronautics needs usually of a time to establish the technology reliability and it is usually more this time than the maturation of the technology. The technology is mature, but aeronautics does not allow it to be integrated in order to assure that it is reliable. (General Executive Manager, 2015)*
Challenges for the Integration of Small TBF in Aeronautics	Business Diversification	*When you start to think that you could sell, for instance, for US or Europe, then you start to encounter some barriers. (Director, 2014)* *The materials are all imported. So, we would need a department to take care of that, inspect the materials with all procedures that we currently do not do. This change would complicate significantly our life. We like to work as we are. (Sales Manager, 2014)* *I have a client in the US, but I supply very little. We do replacement parts for them also in aeronautics. We have clients in Spain also in aeronautics. But, Embraer accounts with 90% of our activity. It cannot be different. Here, as a strategy, we tried automotive, but we there is no way, we could not enter because we are prepared to aeronautics. The difference between aeronautics and other clients in the control of the processes (CEO, 2014b)*
Challenges for the Integration of Small TBF in Aeronautics	Long Cycles	*It is an intensive capital industry. The development and breakeven cycles are very long. So, the solution unfortunately is not simple. I think that it is necessary to think and to have a medium/long term plan. (Head of Engineering and Quality, 2014)* *Aeronautics is a market were you put a lot of money and receive very slowly. (General Manager, 2014)* *Portuguese companies cannot supply (…) It has nothing to do with the technological capacity. It has to do with financial capacity. In other words, OEMs have to believe that firms will hold through the life cycle of that product, that it will exist. We are speaking about 30 year life cycles. What do we know in 30 years? (…) A Portuguese firm that wins that business has to assure from the start the system will be maintained through 30 years. Who is able to guarantee that? A Portuguese SME? I think they have difficulties even to assure something for the next 5 years. (CEO, 2014c)*
Challenges for the Integration of Small TBF in Aeronautics	Low Volumes	*Why did companies die in that time? Because of the production volume. There was a big production volume, but afterwards there were no more demand and the companies died. (…) It is a low volume type of industry. If you compare it with the automotive industry, it is of really little volume.* (CEO, 2015b) *The company does not even accepts to make quotations for volumes inferior to 30 thousand parts in the case of low value added parts. It is not competitive for the company. That is why the company concentrates exclusively in the automotive sector. These volumes are not even matched when we think in the life cycle of the aircraft.* (President, 2014)

	Companies Dimension	*The key element is having an industrial dimension that supports it.* (Executive Director, 2015) *In brief, the possible Brazilian suppliers do not have dimension to supply for Embraer, despite the policy tentative to foster the industry in this direction.* (Full Professor, 2014b) *I would say that more than this kind of existence is a question of having a dimension that allows investments that complement our offer. In order to have a finished product we have to resort almost always to a company that is not in Portugal, with the associated logistics and time costs. (…) I think that the crucial question at a strategic level would pass through having a firm that agglutinated a series of other firms. Firms that could gain some dimension… (Aeronautics Manager, 2015)*
	Previous Experience	*There is a big lack of knowledge, competences and experience for obvious reasons. Because, taking out the aerial transportation market and the MRO services, the industrial component in terms of design and development and in terms of manufacturing was residual. Despite the lack of competences that currently do not exist in Portugal, but we have to work within a network and get them outside, and afterwards manage to fix the knowledge*. (Head of Aeronautics and Space Business Developer, 2014) The necessity of gaining trust from the clients is an essential and time-consuming process. (Quality Engineer, 2014)
	New Big Projects	*If we look into all the research that is developed, we realise that each one ends up looking into its own business, but it does not have a larger direction. In our case there is no big project, which I call integrator. (…) In that way you would include dozens, hundreds of firms that could develop small packages.* (CEO, 2015b) *The main issue is that there are no new projects. New big projects. If we think that there are only two large aircraft manufacturers, Airbus and Boeing, they are finishing products, they are have complete families and relatively modern, and there are no new big aircraft projects. (…) Nowadays, the reality is that these projects are ending. Some ended and others are almost at the end. Of course, small modifications and alterations sill exist, and some bigger modifications like the new A320neo that it is coming and things like that, but these projects do not have the dimension of building an aircraft from scratch. Thus, the industry is at moment were engineering is stopping or slowing down, and we fell that.* (Engineering Director, 2014)
	Liability	*Traceability is fundamental in aeronautics. Embraer is always responsible for the aircraft while it is in service. For instance, Embraer is still responsible for Bandeirante.* (Meeting, 2016) *Given that we work in the aeronautics sector, we manage raw material, and thus the traceability processes are well established. There is this policy that nothing moves inside the firm if it is not documented accordingly. This is also a requirement from the norm*. (Commercial Coordinator, 2014)
	Specialized Knowledge	*Does any one know who on the market write the specifications? The market is an amorphous being, lots of people, things, and noise. You can put together 30 airline captains, and they will not provide you the exact specifications that you need to design the aircraft. That does not happen. It is almost like art. You talk with one and another until you realize their unspoken expectations, and it is only then that you can meet this unspoken expectation. This is Embraer's know-how.* (Technical Director, 2014) *I had no idea, but nowadays there are people working in aeronautics, in different aircraft manufacturers that make million dollar job transfers from one firm to another. It is no joke. Engineers that go from a team in Boeing to another company, such as Embraer. The specialized knowledge is in a few people, other knowledge is more generic…* (Director, 2015)

	Parts Dimension	*Given the larger size, when we process these materials, especially the 7000 series aluminium, what happens is that they deform a lot and controlling for this deformation is not easy, it is necessary to have a good command of the material properties, understand the operation process, the number of clamps, and tools because when we are cutting the material we are also inducing a certain tension. (…) There are a number of fields that it is important to master so that we can machine certain types of parts for aeronautics, which are normally high parts with very firm walls. So, we need to know how to master the dimension.* (R&D Manager, 2015) *When you change the dimension, you have a series of problems that happen. For instance the part starts to vibrate, which interferes with the finishing.* (Director, 2014)
Opportunities for the Integration of Small TBF in Aeronautics	**Technolo gi cal Niche**	*Portugal has to choose niche markets, both in the area of software and aerostructures.* (Former Head of Strategy & Business Development, 2014) *Now, we have to find what is very often called "the blue ocean", the specific areas where we are not constantly fighting with other. Specific areas where we want to be the best.* (Head of Aerospace, Security and Defense, 2014)
	Acquiring Expertise	*This Embraer project provided an opportunity for companies to work in the aeronautics market, and overcome the challenges that they needed to overcome in order to enter this market, and learn a lot, which ultimately will allow us to go to the international market, and to other manufacturers and firms to loon for work. (Engineering Director, 2014)* *I am an Airbus 1st Tier, but is to the design, not to supply components. Of course that I am there, which means that I could start a set of processes to do it. I have another advantage, which is being invited to do more things. (CEO, 2014a)*
	TBF Acquisition	*One has to attract 1st Tier, 2nd Tier and 3rd Tier so that local firms become suppliers or become acquired by those firms. (CEO, 2015b)* *The critical thing is the client looks at us as a supplier. Product supplier, not a supplier of ideas and technology because that is a well defined process where I have to have a certified firm. The supply chain is completely defined. In order to become a supplier, I have to partner with someone that already produces or I can subcontract and supply directly to the client. I can enter with a partner that ends up buying X% of the company. I get know-how, acquire a small engineering department, and boost the business. Typically, this is the ideal partner, not doing all the way from A to Z because in that way it will never happen. The way is to find the ideal partner that buys the company and goes to the market, produces and goes to the market. And I stay doing what I know how to do, which is innovation. (CEO, 2014a)*
	Spillovers	*Gamesa is a very good example. At some point, one of the departments created the firm Gamesa Eólica. (…) This happened when there was an increase in the wind turbines parks in Spain, and they entered a niche market. They are manufacturers of wind turbines and spread them across Spain. (General Executive Manager, 2015)* *One of the students that worked here is at an incubator with a project from a robotized snake that enters the wing of the plane. This can now be an opportunity with the offsets from the GRIPEN because inspecting the wings of the military aircrafts is much more serious since there is much less space. (Full Professor, 2014a)*
	Profit	*I always start from the assumption that the vast majority of entrepreneurs are not stupid, and therefore an entrepreneur is no more than someone who creates added value. (…) The entrepreneur has to have a return. (CEO & Business Manager, 2015)* *Embraer before its privatization had no market vision. The return on investment just started after its privatization when it went into other hands. They had lost 300 millions at the time. Privatization meant globalization. (President, 2016)*

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