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Master’s Thesis – Innovation Sciences

Diversification of the Technological Knowledge Base of Aerospace Companies

Analysing the influence of competitive and technological context conditions

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"In an economy where the only certainty is uncertainty, the one sure source of lasting competitive advantage is knowledge."

(Ikujiro Nonaka, "The 'knowledge-creating'company)

Abstract

The aerospace industry is one of the hardest to innovate. New product development is costly and lengthy, there is low space for new entrants and products are 'multitechnological', requiring a large technological knowledge base. In this scenario, the diversification of the knowledge base becomes a requirement for aerospace companies (ACs) to strive, leading to more competitive advantage and opportunities for growth. When choosing to diversify, managers have to consider internal capabilities, resources availability, external environment, among other context conditions. The current research focus on two of them that are not fully understood in literature: in the competitive context, the occurrence of coopetition to develop new technological knowledge and, in the technological context, the technological strength of ACs. Coopetition is the concomitant competition and cooperation with competitors and the technological strength refers to the ability of firms to use various technologies, applying them in new product development and generating technological innovation. Hence, the following research question is posed: *To what extent do coopetition and technological strength influence the diversification of the technological knowledge base of aerospace companies?* Patent data of 60 ACs and subsidiaries are analysed for the period between 1995 and 2013. Technological knowledge diversification is measured through IPC classes, coopetition, through patents deposited with competitors and patents deposited by joint-ventures, while the technological strength is measured by the number of citations received by each company's patents. OLS regression model is applied to find statistically significant relations. Results show that the more an AC forms coopetitive alliances, the more specialized its technological knowledge base becomes, however patents deposited in coopetition have a higher technological strength, leading to a greater portfolio leverage and competitive advantage. ACs with a high degree of technological strength are more diversified in their technological knowledge base, the opposite observed in other non-high-tech industries. For ACs with low or moderate degrees of technological strength other factors might be in place to determine the diversification of their bases, as no statistically significant relation was found for them. In general, Asian and larger ACs have the most diversified technological knowledge base. And, in the industry-level, interest moved from peripheral components to core technologies in the period, indicating that ACs are focusing more on improving the efficiency and safety of their products.

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1. Introduction

Scholars have described the current period we live in as a 'knowledge-based economy' (Lundvall 1988; Cooke & Leydesdorff 2006; Godin 2006), in which economics are a result of the "production, distribution and use of knowledge and information" (OECD 1996, p.7). In fact, Dosi (1982) described the accumulation of knowledge as part of the innovation process, leading to a certain technological trajectory in industry.

Mainly after the 1970's, based on the coupled growth of global economy with rapid scientific development, industry as a whole has focused on knowledge diversification as a way to thrive in competitive markets (Dosi 1988; Nelson & Winter 1977; Grant 1996). By diversifying, a firm expands the breadth of its knowledge and explore new possibilities of innovation, leading to more competitive advantage and opportunities for growth (Bierly & Chakrabarti 1996; Wang & Tunzelmann 2000). However, as a downside, it requires more coordination, increases the transaction costs and results in higher uncertainties (Bathelt et al. 2004; Chiu et al. 2010).

Managers have to consider internal capabilities, resources availability, external environment, among other context conditions when choosing a certain technological trajectory to be followed (Trott 2017). This is a critical decision for industries that heavily depend on technologies to remain competitive, like in the case of aerospace companies (ACs). In this high-tech industry, firms have to be more innovative, win new markets and use resources more efficiently, while facing intense competition and shorter life cycles for their products (Hatzichronoglou 1997; Qian & Li 2003).

Aerospace products are developed based on several technological areas, e.g., thermodynamics, material science, fuel chemistry and electronics, making them 'multitechnological' firms (Brusoni et al. 2001). Furthermore, the industry is characterized by a 'production-centred innovation', in which technological knowledge is vital for the development of new products. These characteristics make the aerospace industry one of the hardest to innovate, with low space for new entrants and a concomitant need of knowledge expansion and specialization (Acha et al. 2007). In fact, technological knowledge has been shaping the leadership composition of the industry, as seen in the current interest of Airbus and Boeing in Bombardier and Embraer, respectively, due to the knowledge of the latter two in the production of mid-size jets (Reed 2017).

Recently, literature has brought some interesting insights into discussion regarding knowledge in ACs. Brusoni et al. (2001), analysing the development of aircraft engines to understand the specialization of firms, described a need of knowledge in excess to effectively generate innovation. Jordan & Lowe (2004) discuss both sides of knowledge sharing for ACs: on the one hand, collaboration is necessary, but on the other hand partners are usually direct rivals. The authors call for more investigation to explore knowledge sharing in this case. Dangelico et al. (2010) show, for the aerospace district of Seattle, that knowledge sharing and creation are favoured by more cognitive and organizational proximities. Ardito et al. (2016) analysed patents published over 62 years in the aerospace industry, finding an inverted U-shaped relationship between the establishment of technologies in previous knowledge and the likelihood of them to become breakthrough ones. Park et al. (2012) developed a systematic method to analyse technology transfer for the case of the Korean aerospace industry. Acha et al. (2007) discuss, in a theoretical paper, the knowledge base of aircraft manufacturers based on the rationale of competitiveness, product complexity and firms' boundaries.

Nevertheless, it is not fully understood in literature how the technological knowledge base of ACs responds to different environmental factors, which constantly challenge companies on their strategic decisions. This study sheds light on this topic by focusing on two important contexts: in the competitive context, the occurrence of coopetition to develop new technological knowledge and, in the technological context, the technological strength of ACs. Coopetition, which is the concomitant competition and cooperation with competitors, has long been recognized in the aerospace industry as a way to reduce risks and to tackle uncertainty in product development (Salvetat et al. 2013). The technological strength of ACs refers to the ability of firms to use various technologies, applying them in new product development and, consequently, generating technological innovation (Song et al. 2005; Chen et al. 2007; Srivastava & Gnyawali 2011). Firms with higher technological strength can better identify technological opportunities, adapt to changes in the industry and apply the state-of-art technologies, becoming a continuous source of competitive advantage to the firm (Xu et al. 2013).

According to Prencipe (1997, p.1274), "technological knowledge is, in fact, 'localised', path-dependent in its development and context-dependent. This means that 'contexts' provide the *sine qua non* for generating new knowledge". Therefore, the following research question is posed:

To what extent do coopetition and technological strength influence the diversification of the technological knowledge base of aerospace companies?

Analyses are based on patents deposited by the 60 main companies, which are expected to be more influential in defining the technological trajectory of the industry, covering the period between 1995 and 2013 (the latest year with full data available). Theoretically, perspectives from strategic management and resource-based view theories are utilized.

The scientific relevance of the current study relies on the improved understanding of the diversification of technological knowledge in a field where innovation is complex, expensive and a requirement to thrive. With the increasing size of commercial aviation market and the foreseen new momentum of outer space exploration, this industry's knowledge becomes even more relevant to be studied (Grush 2017; Kletzel & Terry 2017; Allen 2017). Managers will have new competitive and evolutive insights to take strategic decisions regarding alliances and technological development. Policymakers will have a more informed overview of technological and competitive context to design policies aiming at technological development and innovation in the aerospace industry. Society will benefit indirectly through the continuous development of the industry and the technological and scientific benefits it brings.

The remaining parts of this thesis are structured as follows: in section two, the theoretical background will explain the main theories and concepts to be applied in the current research. Section three will describe the methodology applied to perform this research and which tools will be used in this process. Results are described in section four, followed by conclusions in section five. Finally, discussions are held in section six.

2. Theoretical background

The aerospace industry possesses a combination of features that make it unique and relevant to be studied. Aerospace products are classified as Complex Products and Systems (CoPS), which means they are built based on engineering-intensive goods with high value and a large number of components to be assembled (Acha et al. 2004; Hobday 1998).

Aerospace products do not follow the common logic of "mass production", but they are only batch-produced according to client orders. In fact, the client's specifications are an important part of products design (Acha et al. 2007). As a way to improve efficiency and reduce costs, ACs have focused on the maximization of commonality, in this way the same technological solution can be applied to several products, only with minor adaptations of size and technical specifications (Aerospace Commission 2002; Breschi et al. 2003). A current example of this commonality is present in the new engine option (neo), from Airbus; this technology allows to reduce weight and fuel consumption, being currently applied to the majority of aircrafts manufactured by the company (Airbus 2017).

Frenken (2000) studied several technologies related to aircrafts, concluding that transnational and specialized networks are a result of self-organizing users, producers and governmental bodies, a phenomenon seen specially after World War II; each member of the network specializes in particular technologies or markets in a way to cope with the inherent complexity of the products. The complementary competences developed within this configuration can be shared among members in order to achieve successful innovations. The transnational characteristic of the network has a similar goal, as "from an evolutionary perspective, one expects that countries in a transnational collaboration recombine their individual national specialization pattern" (Frenken 2000, p.269). The author provides Airbus as example as well, which is a result of the merger of several European companies from different countries in the 1970's.

However, networks are formed also with other structures of collaboration. In this industry, coopetition (simultaneous competition and cooperation) is attractive to face risks and decrease developmental costs (Klepper 1996; Acha et al. 2007). This can be present in the form of project-based alliances or through joint-venture, for instance (Bengtsson & Kock 2000). As a result, production is distributed along the supply chain and even among competitors. Companies have to use the knowledge from their specialized networks to assemble final products (e.g., aircrafts and satellites) instead of developing all parts and components in-house, which would be impractical considering the multitechnological characteristic of their products (Brusoni et al. 2001; Leten et al. 2007). This vertical integration also means that successful ACs must have strong integrative capabilities, which is essential to master the continuous evolution of product development (Prencipe 1997).

In reality, multitechnological firms generate variety by developing distinct bodies of knowledge during R&D and innovation activities. They coordinate learning processes that are disperse internally and throughout the network. Finally, they deepen the knowledge during its application to achieve the goals set by the firm (Brusoni et al. 2001).

Another feature of the aerospace industry is related to the nature of its innovation. In the aerospace industry, innovation is focused on more practical and engineered knowledge with a more directly applied view of new developments. Vincenti (1984) called this *production-centred innovation,* while Eliasson (1996) used the term *integrated production* to describe the same phenomenon. In this scenario, a technologically stronger firm is better equipped to respond to the requirement of constant innovation present in the industry if it knows how to combine internal and external knowledge and to manage the breadth of its knowledge base (Gopalakrishnan & Bierly 2006; Xu et al. 2013). The knowledge about its technological strength is a powerful strategic tool for companies to identify new business opportunities and to invest in new R&D activities or to specialize in existing technologies (Seol et al. 2011).

In summary, two major contexts defining the uniqueness of the aerospace industry are identified. Firstly, the competitive context; which is a reflex of the complexity of products and systems, making the use of specialized networks vital for survival and growth. More specifically, coopetition is recognized as a common strategy to develop technological innovation. Secondly, the technological context, in which many distinct technologies have to be assembled together to form final products; in this context the technological strength of an AC indicates its ability to continuously generate innovation and, ultimately, to strive.

In order to conceptualise the theoretical background to fit this particular study, the core concepts identified are outlined. 'Knowledge' is many times divided into tacit and explicit in literature (for instance, Nonaka 1994; Brown & Duguid 2001; Spender & Grant 1996 research on tacit and explicit knowledge in firms from different perspectives). Both types are taken in consideration here, but the focus lies on the more 'technical' or 'technological' aspect of knowledge, meaning the one that can be translated into new inventions and products in a more direct way.

Trott (2017) describes the knowledge base of an organisation in five dimensions:

- Individuals assets: skills and knowledge of individuals;
- Technology assets: capabilities that are replicable in product, processes and correlated areas;
- Administration assets: routines, procedures and systems developed within the organisation;
- External assets: relations established with partners, competitors, customers, etc;
- Project assets: the *modus operandi* through which other assets are deployed.

It is clear, then, that the knowledge base is a complex composition of assets from different dimensions, which are hard to quantify and comprehend. Although significant and crucial, technologies are, in fact, only a part of the knowledge base of any company. Technology-oriented companies need to integrate their technological knowledge and internal capabilities in order to remain competitive; the current level of technological development also requires constant learning and knowledge creation through the interaction of explicit and tacit knowledge (Nonaka & Konno 1998).

Based on the previous definition, the 'technological knowledge base' represents the body of technical knowledge and capabilities available for a firm to develop new products. Accordingly, a 'technology' is seen as an invention that can be directly applied in a product or process. Pavitt (1998) describes a technology as a body of knowledge with two complementary elements, a 'body of understanding' and a 'body of practice'. Dosi (1988) even claims that, in the current stage of scientific and technological development, knowledge and technology are entangled in each other and that a technology cannot be understood as a mere combination of production factors.

Additionally, a distinction between 'technological diversification' (or 'technological specialization' or even the neutral term 'technological scope') and 'technological *knowledge* diversification' is necessary. Literature usually uses patents to quantify the 'technological diversification' of companies (see Chiu et al. 2010; Srivastava & Gnyawali 2011; Leten et al. 2007). While the measurement seems appropriate, the definition could be improved. For many years scholars have debated the meaning and value of patents, finding that only a small set of patents has significant economic and technological value (Bessen 2008; Gambardella et al. 2008), the majority of patents receives zero or few citations (Trajtenberg 1990; Hall et al. 2005), while the existence of "patent trolls" has been long recognized (Pohlmann & Opitz 2013). Despite such issues, patents are still commonly used to measure technologies, mainly because of a lack of alternatives and reliable data sources. However, a more precise measurement can be extracted from patents by a small change in the definition of the concept: while only some patents actually become a real 'technology' in the market, when an organisation goes through the process of writing and depositing an application for a patent, it is a *sine qua non* condition to possess the knowledge regarding the putative technology being described, independently of how the patent will be used or its initial intention. So, even when a patent does not lead to a an actual technology, the technological has to be present once the patent has been deposited. Therefore, the term 'technological knowledge diversification' applied here seems more accurate than the commonly used 'technological diversification'.

'R&D' refers to the set of activities performed in a structured and planned way to achieve discoveries, create inventions and potentially lead to innovation.

The interpretation of innovation used here is the one for 'product innovation' in the Oslo Manual, which is "the introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses" (OECD & Eurostat 2005, p.48).

Finally, context conditions represent the evolving background under which technological development occurs; they determine technological bottlenecks, opportunities, experiences and skills, being specific to organisations and regions, constraining and stimulating innovation (Dosi 1988).

2.1. Competitive context: Coopetition

Coopetition is the concomitant cooperation and competition between competing firms. This requires two different logics of interaction at the same time: while partners have conflicting interests, which means they still have to protect their resources and capabilities, they also have to trust each other and share strategic information (Bengtsson & Kock 2000). Only recently literature has started looking at this complex and counter-intuitive kind of interaction, previously the focus was either in competition or cooperation separately, the more logical and straightforward expected interactions (Quintana-García & Benavides-Velasco 2004).

Considering the newness of the term, a brief discussion regarding its definition is necessary. Brandenburger & Nalebuff (1997) have applied a more general use of the term, in which coopetition is considered present if the product of one partner decreases the perceived value of the other's product. Bengtsson & Kock (2000) give the example of a partnership between a bank and a car manufacturer, in this case the conditions offered by the bank to grant loans affect the price of the car. These authors prefer a narrow definition of the term, limiting it to competitors that manufacture the same products, even though the cooperation might be specific to products in which they differ. Park et al. (2014) applies a definition closet to Bengtsson & Kock (2000), but includes all competitors in the same industry. This considers the fuzzy boundaries of firms and the difficulty to identify all dimensions in which one company might affect others, while still keeping a conservative approach. Hence, the latter is the definition of coopetition used in this study.

Historically, competitors have avoided each other, the need to protect resources, knowledge and capabilities was a stronger force repealing interactions that could result in knowledge spillover or leakages. However, with the increasing demand of R&D activities resources and shorter product life cycles, especially in high-tech industries, firms have realized that partnering with competitors could be a way to reduce risks and to avoid falling behind (Gnyawali & Park 2009).

On the one hand, coopetition opens the window to opportunistic behaviour among competitors, knowledge leaking and unbalanced learning, especially when partners have different levels of tacit knowledge or have different motivations (Ingram & Yue 2008; Chen et al. 2007; Salvetat et al. 2013). On the other hand, competitors share similarities on their knowledge bases, but possess different skills and capabilities, which facilitates comprehension and open space for shared learning and technological skills.

Nevertheless, the fact that both companies have access to the same knowledge does not entail an automatic acquisition of such knowledge (Salvetat et al. 2013). A firm needs to be open to acquire capabilities and skills from the coopetition, otherwise it will not result in long-term competitive advantages. Park et al. (2014) found that companies with an appropriate mindset and with more experience in coopetition have a greater benefit on the innovation outcome.

Gnyawali & Park (2011) designed a conceptual model of coopetition between large companies in a high-tech industry (Figure 1): technological challenges and opportunities, resources and capabilities and firm strategies are all driving forces favouring coopetition; value creation, technological development and gained competitive dynamics were identified as possible outcomes of this type of partnership. Moreover, by partnering together, competitors also share costs of development, decreases risks and gain access to new markets (Lei & Slocum 1992).

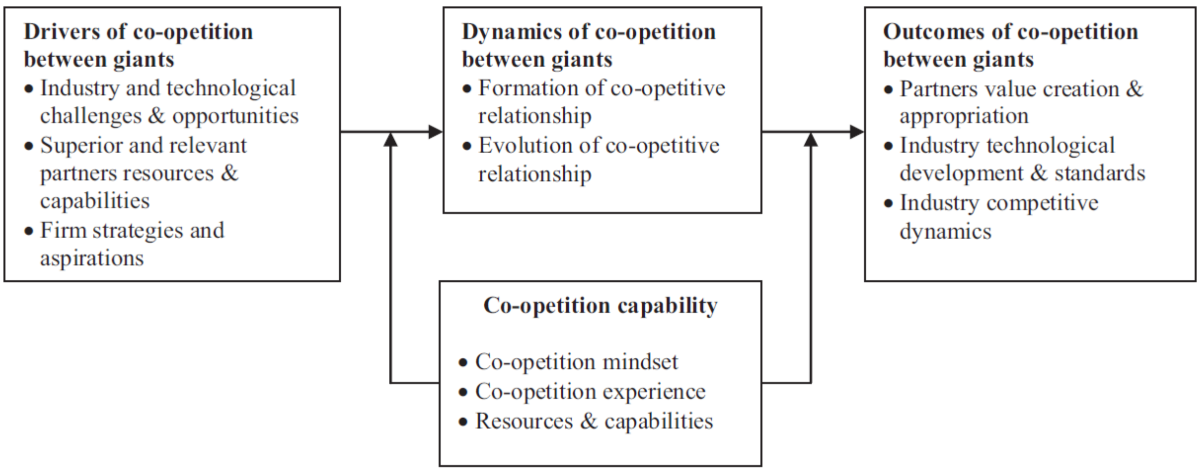


Figure 1 - Conceptual model of coopetition
Source: Gnyawali & Park (2011, p.658)

Coopetition can appear in different ways. A strategic alliance refers to the establishment of common goals to be pursued jointly while the partners remain as independent organizations. This setting gives the possibility for each partner to complement production, enter in new markets or develop new products with the know-how of the other one (Lei & Slocum 1992). Another type of alliance is the joint-venture, where two or more competitors form a new company that is affiliated but independent to them. Joint-ventures usually focus on specific range of products or services that the parents companies can better develop by combining resources, capabilities and knowledge. A project-based alliance is another common way of collaboration, in this case alliance is focused on knowledge production and it is only alive while bringing new technologies.

Gnyawali & Park (2011) show, for the specific case of technological collaboration, that coopetition positively affects the technological development and it has the side effect of stimulating other competitors to also pursue coopetition, helping to change the competitive composition of the industry. Similarly, Park et al. (2017) found that moderate to high levels of coopetition are positively related to the innovation performance of the firm.

Considering their multitechnological characteristic, high-tech firms have greater difficulties in knowledge management, so coopetition is seen as a mechanism to benefit from a different knowledge base, while keeping knowledge creation and application (Salvetat et al. 2013). Additionally, in cooperation with mutual strategic benefits, partners gain access to each other's knowledge bases and technological capabilities, also creating and sharing knowledge related to the organisation and to the market (Bosch-Sijtsema & Postma 2009).

Grant & Baden-Fuller (2004) shows that the formation of strategic alliances contributes to an efficient application of knowledge; in its turn, knowledge application in goods or services require combination of different types of knowledge, therefore alliances have a positive effect on knowledge diversification. In fact, Zhang et al. (2007) found a positive relation between technological knowledge breadth and the strategic alliances formation.

Furthermore, as costs and risks are shared in coopetitive alliances, more resources are expected to be available for firms to invest in other R&D activities. With more projects being executed, the technological knowledge base of ACs in coopetition can diversify more than those not making use of coopetition. Therefore, the following hypothesis is posed:

H1: The establishment of coopetition by a focal AC is positively related to the diversification of its technological knowledge base.

2.2. Technological context: Technological strength

The technological strength of a firm is a result of its R&D activities and empirical experiences, like learning-by doing and learning-by-using. By building its technological strength an organisation is better able to recognize the value of new technological development, becoming a source of competitive advantage (Xu et al. 2013; Cohen & Levinthal 1990). Hence, a technologically strong firm is able to utilize various technologies and apply them in new product development, which leads to more technological innovation than its competitors (Chen et al. 2007; Srivastava & Gnyawali 2011; Song et al. 2005). As described by Xu et al. (2013, p.753), a technologically strong firm "excels in identifying new technologies, responding to technological changes, and applying state-of-the-art technologies to enhance its product design and quality".

Previous studies have concluded that technologically weaker firms tend to take more risk when pursuing innovative activities, as they have to seek for more knowledge outside their base and fear less the potential of knowledge leaking (Ahuja 2000; Srivastava & Gnyawali 2011). On the other hand, stronger firms prefer to remain in the path dependency of their own technological trajectory (Arthur 1989). Srivastava & Gnyawali (2011) describe this as a "competency trap": firms with strong patent portfolios might become so internally oriented that it adopts not-invented-here mindset, resulting in an inferior use of its own resources. Xu et al. (2013), studying biotechnology firms from USA, show that the technological strength of firms have an inverted U-shaped relationship with radical and incremental innovation development.

However, Srivastava & Gnyawali (2011) also describe that companies can overcome this hurdle by building a capability termed "portfolio leverage", in which the portfolio is exploited, but does not limit exploration and strategic alliances are utilized to leverage external resources. This is expected to be the case of ACs. The multitechnological characteristic of the aerospace industry means that complexity increases in the industry, which opens new fronts of exploration for the development of new technologies (Hobday 1998; Leten et al. 2007). Chiu et al. (2010) highlight that, as a response to technological development, the knowledge base of ACs diversify to technological areas that were not initially the main goal of the firms. For instance, in the 1970's, ACs had to start specializing in softwares and digital technologies, while at the beginning of the industry the main focus was in mechanics and electrical components. Complexity for the aerospace industry has a double effect; as described by Mahoney (1992, p.366), "specialization induces diversification" in firms. This is seen as an interplay between the necessity of specialization, which requires growth, and the necessity of growth, which requires specialization and diversification. Grant & Baden-Fuller (2004) make a similar argument, stating that knowledge creation requires specialization (to create novel knowledge, one needs to specialize in its understanding), while diversity is a requirement of knowledge application (to make knowledge applicable, one needs to combine it).

Therefore, technologically strong ACs cannot simply rely on their internal knowledge and readily available internal capabilities. The technology management literature highlights that it is through the recombination of new and established technological knowledge that new inventions are created (Albino et al. 2014; Ardito et al. 2016). So, the recombination of knowledge in the aerospace industry requires diversification in the knowledge base to effectively generate innovation. In fact technologically strong firms are attractive to each other, as they can share risks and leverage from each other's resources and knowledge (Rosenkopf & Nerkar 2001). Hence, the following hypothesis is posed:

H2: The technological strength of a focal AC is positively related to the diversification of its technological knowledge base.

The theoretical model (Figure 2) shows the hypothesized relations in the current study. Control variables are also included, these will be explained in details in the next section.

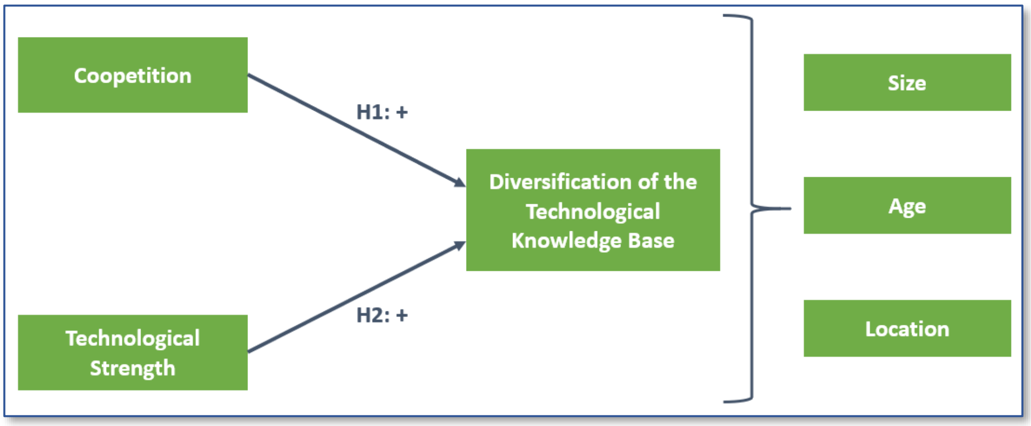


Figure 2 - Theoretical model

3. Methodology

3.1. Research strategy and design

To answer the hypotheses and the research question, the present research evaluates correlation between two separate independent variables and one dependent variable through a deductive research strategy, in which hypotheses are deduced from previous established theories and guide data collection for analysis (Bryman 2013). This is applied in a longitudinal or panel research (Xu et al. 2013), because only quantitative data are collected for a certain period in time, more than two variables are used and possible existing patterns are checked.

3.2. Sampling strategy

ACs comprise the unit of analysis, while the unit of observation is made by their respective patents. Sample comprises 60 ACs and their subsidiaries; these companies were identified from the publication "Top 100 Aerospace Companies" study (FlighGlobal & PwC 2015). From the top 100, companies with less than 10 patents in the period of analysis or with less than 1% of the size of Boeing, the largest firm in the industry, were excluded, resulting in the final 60 ACs. This purposive sampling strategy intends to retrieve data from the most important players in the industry, as these 60 companies accounted for more than 90% of the revenues in the industry in 2015 (FlightGlobal & PwC 2015), while providing sufficient amount of data for meaningful statistical analysis. Furthermore, smaller companies have lower resources to apply in new R&D activities, new product development and innovation, limiting their ability to diversify and to impact on the industry technological trajectory; however "tier 2" and "tier 3" companies, as they are generally referred, still have a relevant role in the industry as supplier of smaller and less technological components and designs for "tier 1" firms (Acha et al. 2007; Salvetat et al. 2013). The full list of companies can be found in Appendix I.

3.3. Data collection

Each patent is considered a proxy to an invention, which can represent a part of or a whole technology. The technological knowledge is represented by International Patent Classification (IPC) classes, accordingly the technological knowledge base is measured by the variety of IPC classes deposited by ACs. The IPC is an hierarchical classification system established in 1971, it contains more than 70.000 subdivisions for codes up to 12-digits (WIPO n.d.). Each patent can be classified in one or several IPC classes, depending on the breadth of knowledge it covers.

First, subsidiaries names of ACs were searched in the Orbis database, from the Bureau van Dijk, which contains names and affiliations for firms around the world. After cleaning, there were over 3000 subsidiary names, which were all included in the query in order to have a more comprehensive coverage of patents.

Then, patent data were retrieved from PATSTAT, the European Patent Office (EPO) database, which was available offline in the Centre for Science and Technology Studies (CWTS, Leiden University). This was performed through queries in the SQL Server Management Studio. Data regarding patents published by at least one of the ACs under analysis (or subsidiaries) described as applicants were saved in a separate database. Furthermore, patents were considered as part of patent families, grouping those related to the same inventions deposited in several countries or deposited in the same country but in different moments in time. The earliest filling date was considered as the year of deposit of each patent family. Data for approximately 595 thousand patent families were retrieved, which accounted for 1.16 million unique application IDs.

Throughout the cleaning process, manual checks were performed to verify if retrieved data actually belong to the firms of interest or if improvements in the query were necessary (e.g., in the case of ambiguous names or misspellings).

As part of the "coopetition" measurement, joint-ventures companies were identified in a separate field. In the Orbis database, a joint-venture can be recognized by being assigned to more than one parent company. Additionally, desk research was used to identify dismissed joint-ventures or those not identified in the database.

To calculate the technological strength of firms, data regarding forward citations were also collected, being grouped in patent families as well. ACs patents were cited for approximately 3.6 million different patents (counted in application IDs).

3.4. Operationalization

Dependent and control variables were measured over a timeframe between 1995 to 2013, which is the latest year with full data available in PATSTAT in the moment of data collection. This 19-years span is expected to provide sufficient data for analysis and to represent well the technological knowledge diversification in the industry.

Independent variables were lagged in five years, so they cover the period between 1990 and 2008. The lag period accounts for the temporal gap for the independent variables to have an effect on the dependent one.

Bacchiocchi & Montobbio (2009) found that forward citations still occur in a significant proportion even after 20 years after a patent publication, especially for those deposited by companies (in contrast to universities and public research organisations), so no maximum citation lag was set in this research.

To increase reliability, a thirteen-year timeframe and a two-year lag for the independent variable were also tested and, in both cases, results in the same direction as those presented here were found, only with some differences at the significance level.

3.4.1. Dependent Variable: Technological Knowledge Diversification

The diversification of the technological knowledge base of ACs was calculated through the Herfindahl index, which measures the level of concentration in specific IPC classes for each firm (Chiu et al. 2010; Gnyawali & Srivastava 2011; Quintana-Garcia & Benavides-velasco 2008; Rafols & Meyer 2010; Porter & Rafols 2009). Full-count of IPC is accounted instead of fractional-count, which allows the index to vary to values above one; this is the case because a patent regarding a more complex technology might be classified in several IPC classes, but this does not imply the existence of an upper-limit for the knowledge being used in that technology.

However, following Leten et al. (2007), a transformation was applied to the index by taking its inverse. Therefore, Technological Knowledge Diversification (TKD) was obtained by taking the inverse of the Herfindahl index:

$$TKD_i = 1 \Big/ \sum_{c=1}^{n} \left(\frac{P_{ic}}{P_i}\right)^2$$

Where c represents each patent class, n is the total number of classes in patents deposited by each company i and P is the total number of patents deposited.

3.4.2. Independent variables: Technological strength and Coopetition

Some studies have measured the technological strength of firms simply by counting the number of patents deposited by each firm. However, there are some issues related to this way of measurement: patent strategies vary among companies regarding frequency and secrecy, not all technological capabilities are patentable and patents differ in their economic and technological values (Griliches 1990; Gopalakrishnan & Bierly 2006).

Therefore, a different methodology was applied here, accounting for the average impact of a firm's patents in generating innovation, as described by Kayal & Waters (1999) and Chen et al. (2007). First, the Impact Index (II) was calculated, this is the average number of citations received by a focal firm's patents, normalized by the industry average; self-citations, which accounted for 4.3% of all citations, were excluded from the calculation:

$$II_i = \frac{C_i / P_i}{\sum_i^{60} C_i / \sum_i^{60} P_i}$$

Where C_i is the number of citations received by the patents of company *i* and P_i represents the number of patents deposited by company *i*. Then, to calculate the Technological Strength (TS) of each focal firm, *II* was multiplied by the number of patents of each firm:

$$TS_i = II_i \times P_i$$

$$TS_i = \frac{C_i}{\sum_i^{60} C_i / \sum_i^{60} P_i}$$

Coopetition was measured by the percentage of patents deposited by each focal firm in which coopetition with the remaining ACs under analysis is present during the specified timeframe, either through co-authorship of patents or joint-ventures as authors.

3.4.3. Control variables: firm age, size and location

In addition to technological strength and coopetition, there are other variables that may affect the diversification of the technological knowledge base of ACs and must be controlled. Therefore, the influence of these variables must be accounted on the dependent variable.

The first control variable is *firm size*. It's effect has long been described on innovation related studies and different effects have been described (Xu et al. 2013; Chandy & Tellis 2000). Size will be accounted by the total revenue of each company, according to the data available in the "Top 100 Aerospace Companies" study (FlightGlobal & PwC 2015).

The second control variable is *age*, which is also commonly considered in innovation studies (Gopalakrishnan & Bierly 2006; Srivastava & Gnyawali 2011). Some of the companies included in these studies have over 200 years of history, which is longer than the aerospace industry exists. In order to avoid bias, age was not accounted by firm's age, but by the time each firm started to manufacture and sell aerospace-related products. Desk research was performed, searching in the "History" section or similar in each company's website to set the starting date.

Finally, literature has shown that *location* also influences the knowledge stock and knowledge flow of companies (Decarolis & Deeds 1999). Dummy variables were included to account for location, three groups were identified: companies from North America (30 observations), Europe (20 observations) and other regions (Asia, Latin America and Middle East, 10 observations)

Table 1 presents the operationalisation of all variables.

Table 1 - Operationalisation table

Variable	Description	Values
Dependent variable		
Technological Knowledge Diversification	Inverse of Herfindahl index	0 - inf
Independent variables		
Coopetition	Share of patents in coopetition	0 - 1
Technological strength	Normalized number of citations received	0 - inf
Control variables		
Age	Years since beginning of aerospace-related manufacturing	0 - inf
Size	US$ billions in revenues	0 - inf
Location	World region (North America, Europe or other regions)	0 or 1

3.5. Data analysis

Ordinary Least Square (OLS) regression analysis was applied. Variable transformations were used when necessary to reduce skewness or extreme deviations.

Several models were designed to test for significant correlations between the independent and dependent variables. In total five mains models were constructed through R software:

- Model 1: in which only control variables and TKD were included;
- Model 2: in which control variables, TKD and coopetition were included;
- Model 3: in which control variables, TKD and technological strength were included;
- Model 4: in which control variables, TKD and both coopetition and technological strength were included;
- Model 5: in which control variables are excluded, keeping TKD, coopetition and technological strength.

OLS regression analysis is a good way to identify to what extent independent variables influence the dependent one. When making conclusions out of linear regression models, several assumptions must be met. First, variables must be close to a normal distribution, this was tested through the measurement of skewness and kurtosis. Second, there must be a linear relationship, which was tested by drawing scatter plots. Third, the errors must be statistically independent; to check if this assumption holds, Shapiro test was performed and a plot of residuals was analysed. Fourth, multicollinearity shall not be present. For this, the different independent variables were tested for correlation and a variance inflation factor test was performed, assuring the absence of multicollinearity. Fifth, autocorrelation was checked by performing a Durbin-Watson test. Finally, homoscedasticity was verified with a non-constant error variance plot. When an assumption was not met, an appropriate measure was taken to assure the quality and reliability of the regression model.

3.6. Quality of research

3.6.1. Reliability

According to Bryman (2012), reliability is related to the consistency of how a given concept is measured. The author breaks down this definition in three factors involved when considering the reliability of a measure:

- Stability: this is related to the fact that a certain measure should be stable over time, so the results do not fluctuate;
- Internal reliability: if the indicators chosen are consistent;
- Inter-observer consistency: in the case of subjective judgement involved in a study performed by several researchers.

Concerning stability, data regarding all companies were retrieved simultaneously for each variable, which lasted for *circa* three months. All variables have been used in literature for a long period and their strengths and limitations are well-known in the scientific community.

For the internal reliability, EPO data has been largely used in literature and it has an extensive coverage of patents. EPO does not cover all patents in the world, but it includes all patent offices related to the original country of the 60 ACs in analysis and many others, reducing the risk of overlooking important trends.

And inter-observer consistency was not considered an issue, because the research was conducted by only one master student. Additionally, subjective methodological decisions were discussed with both supervisors.

3.6.2. Validity

Validity refers to the integrity of the results and conclusions in a research. Bryman (2013) states that this is the most important criterion for the quality of a research, also breaking down in three types of validity:

- Measurement validity: if a measurement actually reflects the concept it intends to measure. This definition overlaps with the definition of stability of a certain measure;
- Internal validity: this is related to the causality; if a researcher suggests that *x* causes *y*, how can he/she be sure that *x* is actually causing *y* (and not some other variable)?
- External validity: there is external validity when the results can be applied to other cases or studies.

For the measurement validity, technological knowledge has been proxied by patent' IPC classes. Although shortcomings have been identified and long debated in literature, patents are widely used in studies measuring knowledge, technology, R&D activities and innovation in literature (see Hagedoorn & Cloodt 2003; Bollen et al. 2009; Duguet & MacGarvie 2005; Sweet & Maggio 2015; Nakamura et al. 2015).

The same argument stated above holds for internal validity. Hypotheses were made based on well-established theories and following some of the most important authors in the field. However, there is always a risk that unseen or unpredicted factors affect the outcome. The use of a large literature partially minimizes such risk and, additionally, discussions were held with supervisors and peers, allowing for different points of view to be brought into light.

External validity is limited in the sense that many of the findings are specific to the industry under study. However, generalizations are possible for similar situations (e.g., for other high-tech companies and for firms in other countries) provided that differences for each case are acknowledged.

Furthermore, convergent validity was also considered, which analyses the degree to which two measures converge. This was tested by sending a previous version of this thesis to several experts, one of them agreed to assess it: Dr. Delio Luceno-Piquero (University of Toulouse). His contributions are identified throughout the thesis.

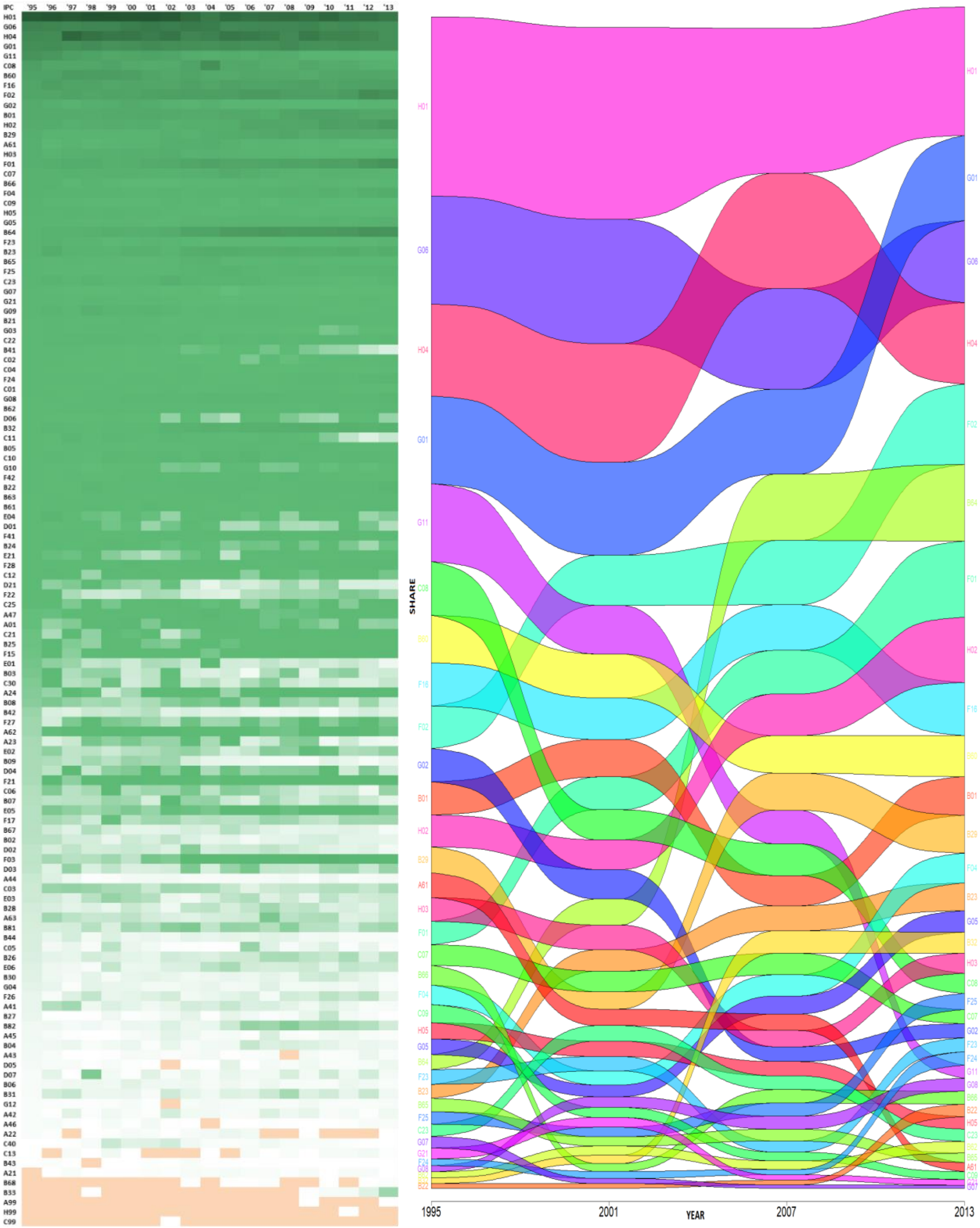
4. Results

Before analysing the two proposed hypotheses, each variable is studied separately in order to comprehend industry-level trends, besides firm-level ones. Conclusions will be drawn by comparing results from both levels, which will allow to construct an overarching scenario of the aerospace industry development, providing insights on the evolution of this industry during the period under study.

4.1. Technological knowledge diversification

Does the diversification of companies also means an increased diversification of the technological knowledge of the aerospace industry as a whole? To start answering this question Figure 3.a displays a heatmap of 3-digits IPC classes from all patents deposited by AC companies between 1995 and 2013 (the darker the shade of green, the higher the frequency of occurrence). The map was constructed using the conditional formatting tool in Excel. There are only 13 IPC classes not present in all years (orange background) and only five not present in at least half of the years (B68, B33, A99, C99 and H99). Classes ended in '99' are only present to include subject matters that could not be included in any other section, hence they are not actually informative. 'B68' is related to saddlery and upholstery, appearing for the first time in 2003, but always remaining with one of the lowest occurrence share. 'B33' is an interesting case, it appears constantly since 2009, but with a frequency 36 times higher in the last year; this class refers to 3D printing technologies, evidencing its fast and increasing adoption by ACs.

This analysis shows that the technological knowledge base of the aerospace industry remained practically unchanged between 1995 and 2013. The only significant addition to the knowledge base are 3D printing technologies, which are quickly becoming pervasive. The use of 3D printing opens opportunities to decrease development costs and time, valuable gains for a high-tech and high-cost industry. However, data have shown that in this case there are two leading companies (Safran and Hexcel) developing this technology in the industry. These two companies are both suppliers of technologies and components, therefore their clients and partners might be benefiting from the development as well.



(a) Heatmap of IPC classes share by year (b) Alluvial map of IPC classes *versus* share by year

Figure 3 - Share of IPC classes by year

The stability of the industry technological knowledge base does not mean that knowledge is not being developed, only that the space for development is well-delimited and accepted by the companies. In this scenario, incremental innovation is predominant, technological discontinuities are infrequent and a strong appropriation regime is present (Utterback & Suárez 1993).

Furthermore, some classes have lost great part of their share along the years, e.g., B41 (printing, typewriters and stamps), C11 (oils, fats and detergents), E04 (building of fixed constructions) and D01 (threads or fibres. On the other hand, other classes, like F02 (combustion engines), F01 (machines or engines), B64 (aircraft, aviation and cosmonautics) and F03 (machines or engines for liquids or wind), had a sharp increase in their frequency of occurrence.

Also, it was investigated how the loss of share from one class compares to the variation of the remaining classes. Based on the standard deviation of the variation in the ranking of IPC classes between 1995 and 2013 (equals to 8.995), classes were categorized as follows: if it gained nine or more positions, a class was labelled as "increased interest"; if it lost nine or more positions, "decreased interest" was assigned, "stable" was assigned otherwise (this analysis was performed based on ranking instead of share as the variation in share is far greater for classes on the top of the ranking than those in the bottom part). An alluvial map was constructed to graphically display such variations (Figure 3.b), this was performed in R Studio using the package 'alluvial'. For the sake of visual clarity only four selected years (1995, 2001, 2007 and 2013) and the top 30 IPC classes by share regarding the years of 1995 and 2013 are displayed (which account for over 80% of the share of all IPC classes). A full description of classes and variations from Figure 3.b are displayed in Appendix II.

Despite losing 6.56 percentage points (pp) in share, the top four IPC classes remain the same along the years (i.e., H01, G01, G06 and H04). IPC classes related to peripheral instruments or compounds faced loss of interest (e.g., G07 – checking devices, G11 – information storage and C09 – dyes, paints, etc), altogether losing 11.49 pp in share. Interest, then, moved to heavy machineries and their physical characteristics (e.g., F01 – machine or engine in general, F24 – heating and ventilating, B22 – powder metallurgy and B32 – layered products), with a gain in share of 12.48 pp. Stability was found for classes related to electrical parts, chemical compounds, combustion processes and other common elements in aerospace products, their total share variation was only of -0.25 pp.

These observations, coupled to those derived from the heatmap, indicate that interest moved from peripheral instruments or compounds and other technologies to heavy machineries and their functioning. This represents an increased focus in developing technologies related to the core components of aerospace products and their functioning, which indicates a higher interest of ACs in gains of efficiency, safety and costs reduction in their products (Lee 2000; Grose 2013).

Additionally, Figure 3.a and Figure 3.b visually indicates that, within the existing group, the share of IPC classes is becoming more evenly distributed along the years. However, a better way to measure such assumption is through the Berger-Parker index of diversity, which is capable of measuring the internal diversity (or concentration) of a population in a defined number of categories. For instance, assuming the existence of three different categories, if in one year each category accounts for one third of the share, but in the following year a class accounts for 60%, one can say that diversity has decreased (or concentration increased). Figure 4 displays the normalized index. It is interesting to note that the Berger-Parker index has a descent trend until 2001, year of the 9/11 attacks. In 2002 there is a small increase in the index and a sharp increase in 2003, which has been sustained ever since. 2003 also marks the year when the aviation sector recovered its growth after the attacks (IATA 2011).

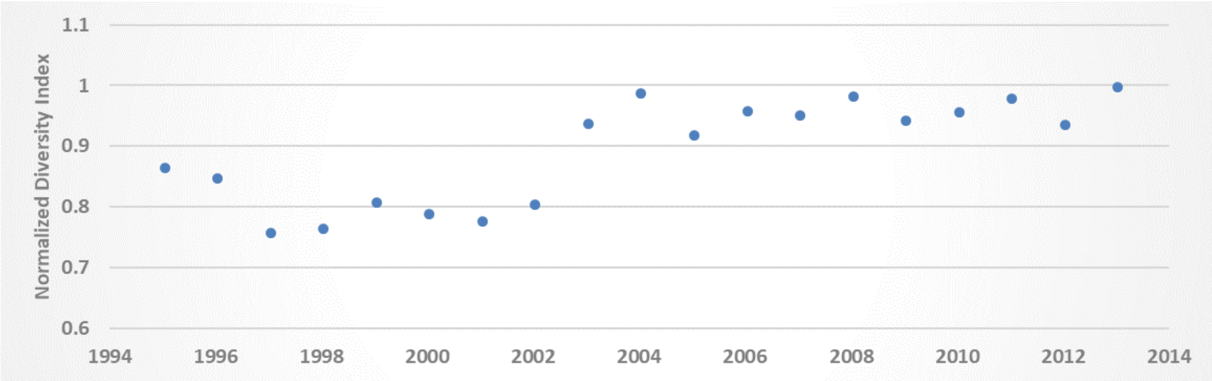


Figure 4 – Normalized Berger-Parker Index of Diversity along the years

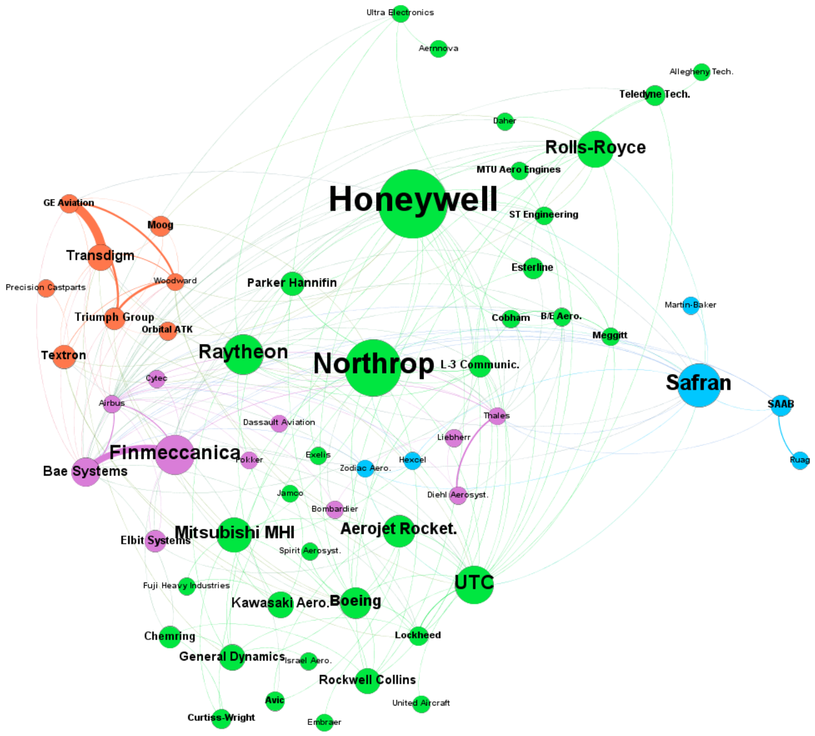
4.2. Coopetition

The analysis of coopetitors reveal who are the preferential partners, who are the main players connecting the network and also geographical preferences, providing a structural overview of the aerospace industry.

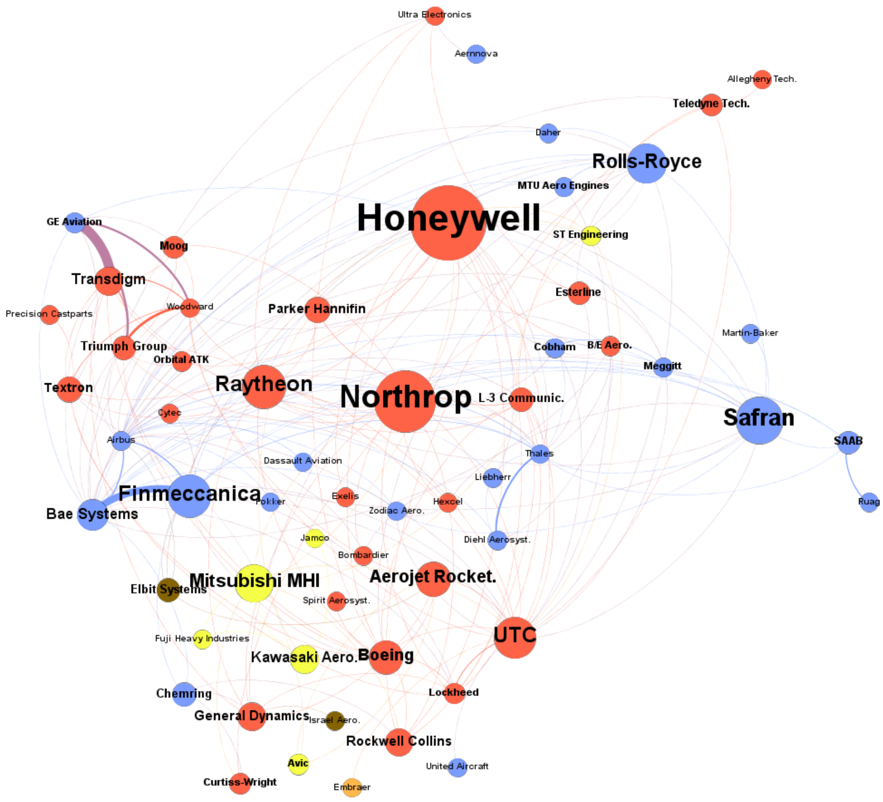
Figure 5.a shows the network of coopetitors, which was built applying an OpenOrd layout (edge cut equals to 0.8, three threads and 750 iterations) adjusted by a Noverlap layout (ratio 2.1) in Gephi. Nodes size are based on betweenness centrality and communities are clustered applying the modularization algorithm with a resolution of 2.5, with randomized data and applying weights, modularity is equal to 0.582. The average degree of the network is seven, diameter is equal to five, density is equal to 0.118 and the average path length, 2.073.

Honeywell, Northrop, Safran, Raytheon and Finmeccanica have the highest centrality in the network, indicating that these are the better connected companies in the aerospace network of coopetitors. These five companies are mainly high-tech suppliers of components for commercial aviation and armaments for national defence and specially develop space products for other companies and governments (e.g., satellites and rocket launchers). Honeywell is present in other industrys as well, like oil, gas, building and even footwear.

Four clusters are formed and identified by distinct colours. The green cluster is the largest and most diversified one, comprising 35 companies; this can be seen as the backbone group of this industry, as all other clusters orbit around it. The blue cluster is dominated by Safran; SAAB and Ruag are isolated with few ties, conversely Zodiac Aerospace and Hexcel are close to the green and purple clusters, occupying a more central position in the network. In the purple cluster, Finmeccanica and Bae Systems have a high level of coopetition with each other, while Thales is well connected to others, holding several ties with the green and blue clusters. Finally, GE Aviation, Transdigm, Triumph Group and Woodward have the strongest ties in the orange cluster. Considering ongoing negotiations, it is not a surprise to see Airbus and Bombardier in the same cluster (purple one) and Boeing and Embraer together as well (green cluster).



(a) Clusters' colours based on modularity



(b) Clusters' colours based on geographical location

Figure 5 – Network of coopetitors, betweenness centrality defining node size

Figure 5.b displays the same network, but with clusters coloured based on company's geographical location: red is for North America, blue for Europe, yellow for Asia, brown for Middle East and orange for Latin America. Conclusions are drawn by comparing both networks. The blue cluster in Figure 5.a is comprised mainly by European companies working together, the exception being Hexcel (North American). A similar observation applies to the purple group, where only Bombardier, Cytec and Elbit are non-European. The opposite case holds for the orange cluster, where all companies but GE Aviation are North American. Finally, the green group is the most internationally oriented one; all Asian companies are clustered together, although ST Engineering (from Singapore) is far from other companies from the same region; the remaining ones are formed by one Middle-Eastern, one Latin American, 19 North American and eight European ACs.

The only two Middle-Eastern companies were clustered separately, since they do not share any single tie. Asian companies, on the other hand, belong all to the same cluster; within this group Mitsubishi MHI, Fuji Heavy Industries, Jamco and Kawasaki Aerospace share stronger coopetitive ties, evidencing a clear geographical preference. By comparing both figures, the blue, purple and orange clusters (in Figure 5.a) indicate the existence of geographical preference among North American and European companies, but only with selected competitors, as for other companies in the same region they are distant located in the network, indicating that these firms are carefully choosing those competitors they can work with and those that represent a larger threat and, therefore, should be avoided. Once again, the green cluster seems to be the backbone of the industry, as it includes companies from five different world regions. Geographical proximity has been explored in literature related to strategical alliances, as it facilitates knowledge sharing and usually also means cultural proximity (Boschma 2005).

In appendix III variations of the same network are displayed, including node sizes based on company sizes and degree (number of company's ties). Company size is not related to the centrality of a company in the network, the two largest companies (Airbus and Boeing) have a high number of ties (degrees), but only with some preferential partners; their suppliers are smaller, but cooperate more with other ACs. Airbus and Boeing, operating mainly on a business-to-consumer (B2C) model, focus on strengthening ties with partners possessing extensive portfolio of technologies, instead of developing all technologies by themselves. Suppliers, on the other hand, operate on a business-to-business (B2B) model, which means they are responsible for developing the majority of technologies, forcing them to increase the number and diversity of ties.

4.3. Technological strength

To visualize the technological strength of aerospace companies a heatmap was generated including all 3-digits IPC classes deposited between 1995 and 2013, once again the conditional formatting tool in Excel was used to generate the map (Figure 6). As in the measurement for the regression analysis, self-citations were excluded. White cells indicate no citations received and darker shades of blue indicate higher values for the normalized number of citations received by a given company in each IPC class.

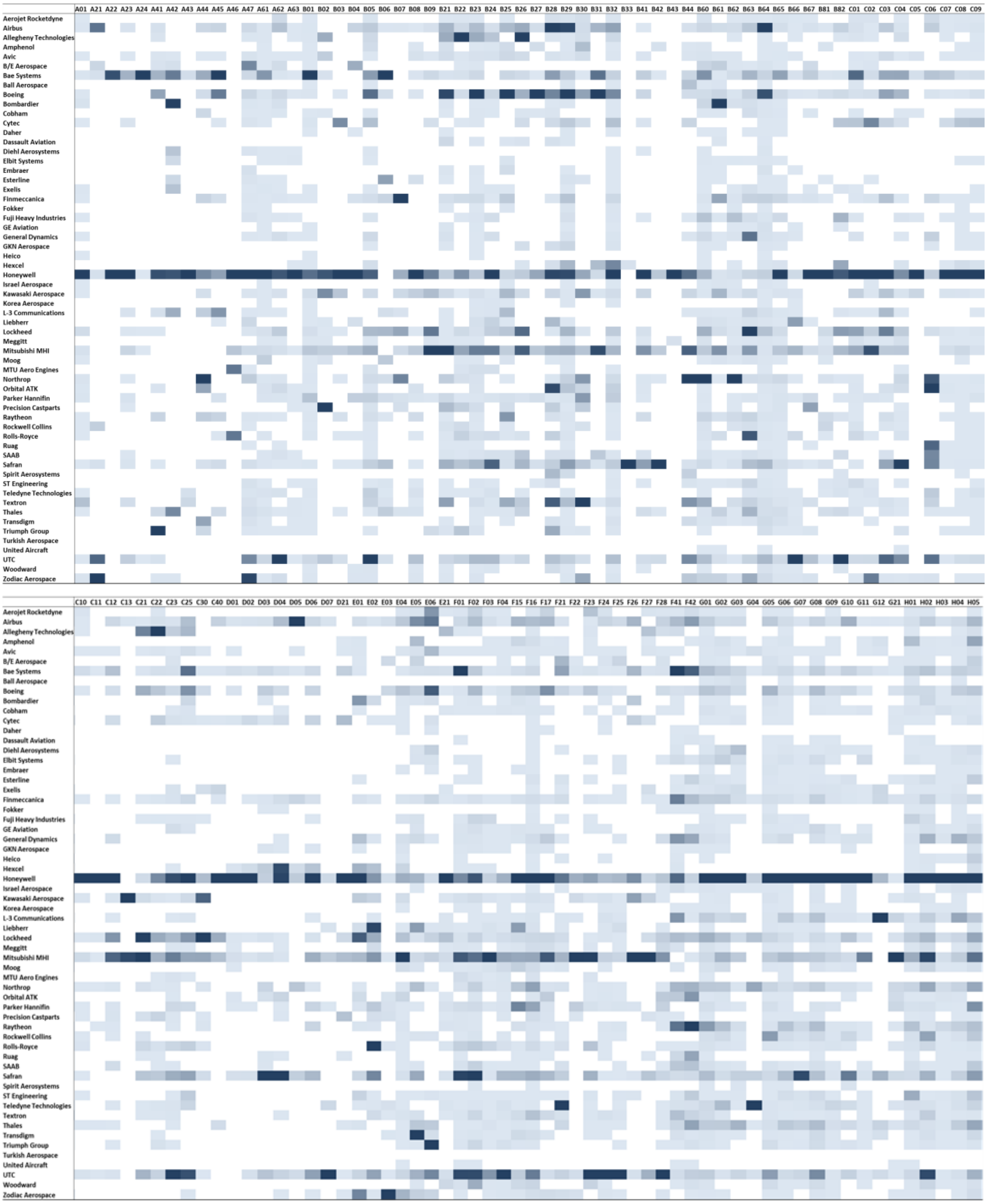


Figure 6 – Heatmap of citations received by IPC classes and companies, 1995-2013

Firstly, it is interesting to note that the majority of ACs has some technological strength in a large number of different classes, spread throughout the IPC classification system. This visually shows how large the technological knowledge base of the aerospace industry is, ACs have to understand not only the core functioning and operation of their products, but also several other peripheral aspects, from human necessities to the chemistry of paints. However, in general, ACs are technologically weaker in some group of classes, for instance, A2 (foodstuffs, tobacco), A4 (personal or domestic articles), B4 (printing) and D0 (textiles or flexible materials). As encountered earlier, these are not classes directly related to aerospace products and, hence, it is not a surprise that several companies are not particularly strong (or they are even absent) in these technologies.

On the opposite side, there are classes where ACs are, in general, technologically stronger: B28 (working cement, clay, or stone), F41 (weapons), F42 (ammunition and blasting), H02(generation, conversion, or distribution of electric power) and H05 (electric techniques). The strength in weapons and ammunitions is a result of the interchangeability of technologies between aerospace and defence products. In fact, many ACs also develop solutions for military and defence purposes, either through whole products (e.g., aircrafts, tanks and satellites) or new techniques or technologies (e.g., optics and communication). And the strength in electric-related technologies is due to the relevance of electric components in aerospace products, most commands nowadays rely on digital and/or electric signalling, which explains the expertise of aerospace companies in developing such field of knowledge.

When looking through each company, patterns can also be observed. Turkish Aerospace's, United Aircraft's and Daher's patents have received few citations when comparing normalized values; Honeywell, Mitsubishi MHI and UTC are those that have, on the overall, the highest technological strength, they are also the three companies with strength spread through a large number of different classes, as evidenced by the Berger-Parker Index of Diversity calculated by firm (Figure 7). Safran, Bae Systems, Boeing, Lockheed and Airbus also possess great strength, although for them it is more localized in fewer areas of technological knowledge.

In some classes only one or a few companies are technologically strong, e.g., A21 (baking and equipment for making doughs), in which Airbus, UTC and Zodiac Aerospace are equally strong; B33 (3D printing technologies), in which only Safran and Hexcel have strength; C13 (sugar industry), only Kawasaki Aerospace and Mitsubishi MHI; D07 (ropes and non-electric cables), UTC; and G04 (horology), Teledyne Technologies.

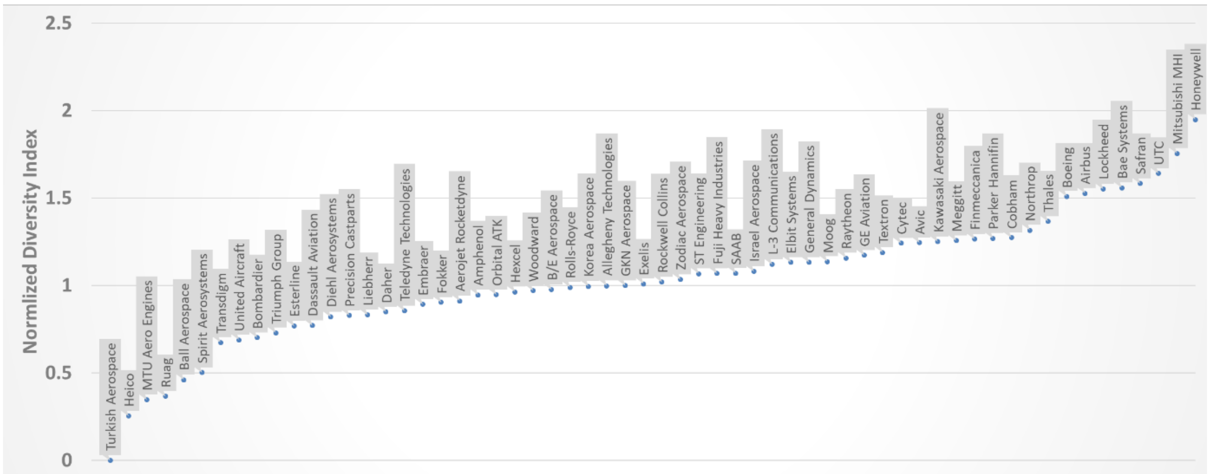


Figure 7 – Berger-Parker Diversity index of technological strength, log-transformed (base 10)

Additionally, an analysis of the strength of coopetitive and non-coopetitive patents was performed and a significant difference was found: patents deposited in coopetition have a technological strength, on average, three times higher than non-coopetitive patents (2.901 to 0.946, respectively), although the large majority of patents in both group does not receive any citation (Table 2), which is in line with previous observations (see Trajtenberg 1990; Hall et al. 2005). This indicates that by combining knowledge, capabilities and resources, ACs are successful in generating technological knowledge that is being more applied in the technological development of the industry. Consequently, in the long-term, ACs in coopetition will leverage their dynamic capabilities, become better equipped to identify new technologies and be more prepared to adapt to changes in comparison to those not making use of coopetition.

Table 2 - Technological strength of coopetitive and non-coopetitive patents

	Mean	SD	Sample size	Median	Min.	1st Qu.	3rd Qu.	Max.
Coopetitive patents	2.901	14.644	5,933	0	0	0	0.300	481.987
Non-coopetitive patents	0.946	8.183	395,474	0	0	0	0	457.535

Difference: 1.954; confidence interval: 1.194 to 2.715; confidence level: 0.0001 (z = 3.99)

4.4. Regression analysis

Table 3 presents descriptive statistics of the variables. TKD varies from 0.037 (for Allegheny Technologies, which indicates a largely specialized technological knowledge base) to 69.764 (for Korea Aerospace, the largest diversification in the industry); as indicated by the third quartile, most companies have TKD values below four, in fact, only five companies have values above ten. There is a large variation in age, covering 110-years span and an average age of 65.8 years. Regarding size, the majority of companies had revenues below US$ 10 billion. For coopetition, four companies did not take part in any patent with competitors or did not form any joint-venture (namely, Amphenol, Ball Aerospace, Turkish Aerospace and Korea Aerospace); on the opposite extreme, two companies (Diehl Aerosystems and Dassault Aviation) only had coopetitive patents. And while Turkish Aerospace had a TS equals to zero (i.e., it did not receive any citation), Honeywell had the highest TS (622.134).

Table 3 – Descriptive statistic

Variable	Minimum	1st Qu.	Median	Mean	3rd Qu.	Maximum	SD
TKD	0.037	0.845	1.531	4.880	3.859	69.764	10.923
AGE	7.000	45.750	68.000	65.800	91.000	117.000	28.922
SIZE	0.917	1.630	3.370	9.501	10.025	90.800	16.741
COOP	0.000	0.010	0.036	0.114	0.104	1.000	0.206
TS	0.000	24.880	98.601	622.134	391.460	152720.110	2087.468
II	0.000	0.319	0.497	0.568	0.724	2.650	0.432
				Number of observations			60

Measurements of skewness, kurtosis and the normality of distribution are displayed in Table 4. Values of skewness and kurtosis depicted below represent the 'excess', so values between -1.000 and 1.000 are considered acceptable. In order to a distribution be considered normal, its p-value should be above 0.05, the threshold of statistical significance adopted in this study.

Table 4 – Skewness, kurtosis and normality test

Variable	Skewness	Kurtosis	Normality test W (p-value)
TKD	4.288	20.270	0.427 (0.000)
TKD log 10	-0.016	0.558	0.978 (0.335)
AGE	-0.361	-0.940	0.957 (0.035)
SIZE	3.400	12.214	0.524 (0.000)
SIZE log 10	0.713	-0.319	0.932 (0.002)
COOP	3.034	9.416	0.555 (0.000)
TS	6.352	42.676	0.282 (0.000)
II	2.033	7.139	0.845 (0.000)

Due to high skewness and infrequent extreme deviations (i.e., high kurtosis values), TKD and size were log-transformed on a base ten, which brought values within the acceptable range for all measurements. Normal distribution is especially important for the dependent variable and the transformation of TKD was able to lead to normal distribution. Ideally, all variables should be normally distributed, however when dealing with real life data this is hardly ever the case. For the independent variables this is not a problem, therefore the outcome of the analysis is not compromised.

Coopetition and TS also presented high values of skewness and kurtosis, however a log-transformation was not possible in their cases due to the presence of null values. Hence, a different strategy was adopted, turning both into categorical variables. Based on the descriptive statistics data, a low degree of coopetition was defined when its value was below 0.001, a high degree for values equal to or above 0.100 and moderate for values in between. Similarly, values below 25.000 indicated a low degree of TS, high degree for values equal to or above 250.000 and, again, moderate for values in between. For coopetition there are 15 companies in the low, 29 in the moderate and 16 in the high degree category; for technological strength, there are 15, 26 and 19 companies in each category, respectively.

Table 5 displays analysis of correlation among different variables. Impact Index (II) is included as an alternative measurement for the technological strengths of ACs, as it is a *quasi-size-independent* measure.

No correlation is found between TKD and firm age, but there is a significant correlation between size and TKD, indicating that the larger an AC gets, the more diversified its technological knowledge base becomes. There is also a statistically significant and positive correlation between size and age, evidencing that older ACs are also larger than newer ones. Correlation is also found between size and TS; however, as TS is an independent variable, this finding has to be further analysed. In Table 6, model A displays the regression analysis considering TS as the dependent variable and size as the independent one and, in model B, II is the dependent one.

Table 5 – Correlation between variables

	TKD[a]	COOP	TS	II	AGE	SIZE	Europe	N. America
COOP	-0.144	-						
TS	0.159	-0.094	-					
II	-0.072	-0.058	0.720***	-				
AGE	0.072	-0.063	0.131	0.239⁺	-			
SIZE[a]	0.294*	0.027	0.294*	0.358**	0.377**	-		
Europe	-0.113	0.395**	-0.110	-0.275	0.187	0.098	-	
N. America	-0.150	-0.235⁺	0.151	0.445***	-0.055	0.030	-0.707***	-
Other regions	0.344**	-0.184	-0.063	-0.249⁺	-0.164	-0.164	-0.316*	-0.447***

a. log-transformed, base 10 ⁺ p < 0.10 * p < 0.05 ** p < 0.01 *** p < 0.001

Table 6 – Regression analysis: TS, II and size

	Model A	Model B
Dependent variable	TS	II
Intercept	-134.200 (414.100)	0.378*** (0.084)
Size[a]	1204.800* (513.800)	0.304** (0.104)
R^2	0.087	0.128
Adjusted R^2	0.071	0.113
F-value	5.499*	8.540**

a. Log-transformed (base 10) * p < 0.05 ** Standard error within brackets

Size is correlated with both TS and II at a 0.05 significance level, indicating that size and technological strength are positively related in the aerospace industry. It is interesting to note that II, which partially controls for size, has a statistically stronger correlation with size, evidencing that size *per se* does not lead to more citations and, concomitantly, to higher technological strength.

In the main models (with TKD as dependent variable) TS and size are only significant when added separately, but when both are included in the same model, then statistical significance is lost for both of them (models 3b and 4b in

Table 7). Such observations lead to the conclusion that size is acting as a confounding variable, which is "defined as the variable correlates (positively or negatively) with both the dependent variable and the independent variable. A confounder is an extraneous variable whose presence affects the variables being studied so that the results do not reflect the actual relationship between the variables under study" (Pourhoseingholi et al. 2012, p.79).

Literature describes several common practices to circumvent such effect, like matching and randomization (Mackinnon et al. 2010; Pourhoseingholi et al. 2012); however, they are not applicable in this case, considering the type of data and sample size. The use of II as an alternative measure, which was expected to statistically control for size, showed an even stronger correlation with it. Therefore, a different approach had to be used in this case: both size and TS were included in different models, but they were not added together in the same ones. With this approach, their real effect can be analysed; for the other variable, their values remained practically unchanged and no difference in statistical significance was found with such approach.

Five main linear models were run to test for TKD, coefficients and values are displayed in Table 7. For location, other regions (comprising Asia, Latin America and Middle East) are the reference category. For coopetition and TS, low degree is the reference category.

Table 7 – Regression analysis: main models

	Model 1a	Model 1b	Model 1c	Model 2	Model 3a	Model 3b	Model 4a	Model 4b	Model 5
Intercept	0.492*	0.533*	0.698***	0.665**	0.711***	0.666**	0.852***	0.801***	0.512 **
	(0.233)	(0.246)	(0.192)	(0.201)	(0.192)	(0.206)	(0.201)	(0.210)	(0.180)
Size[a]	0.447**	0.450**		0.497**		0.127		0.166	
	(0.159)	(0.147)		(0.146)		(0.198)		(0.196)	
Age	0.000								
	(0.003)								
North America	-0.671**	-0.670**	-0.580*	-0.588**	-0.720**	-0.715**	-0.659**	-0.651**	
	(0.211)	(0.209)	(0.222)	(0.207)	(0.209)	(0.211)	(0.207)	(0.207)	
Europe	-0.703**	-0.701*	-0.586*	-0.545*	-0.686**	-0.699**	-0.536*	-0.550*	
	(0.228)	(0.223)	(0.235)	(0.231)	(0.214)	(0.216)	(0.221)	(0.223)	
COOP – Moderate				-0.362+			-0.314+	-0.338+	-0.384*
				(0.185)			(0.177)	(0.180)	(0.186)
COOP – High				-0.429			-0.423*	-0.428*	-0.524*
				(0.214)			(0.206)	(0.207)	(0.206)
TS – Moderate					-0.158	-0.161	-0.107	-0.108	-0.225
					(0.182)	(0.183)	(0.180)	(0.180)	(0.187)
TS – High					0.502*	0.401	0.568**	0.443+	0.389+
					(0.198)	(0.253)	(0.198)	(0.247)	(0.201)
R^2	0.245	0.245	0.119	0.308	0.320	0.325	0.375	0.383	0.254
Adj. R^2	0.190	0.205	0.088	0.244	0.271	0.263	0.304	0.300	0.200
F-value	4.470**	6.067**	3.837*	2.442+	8.140***	3.194*	5.418***	2.900*	4.985*
	55 df	56 df.	57 df.	54 df.	55 df.	54 df	53 df.	52 df	55 df.

a. Log-transformed, base 10 + $p < 0.10$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

In model 1a only control and dummy variables are included; while location is statistically significant, age is not. In fact, age was included in all subsequent models and in no case this variable was statistically significant. Therefore, in model 1b (and in the following ones), age was excluded, only location and size were kept. The F-value is calculated by comparing the model with the mean (baseline) through an ANOVA test and a significant improvement is found for model 1b. Model 1c is constructed to serve as the baseline for the models where size is not included.

Coopetition is added in model 2. Only the moderate degree of coopetition has a weak significance. Based on the F-value, only a weak improvement is observed in this model compared to the baseline. Model 3a includes TS as the sole independent variable. Significance at 0.05 level is found for the high degree of TS and there is a strong improvement in the explanation of the outcome in this model. Model 3b is included only to show the effect of adding size and TS together, both of them lose significance in this case. Model 4 includes both independent variables. Coopetition becomes significant at 0.05 level for the high degree and there is a weak significance (0.1 level) for the moderate degree of coopetition in comparison to the low one. For TS, there is significance for the high degree, but not for the moderate degree of TS. F-value also shows a significant improvement in comparison to the baseline. Model 4b has the same goal and conclusions as model 3b. Model 5 evidences the effect of removing all control and dummy variables.

To further assess the quality of the models, other statistical analyses were performed for models 2 and 4a. All values for the variation inflation factor were below 2.500, indicating no multicollinearity; the highest Cook's distance found was 0.146, indicating the absence of outliers; the plot of predicted against residual standard values evidences that homoscedasticity was met; Durbin-Watson value for model 2 was equal to 1.982 and, for model 4a, 1.848, showing no evidence of autocorrelation in the residuals; the Shapiro-Wilk test indicates that residuals were normally distributed. See Appendix IV for a complete list of graphs and tables related to the models' goodness of fit.

Table 8 – Statistical power

	Model 2	Model 4a
Effect size f^2	0.323	0.437
Number of predictors	5	6
Noncentrality parameter δ	4.401	5.119
Critical t	2.005	2.006
Degrees of freedom	54	53
Power (1 – β error probability)	0.991	0.999

Note: two-tails test, α = 0.05, sample size = 60

Furthermore, the statistical power of the models was tested to ensure that the sample size is sufficient to detect existing effects and to calculate the probability of Type II error (false negative). G*Power software (version 3.1.9.2) was used to run this statistical analysis (Faul et al. 2009). As depicted in Table 8, for both models 2 and 4a, power values are above 0.990 (maximum value is one), which indicates a very low possibility of Type II error. Additionally, the rule of thumb in literature considers a minimum power value of 0.800 to confirm that observations as generalizable; therefore, current observations are statistically representative of the effects being measured. Graphical results are displayed in Appendix V.

Based on model 4a, all variables (except for size) can be analysed individually. According to the literature in the field, 'specialization' is the opposite of 'diversification' and it is adopted here to facilitate the interpretation of negative values.

The technological knowledge base of aerospace companies using a moderate degree of coopetition is 2.061 ($\frac{1}{10^{-0.314}}$) times more specialized than those with low degree of coopetition. However, the statistical significance of such finding is weak (significant at 0.1 level). For ACs with high degrees of coopetition, their technological knowledge base are 2.649 ($\frac{1}{10^{-0.423}}$) times more specialized than those with low degree of coopetition. These results partially confirm a relationship between TKD and coopetition, but in the opposite direction than the one stated in hypothesis 1.

The technological knowledge base of aerospace companies with high degree of technological strength is 3.698 ($10^{0.568}$) times more diversified than those with low degree of technological strength. No conclusion can be drawn for the companies with a moderate degree of technological strength, since no statistical significance was found in this case. Therefore, hypothesis 2 is partially confirmed.

Moreover, it is clear that the aerospace market is dominated by companies from Europe and North America (which together account for 50 out of the 60 companies), but North Americans ACs have technological knowledge bases 4.560 ($\frac{1}{10^{-0.659}}$) times more specialized than ACs from other regions (Asia, Latin America and Middle East). A similar result is found for European companies, their technological knowledge bases are 3.436 ($\frac{1}{10^{-0.536}}$) times more specialized than ACs from other regions.

These results surprisingly indicate that ACs outside North America and Europe have a more diversified technological knowledge base. While high-tech industries normally receive support from national and regional governments, in developing countries governmental support is a requirement for these firms to survive. Even after privatization, governments can act either as large customers, especially for military purposes, or provide economic incentives, like tax exemptions and facilitated loans (Goldstein 2002). However, Asian companies are the determinant factor here, as they have five out of the seven most diversified ACs.

Size is analysed based on model 2. Both size and TKD are log-transformed, hence by removing the transformation of both variables, a "pure" linear interpretation is possible: by each one unit increase in size, diversification of the technological knowledge base of an AC increases in 3.141 units ($10^{0.497}$); in other words, each billion of US dollars in revenues leads to more 3.141 units in the diversification of the technological base of aerospace companies. Hence, larger companies have, in fact, a more diversified technological knowledge base. This can be seen as a result of the larger amount of resources that larger firms have available to invest; smaller firms, on the contrary, have to concentrate their limited resources in a more specialized knowledge base.

5. Conclusion

The present research aimed at answering the question of to what extent coopetition and technological strength influence the diversification of the technological knowledge base of aerospace companies. Patent data of 60 ACs were collected for the period between 1995 and 2013 and analysis was performed by applying OLS regression models.

Surprisingly, results show that the more an AC forms coopetitive alliances, the more specialized its technological knowledge base becomes. This is seen as a result of two main factors: the coordination of coopetition and the protection from unwanted knowledge spillover, which demand a great level of efforts, draining resources that could be applied to increase the diversification of the technological knowledge base. However, analysis shows that patents deposited in coopetition have a higher technological strength, leading to a greater portfolio leverage and competitive advantages, justifying the strategical decision to invest more in coopetition, even if this becomes an obstacle to diversification.

ACs with a high degree of technological strength are more diversified in their technological knowledge base, the opposite observed in other non-high-tech industries. ACs have overcome the competency traps of being too internally oriented, which would reduce their diversification. Honeywell, Mitsubishi MHI and UTC have the highest technological strength, which are spread through a large number of different classes. For ACs with low or moderate degrees of technological strength other factors might be in place to determine the diversification of their bases and no statistically significant relation was found for them in this research.

Furthermore, the technological knowledge base of the aerospace industry remained almost the same between 1995 and 2013. The only addition is 3D printing, which have the potential to enhance prototyping and decrease development costs and time. As showed by the Berger-Parker Index, the technological knowledge is becoming more evenly spread, indicating a trend of knowledge diversification in the company-level. These observations are characteristic of mature industries, with more incremental innovation and few technological discontinuities. Finally, within the existing base, interest moved from peripheral components to core technologies, indicating that ACs are focusing more on improving the efficiency and safety of their products.

In coopetition, ACs have preferential partners, which are mostly located in the same region. However, firms also have identified potential threats, as with other ACs in the same region coopetition is not formed. Despite the regional preference, the network of the aerospace industry is globally oriented and the most important companies connecting the network are high-tech suppliers. Some companies only have ties with one or a few other companies, but the majority has a large number of ties. Airbus and Boeing have a large number of ties, but with a reduced number of suppliers. Four clusters are observed, with the main aircraft companies being placed in different clusters and sharing no direct ties. Companies from North America and Europe are spread through all four groups, while Asian companies are all placed together. The backbone cluster of the industry comprises 35 companies from all regions of the world.

Finally, Asian ACs have excelled in diversifying their technological knowledge base, as they have five out of the seven most diversified ACs, and larger ACs, as expected, do have a more diversified technological knowledge base than smaller companies, which is seem as result of the larger amount of resources they possess.

6. Discussion

6.1 Theoretical implications

Theoretically, this research contributes to the understanding of how companies diversify their technological knowledge base by analysing competitive and technological context conditions. To the best of my knowledge, this is the first time that these context conditions are analysed in combination for the top companies of a sector in a global level. This study builds on strategic management and resource-based view theories. Both theories have been largely explored in literature in the past decades, nevertheless the aerospace industry possesses unique features that hamper generalization from other sectors, making its study even more relevant.

Analysis showed that the technological knowledge base of the aerospace industry remained practically unchanged between 1995 and 2013. Literature has proved that firms tend to enter in new technological domains that are related to their existing capabilities, which allows them to have a better performance (Leten et al. 2010). Furthermore, this is a characteristic of mature industries, where technologies are well stablished, with a well-delimited space for knowledge exploitation. When the majority of technologies in an industry reach maturity phase a techno-economic paradigm is formed; knowledge, skills and capabilities related to all technologies have accumulated and support each other, also acting as a strong barrier for new-entries, due to the high costs for catching-up (Perez & Soete 1988).

The surprising result that Asian firms have the highest level of diversification has historical and economic explanations. Japanese high-tech firms experienced a growth period in the 1980's, resulting in more capital available to be invested in R&D activities; companies, then, strategically diversified into a downstream direction, focusing on the development of core technologies (Gemba & Kodama 2001; Chen 2010), which is in line with the previous finding of this study. Choi (2013), studying institutional context conditions, describes that Chinese firms suffer pressure to partner with foreign partners to diversify, while in Korea there is a focus in specialization due to a financial crisis in 1997 that shortened resources. However, this last observation does not hold in the aerospace industry, as demonstrated here.

Coopetition is a specific type of strategic alliance, in the low and moderate degrees its effect might be being masked by the remaining alliances. A comparative study is necessary to clarify the effect of coopetitive and non-coopetitive alliances separately. The unexpected result for ACs with high degree of coopetition have some possible causes. Based on the finding that coopetitive patents have a technological strength three times higher than non-coopetitive ones, ACs expect a higher success rate of coopetitive alliances. As a result, ACs strategically allocate higher effort and resources in developing technological knowledge in coopetition to the detriment of developing technological knowledge alone; hence, their technological knowledge base becomes more specialized along the years, but with a higher technological strength (observation also supported by model 4a). Furthermore, a high degree of coopetition also poses threats of leakage, forcing companies to allocate resources in protecting knowledge and capabilities that are not supposed to be shared (Park et al. 2014). Salvetat et al. (2013), studying coopetition in the aeronautics industry, developed a conceptual model of the activities required to sustain the coopetitive alliance, describing that legal and risk management of knowledge comprise two thirds of all activities required to sustain coopetition (on the legal side, it includes legal clauses and patent rights; on the risk side, activities related to technology acquisition and avoiding information leakage), evidencing that coopetition requires a large amount of effort and resources from aeronautic companies. However, Park et al. (2014) found that the more experience a company has in coopetitive activities, the better is its innovation outcome.

For the technological strength, ACs with high degrees of technological strength were able to overcome the competency traps of their portfolios (Srivastava & Gnyawali 2011), leveraging their resources to build a more diversified technological knowledge base. As hypothesized, the aerospace industry has a different dynamic than the majority of industries, as an AC that does not identify and apply technological knowledge in an efficient and timely manner will not be able to survive and grow. For ACs with a low or moderate degree of technological strength, their strength might not be sufficient to affect the diversification of the technological knowledge base. In these cases, other variables might have a greater effect. However, in order to build a strong technological portfolio firms have to start from a weaker portfolio, so their technological strength is no less important when seen as a path dependent evolution along time.

6.2 Managerial implications

The current research also provides interesting insights to managers of ACs. First, it is clear that tier one ACs have a diversified technological knowledge base; although each of them have different focus, these companies possess knowledge on many technologies and components directly and indirectly related to aerospace products. Hence, there is a need of tight coordination of knowledge and efficient use of resources to sustain diversity and to generate new technological knowledge.

Second, despite owning a strong and diversified knowledge base, managers have to avoid the competency trap of becoming too internally oriented; in the long-term, such attitude can undermine the potential of the company to generate innovation and to remain competitive.

And third, while coopetition might seem counter-intuitive, for the aerospace sector it has the potential to increase the technological strength of companies, even though this hinders diversification. Coopetition requires several coordination and protection activities, costing resources that could be applied elsewhere. Therefore, managers have to strategically decide the level of coopetition, the type of projects developed in partnership and who are the competitors offering the best complementary knowledge and resources.

6.3 Limitations and future researches

The number of observations applied in this research (60 ACs) is admittedly low when compared to other quantitative studies in literature. This number was a result of the thresholds applied to capture tier one ACs only, which are companies comprising the core of the aerospace industry. Consequently, only a limited number of variables could be measured and the viable options of regression models were constrained. In order to strengthen the analysis, two additional measures were taken: a statistical power analysis was performed to ensure the validity of the models and to reduce the likelihood of false negatives; and convergence validity was tested through the assessment of the thesis by an independent scholar.

Furthermore, each variable was analysed separately, which allowed to build a scenario of the entire industry and its evolution during the period under analysis. Methodologies and visualizations applied here sought to capture different aspects of the industry and results were drawn by combining findings from all performed analyses.

Considering the limited number of tier one ACs, qualitative studies could provide more in depth findings about the competitive and technological context conditions in the aerospace industry. Qualitative studies could also be applied to assess the dimension of a knowledge base for which there are no databases available, like individual and administration assets.

Tier 2 ACs could also be added to the regression models, making the statistical analysis more powerful, also providing a more complete visualization of the sector's network. Different dynamics could be observed in this case, as tier 2 companies have a large amount of ties to tier 1 suppliers.

The current research has not measured the influence of public research organisations (e.g., NASA, in US, and ESA, in Europe) and national or regional governments, which could be accounted as institutional context conditions. In this industry, the support of public and governmental organisations has been fundamental to the development of new technologies; these institutions act either as clients or financial providers for new product development. Therefore, future studies measuring the influence of these institutions could unveil new relations overlooked in the present research.[1]

Also, each company was taken here as one entity, even though several of them have branches in industries like defence and home appliances. There is a challenge to clearly delimit where one industry ends and other begins; for instance, technologies for seats and food conservation are interests of aerospace companies, despite not being directly related to the proper functioning of their products. Therefore, a future research exclusively studying aerospace products and core technologies (and not the industry as a whole) could establish boundaries to the industry. For patents, one possibility is to use the list of IPC classes, but the delimitation of which subsidiaries to include is more challenging.[1]

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APPENDIX I - Top 100 largest aerospace companies in the world

Source: (FlightGlobal & PwC 2015)

Rank	Company	Revenues (US$ bi)	Rank	Company	Revenues (US$ bi)
1*	Boeing	90.8	51*	Moog	1.69
2*	Airbus	80.6	52*	Esterline	1.64
3*	Lockheed Martin	45.6	53*	ST Engineering	1.64
4*	United Technologies (UTC)	36.2	54*	Aerojet Rocketdyne	1.60
5*	GE Aviation	24.0	55*	Hexcel	1.59
6*	Northrop Grumman	24.0	56*	Liebherr	1.55
7*	Raytheon	22.8	57*	Allegheny Technologies	1.36
8*	Safran	18.3	58*	Fuji Heavy Industries	1.35
9*	Finmeccanica[1]	17.2	59*	Diehl Aerosystems	1.29
10*	Rolls-Royce	14.7	60*	Daher	1.29
11*	Bae Systems	13.7	61	Pilatus	1.28
12*	Honeywell	11.9	62*	Ruag	1.14
13*	Bombardier	10.5	63*	Heico	1.13
14*	General Dynamics	10.5	64*	Cytec	1.10
15*	L-3 Communications[1]	10.1	65*	Woodward	1.08
16*	Textron	10.0	66	Lisi	1.05
17*	United Aircraft	7.40	67*	Fokker Technologies	1.01
18*	Precision Castparts	7.00	68*	Turkish Aerospace	1.00
19*	Mitsubishi (MHI)	6.87	69*	Ball Aerospace	0.935
20*	Spirit Aerosystems	6.80	70*	Amphenol	0.917
21*	Thales	6.65	71	Constellium	0.885
22*	Embraer	6.29	72	Senior	0.884
23	Alcoa	5.60	73	Latecoere	0.881
24*	Zodiac	5.54	74	ITP	0.863
25*	MTU Aero Engines	5.19	75	Magellan Aerospace	0.761
26*	Rockwell Collins	4.98	76	Aernnova	0.734
27*	Dassault Aviation	4.88	77	Curtiss-Wright	0.714
28*	Avic	4.18	78	Facc	0.702
29	IHI	4.07	79	Crane Aerospace	0.696
30*	Triumph Group	3.89	80	Kongsberg	0.678
31*	Israel Aerospace	3.83	81	Chemring	0.664
32*	GKN Aerospace	3.67	82	Indra	0.663
33	Harris	3.63	83	Ultra Electronics	0.658
34*	Kawasaki	3.07	84	Jamco	0.643
35*	Orbital ATK	2.99	85	Kaman Aerospace	0.633
36	Hindustan Aeronautic	2.91	86	SKF	0.621

	Top 100 largest aerospace companies in the world (cont.)				
37*	B/E Aerospace	2.60	**87**	Ducommun	0.608
38*	Elbit Systems	2.58	**88**	Marshall	0.506
39*	Cobham	2.50	**89**	Asco	0.439
40*	Teledyne Technologies	2.39	**90**	Griffon Aerospace	0.419
41*	Transdigm	2.37	**91**	Sonaca	0.418
42*	Parker Hannifin	2.24	**92**	LMI Aerospace	0.388
43*	Korea Aerospace	2.20	**93**	Garmin	0.386
44*	Meggitt	2.17	**94**	Praxair	0.368
45	MDA	2.10	**95**	Heroux-Devtek	0.331
46	CAE	1.95	**96**	Martin-Baker	0.326
47	Eaton	1.86	**97**	Elettronica	0.319
48*	SAAB	1.80	**98**	Doncasters	0.293
49*	Exelis	1.77	**99**	Figeac Aero	0.271
50	Irkut	1.71	**100**	Flir Systems	0.271

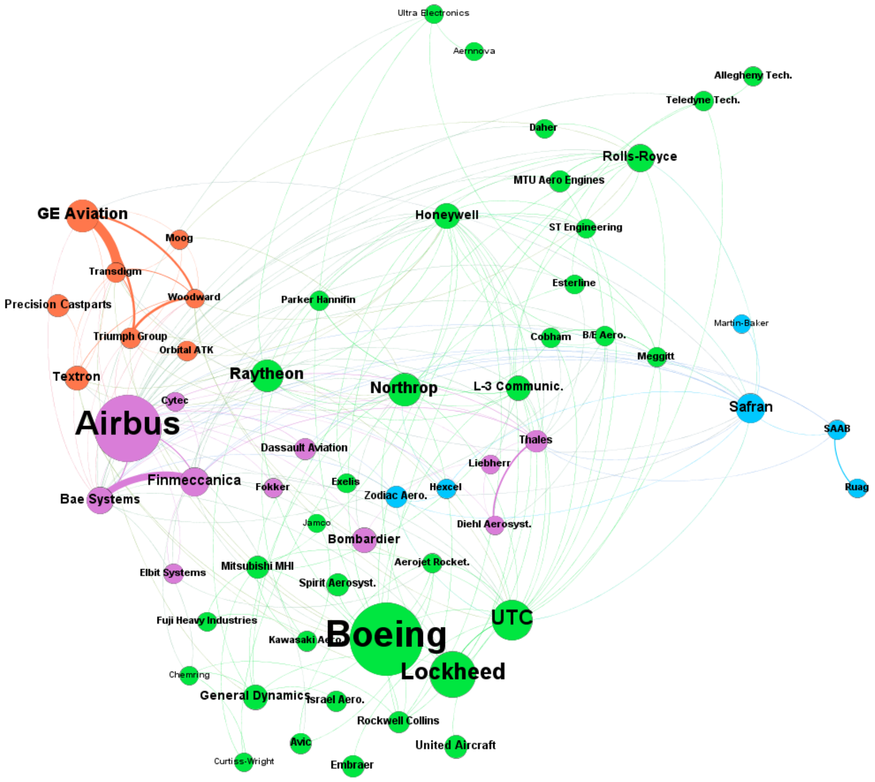
[1]Finmeccanica changed its name to Leonardo and L-3 Communications, to L-3 Technologies. Both changes happened after 2013, therefore both companies are referred here by their previous names.
*Company's ranks marked with asterisk indicate the final 60 ACs analysed

APPENDIX II - IPC classes and their changes in occurrence between 1995 and 2013

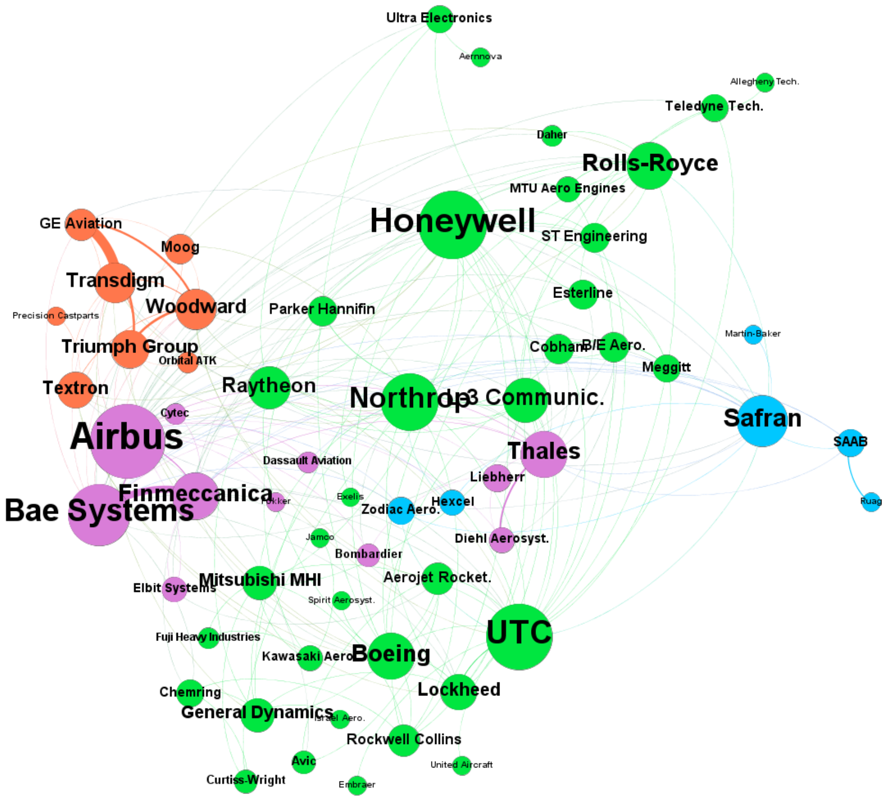
"Increased interest" displayed in green, "decreased interest" in red and "stable" in blue.

IPC	SHARE '95	RANK '95	SHARE '13	RANK '13	SHARE VARIATION	RANK VARIATION	DESCRIPTION
G07	0.84%	29	0.22%	56	-0.62 pp	-27	CHECKING-DEVICES [INSTRUMENTS]
A61	1.80%	14	0.67%	33	-1.13 pp	-19	MEDICAL OR VETERINARY SCIENCE; HYGIENE [HEALTH, LIFE-SAVING, AMUSEMENT]
C09	1.32%	20	0.58%	39	-0.75 pp	-19	DYES; PAINTS; POLISHES; NATURAL RESINS; ADHESIVES; COMPOSITIONS NOT OTHERWISE PROVIDED FOR; APPLICATIONS OF MATERIALS NOT OTHERWISE PROVIDED FOR
G11	5.70%	5	0.95%	24	-4.75 pp	-19	INFORMATION STORAGE [INSTRUMENTS]
G21	0.81%	30	0.42%	44	-0.39 pp	-14	NUCLEAR PHYSICS; NUCLEAR ENGINEERING
C08	3.93%	6	1.48%	18	-2.45 pp	-12	ORGANIC MACROMOLECULAR COMPOUNDS; THEIR PREPARATION OR CHEMICAL WORKING-UP; COMPOSITIONS BASED THEREON
G02	2.43%	10	1.03%	21	-1.4 pp	-11	OPTICS [INSTRUMENTS]
B66	1.44%	18	0.94%	26	-0.49 pp	-8	HOISTING; LIFTING; HAULING [TRANSPORTING]
H05	1.19%	21	0.91%	28	-0.28 pp	-7	ELECTRIC TECHNIQUES NOT OTHERWISE PROVIDED FOR
B65	0.97%	26	0.69%	32	-0.28 pp	-6	CONVEYING; PACKING; STORING; HANDLING THIN OR FILAMENTARY MATERIAL [TRANSPORTING]
B60	3.48%	7	3.00%	10	-0.48 pp	-3	VEHICLES IN GENERAL
C07	1.51%	17	1.03%	20	-0.47 pp	-3	ORGANIC CHEMISTRY [2]
H03	1.75%	15	1.48%	17	-0.27 pp	-2	BASIC ELECTRONIC CIRCUITRY
C23	0.90%	28	0.90%	29	0 pp	-1	COATING METALLIC MATERIAL; COATING MATERIAL WITH METALLIC MATERIAL; CHEMICAL SURFACE TREATMENT; DIFFUSION TREATMENT OF METALLIC MATERIAL; COATING BY VACUUM EVAPORATION, BY SPUTTERING, BY ION IMPLANTATION OR BY CHEMICAL VAPOUR DEPOSITION, IN GENERAL; INHIBITING CORROSION OF METALLIC MATERIAL OR INCRUSTATION IN GENERAL [2]
F16	3.16%	8	3.88%	9	0.73 pp	-1	ENGINEERING ELEMENTS OR UNITS; GENERAL MEASURES FOR PRODUCING AND MAINTAINING EFFECTIVE FUNCTIONING OF MACHINES OR INSTALLATIONS; THERMAL INSULATION IN GENERAL
G06	7.91%	2	6.00%	3	-1.91 pp	-1	COMPUTING; CALCULATING; COUNTING
H04	6.73%	3	5.96%	4	-0.77 pp	-1	ELECTRIC COMMUNICATION TECHNIQUE
B01	2.43%	11	2.83%	11	0.41 pp	0	PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL
H01	13.12%	1	9.41%	1	-3.71 pp	0	BASIC ELECTRIC ELEMENTS
B29	1.90%	13	2.77%	12	0.87 pp	1	WORKING OF PLASTICS; WORKING OF SUBSTANCES IN A PLASTIC STATE IN GENERAL
F23	1.08%	24	1.01%	22	-0.07 pp	2	COMBUSTION APPARATUS; COMBUSTION PROCESSES
G01	6.41%	4	6.24%	2	-0.17 pp	2	MEASURING; TESTING
F02	3.12%	9	5.89%	5	2.77 pp	4	COMBUSTION ENGINES; HOT-GAS OR COMBUSTION-PRODUCT ENGINE PLANTS
H02	2.34%	12	4.77%	8	2.44 pp	4	GENERATION, CONVERSION, OR DISTRIBUTION OF ELECTRIC POWER
F04	1.44%	19	2.18%	13	0.75 pp	6	POSITIVE-DISPLACEMENT MACHINES FOR LIQUIDS; PUMPS FOR LIQUIDS OR ELASTIC FLUIDS
G05	1.15%	22	1.58%	15	0.43 pp	7	CONTROLLING; REGULATING [INSTRUMENTS]
F25	0.93%	27	1.18%	19	0.25 pp	8	REFRIGERATION OR COOLING; COMBINED HEATING AND REFRIGERATION SYSTEMS; HEAT PUMP SYSTEMS; MANUFACTURE OR STORAGE OF ICE; LIQUEFACTION OR SOLIDIFICATION OF GASES
F01	1.70%	16	5.57%	7	3.87 pp	9	MACHINES OR ENGINES IN GENERAL; ENGINE PLANTS IN GENERAL; STEAM ENGINES
B23	1.02%	25	2.03%	14	1.02 pp	11	MACHINE TOOLS; METAL-WORKING NOT OTHERWISE PROVIDED FOR [SHAPING]
B62	0.44%	41	0.85%	30	0.41 pp	11	LAND VEHICLES FOR TRAVELLING OTHERWISE THAN ON RAILS
F24	0.49%	38	1.00%	23	0.5 pp	15	HEATING; RANGES; VENTILATING
G08	0.45%	40	0.95%	25	0.49 pp	15	SIGNALLING [INSTRUMENTS]
B64	1.10%	23	5.61%	6	4.5 pp	17	AIRCRAFT; AVIATION; COSMONAUTICS
B22	0.34%	49	0.92%	27	0.58 pp	22	CASTING; POWDER METALLURGY [SHAPING]
B32	0.41%	43	1.52%	16	1.11 pp	27	LAYERED PRODUCTS [SHAPING]

APPENDIX III - Network of coopetitors



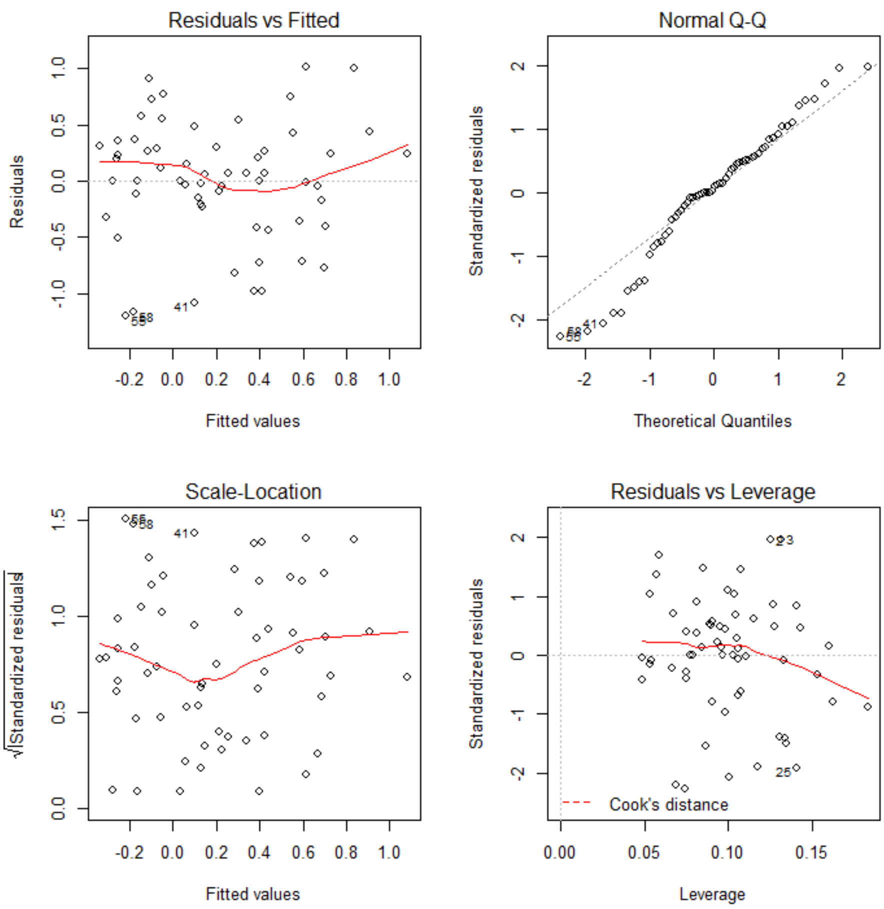
Network of coopetitors, company size defining node size

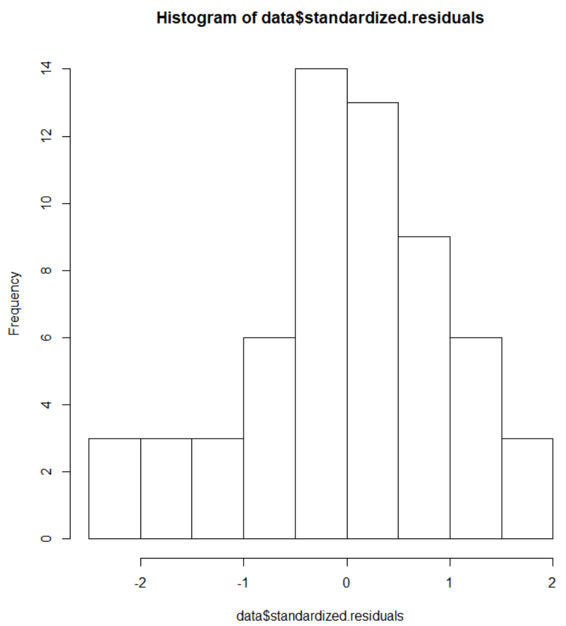


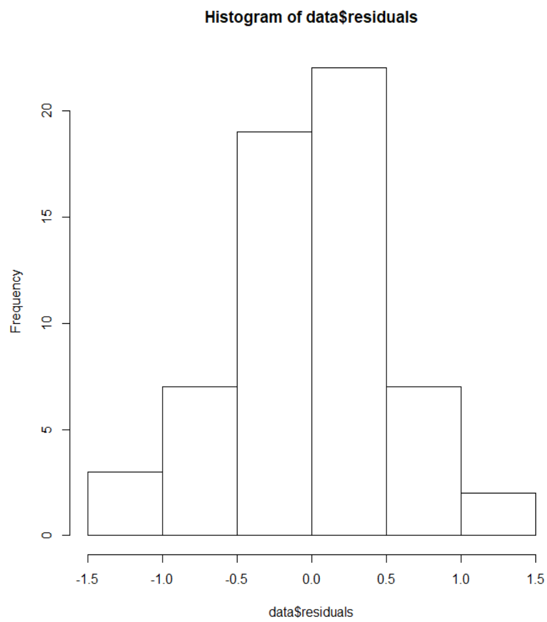
Network of coopetitors, degree defining node size

APPENDIX IV – Goodness of fit

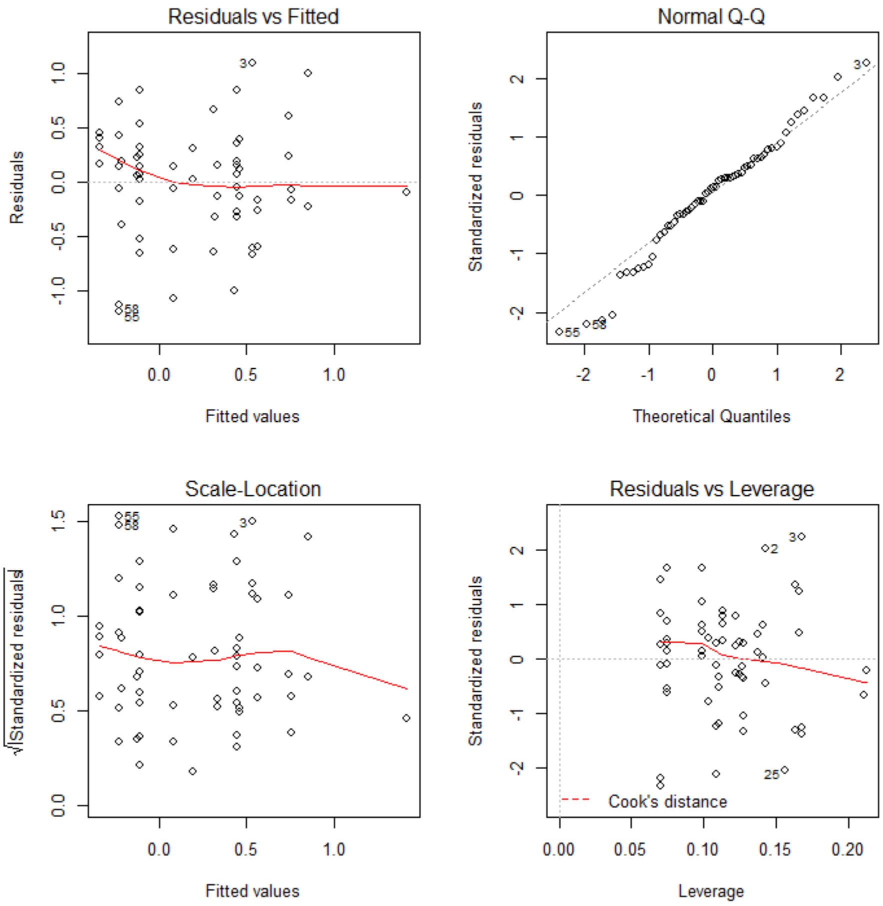
Model 2

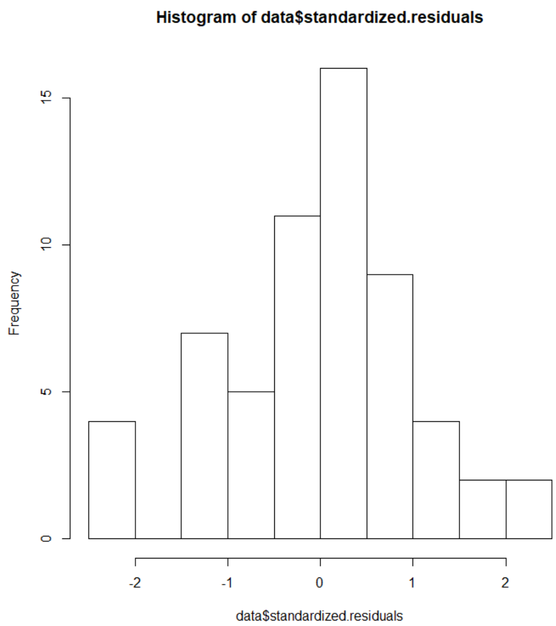


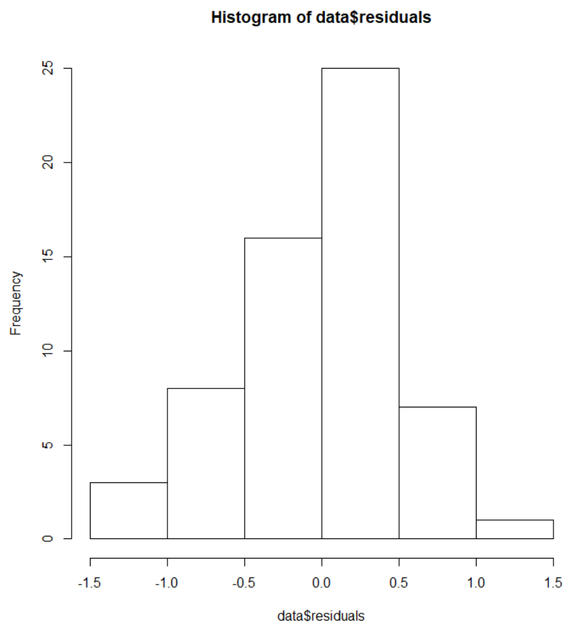




Model 4a


Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage


Histogram of data$standardized.residuals
Frequency
data$standardized.residuals


Histogram of data$residuals
Frequency
data$residuals

Shapiro-Wilk Normality Test

	Model 2	Model 4a
W	0.969	0.979
p-value	0.127	0.398

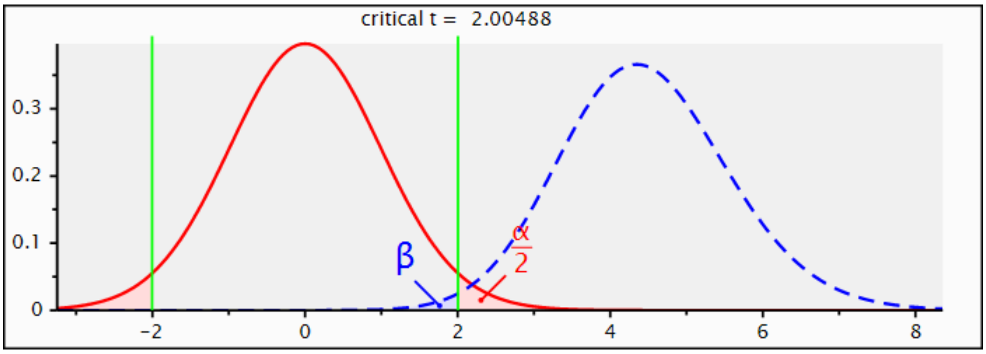
Variation Inflation Factor

		Model 2	Model 4a
Size[a]	GVIF	1.077	
	$GVIF^{1/2Df}$	1.038	
North America	GVIF	2.108	2.277
	$GVIF^{1/2Df}$	1.452	1.509
Europe	GVIF	2.324	2.325
	$GVIF^{1/2Df}$	1.524	1.525
COOP[b]	GVIF	1.222	1.217
	$GVIF^{1/2Df}$	1.051	1.050
TS[b]	GVIF		1.171
	$GVIF^{1/2Df}$		1.040

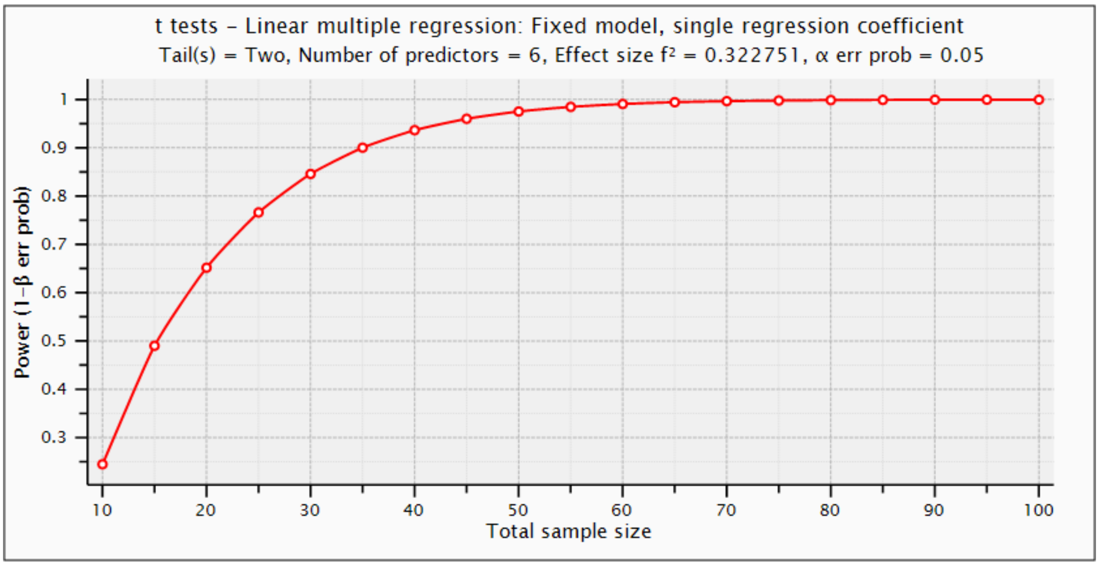
a. Log-transformed, base 10 b. Categorical variables

APPENDIX V – Statistical power analysis

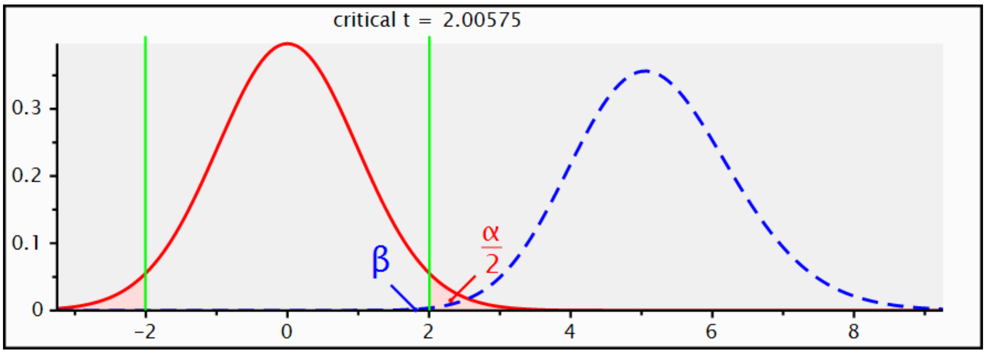
Model 2 – Distribution plot



Model 2 – Sample size and power



Model 4a – Distribution plot



Model 4a – Sample size and power