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Key Enablers for the Evolution of Aerospace Ecosystems

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ABSTRACT

The aerospace industry is experiencing an unprecedented scenario. The air travel drifted from years of constant growth and positive expectations to a place where the uncertainty is the most predominant distinctive. Consequently, the aerospace ecosystem needs to adapt to cope with challenges never faced before. Understanding the evolution of the aerospace ecosystem is thus essential to foster its progression. This research aims at the identification and categorisation of key enablers that have been linked to the growth of aerospace ecosystems. To this extent, key enablers are first identified and then categorised using interpretive structural modelling (ISM) and cross-impact matrix multiplication applied to classification (MICMAC) methodologies. An analysis is elaborated for a developed aerospace ecosystem, the United Kingdom, and an emergent aerospace ecosystem, Mexico. Results evidence a contrasting categorisation of key enablers among both ecosystems. On the other hand, the automotive ecosystem and geopolitical factors are considered as underpinning enablers for both aerospace ecosystems evolution.

Keywords: ISM; MICMAC; Emergent ecosystem; Developed ecosystem.

INTRODUCTION

Since February 2020, the world has been facing an unprecedented public health emergency driven by the coronavirus (COVID-19), causing long-lasting consequences among industrial ecosystems of different nature. Particularly, the aerospace industry is experiencing an unprecedented scenario. The air travel drifted from years of constant growth and positive expectations to a place where the uncertainty is the most predominant distinctive. Abrupt reduction on passenger travels and deferred customers deliveries are among the primary short-term consequences. For instance, in April 2020, airlines around the world reported a drop in air travel of around 96% (Wallace 2020). Furthermore, the International Air Transport Association (IATA) forecasts for 2020 a drop in global airline passenger revenues by around 55% (equivalent to more than US$ 300 billion), compared to 2019 (IATA 2020). The mid and long-term consequences are still unmeasurable. According to Lineberger (2020), the production demand over the next two years is not expected to change because the budgets were already allocated. However, the main long-term impact will be a shortage in cash-flow, increased risk on critical program failure and a weakened supply chain driven by increased production challenges.

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On the other hand, the pandemic cannot last forever. Thanks to the development of a new vaccine at the beginning of 2021, the global economy has started a slight recovery. Although it is still unsure when the world will go back to "normal", it is imperative to be prepared for its evolution. One way to be prepared is by understanding how the aerospace ecosystem has evolved, notably by analysing the key enablers that have fostered its progression. Thus, the aim of this research is the identification and categorisation of key factors that have enabled the aerospace ecosystem evolution. To this extent, two contrasting aerospace ecosystems are analysed. A developed aerospace ecosystem, the UK, and a developing one, Mexico. Key factors are identified through a literature review followed by the application of the interpretive structured modelling (ISM) and cross-impact matrix multiplication applied to classification (MICMAC) methodologies for their categorisation.

METHODS FOR THE CATEGORISATION OF KEY ENABLERS: ISM AND MICMAC

The ISM and MICMAC methodologies are used in this research for the categorisation of the key factors that have enabled aerospace ecosystems evolution. The ISM, proposed by Warfield (1974), is a methodology used to develop a structural model in which the relationship and hierarchy of variables that affect a particular issue are first calculated and then portrayed. In this methodology, the judgment of experts on the field is used for the establishment of relationships. Subsequently, discrete mathematics and graph theory are applied for the development of a structural model.

The MICMAC methodology was developed by Duperrin and Godet (1973) as a tool for categorising the elements of a system. This method is commonly used as a complement of the ISM methodology to categorise each factor depending on its influence towards the other factors. Here, factors are classified as autonomous, linkage, dependent or drivers. Autonomous are those factors that are more disconnected, as they are considered to have the least influence to and from others. Factors are classified as linkage when any action related to them drives an effect on them and others. Dependent factors get the most influence from others, and drivers factors are considered as the key enablers to other factors (Raj *et al.* 2008).

Interpretive structured modelling and MICMAC are complementary methodologies that have been used together by many scientific studies in different fields. For instance, ISM and MICMAC have been used together as the foundation tools to support the implementation of new technologies: Ghobakhloo (2019) combined both methodologies for analysing and categorising implementation factors for a practical application of smart manufacturing. Also, ISM and MICMAC have been applied for helping continuous improvement initiatives: Almanei and Salonitis (2019) categorised the critical success factors for the implementation of ongoing improvement initiatives in small and medium enterprises in the United Arab Emirates.

Interpretive structured modelling and MICMAC have also been used for performance evaluation subjects: Pathak *et al.* (2019) proposed a framework to evaluate freight transportation sustainability performance. Here, authors combined total interpretive structural modelling (TISM), MICMAC and other methodologies for the identification and categorisation of critical success factors. Total interpretive structural modelling is an extension to the ISM, in which the ISM model is elaborated first, and then it is combined with an interpretive matrix aiming at a more extensive interpretation of links.

Besides, ISM and MICMAC have been employed to help the development of policies by the private and public sector. For instance, Kapse *et al.* (2018) identified and classified the factors that motivate people to start a business in the Indian textile ecosystem. Here, authors claim that the outcome of the study could be used as a base for the development of policies to encourage the entrepreneurial culture. Tirpan (2019) applied both methodologies to analyse the Turkish defence ecosystem by categorising the enablers for supply chain development. Tirpan (2019) claims that the Turkish government to improve the supply chain could implement the proposed suggestions. Aiming also at the development of policies, but in the private sector, Jain *et al.* (2017) developed a model categorising the key enablers for resilient supply chains. Authors claim that private organisations could develop improvement strategies based on the proposed model. In this research, ISM and MICMAC methodologies are applied with a similar approach. The outcome of the research intends to nurture the development of policies by the private and public sector, aiming at the development of aerospace ecosystems. A description of the steps followed is detailed next.

KEY ENABLERS FOR THE EVOLUTION OF AEROSPACE ECOSYSTEMS

In this research, key enablers are defined as any policies and/or characteristics inherent to the ecosystem of a country that have helped the development of the aerospace manufacturing ecosystem. Two sources are considered: a literature review and the outcome of the quantitative analysis. For the literature review, scientific journals and reports from government and institutions focused on the aerospace sector are examined. The other source is the outcome of the quantitative analysis presented in Jose Junior (2020) and Luna *et al.* (2018a); among their key findings is the identification of other industrial ecosystems that have endorsed to a certain extent the evolution of aerospace ecosystems. In particular, it is assumed that elements inherent to those industrial ecosystems, like the required infrastructure, manufacturing capabilities and the supplier base, have facilitated the evolution of the aerospace ecosystem.

The key enablers are identified for two types of aerospace ecosystems. An ecosystem within the most developed in the world, the United Kingdom, and another with an emergent aerospace ecosystem, Mexico. The description of the key enablers for both countries are presented next.

Key enablers for the development of the UK aerospace ecosystem

The UK aerospace ecosystem is considered one of the most successful in the world (Braddorn and Hartley 2007; McGuire 2017). Although the UK manufacturing ecosystem has experienced a relative decline since the 1960s compared to other countries and sectors of the UK economy, the aerospace and the pharmaceutical ecosystems have been among the most successful manufacturing sectors in the UK during the last decades (Garside 1998; Kitson and Michie 2014).

The UK aerospace ecosystem is characterised for being a world leader in developing new technologies and having expertise across all aircraft components, such as aerostructures, propulsion, systems, interiors and maintenance and repair operations (United Kingdom 2018). All the top ten aerospace companies in the world have production facilities in this country.

Besides, it is particularly strong in producing aerostructures, propulsion and aircraft systems (including landing gear, fuel systems, communications, electrical power, air, ice protection and data management) (House of Commons 2018a; ATI 2018a). All Airbus aircraft wings are manufactured in Bristol and North Wales, UK. Bombardier also manufactures wings in Northern Ireland. Fifty per cent of the UK aerospace economic value relies on propulsion systems. The UK and the USA are the only countries capable of producing and selling engines to power twin-aisle airliners (ATI 2018a). Engines are designed and produced by Rolls-Royce in different locations across England and Scotland. This company holds around 36% of large engines market (ATI 2018a).

The UK defence sector is positioned as one of the best in the world. From 2009 until 2018, it was considered as the second-largest exporter (ADS Group 2019) (aerospace products represent around two-thirds of the value of all defence exports). In 2018, the UK defence sector held 19% of the world market share, while the USA held 40%, Russia 14% and France 9% (United Kingdom 2019a).

The key enablers for the evolution of the UK aerospace ecosystem are listed in Table 1. A total of 13 key enablers are identified: seven resulted from the literature review and six from the quantitative analysis. The key enablers are mostly a summary of the ones suggested by recognised organisations using reports presented to the House of Commons Exiting the EU Committee, nurtured with secondary sources. Since the UK European Union Membership Referendum held on 23 June 2016, the UK government has analysed impact assessments when leaving the EU coming from different UK economy sectors (House of Commons 2017a). Notably, the UK government has pursued recommendations from civil and public organisations from the UK aerospace ecosystem. Examples of such organisations include the Aerospace Technology Institute (ATI), the Aerospace Growth Partnership (AGP), the ADS group, the University of Sheffield Advanced Manufacturing Research Centre (AMRC), the Department for Business, Energy and Industrial Strategy, the UK Trade Policy Observatory (UKTPO), the Department for Business, Innovation and Skills (BIS) and key companies, such as Boeing. As a result, reports from these organisations have been published containing a description of the aerospace ecosystem, a number of key enablers that have fostered the growth, and the potential consequences of leaving the EU. Thus, the key enablers in this research contain a summary of the ones suggested by such recognised organisations, plus the ones suggested by experts. A description of all the key enablers is presented next.

Table 1. Key enablers for the evolution of the UK aerospace ecosystem.

From literature review	Supplier development programs
	Supporting organisations
	Investment in human capital development
	Geopolitical factors
	Research and design (R&D) public finding
	Privatisation of aerospace companies
	Strategic alliances of manufacturing firms
From network analysis	Automotive ecosystem
	Chemical ecosystem
	Machinery ecosystem
	Pharmaceutical and medicinal ecosystem
	Agricultural products ecosystem
	Nonagricultural products ecosystem

Supplier development programs

This factor refers to the creation and implementation of policies from either the government or the private sector, aiming at suppliers development. The UK government, in conjunction with the civil sector, has historically implemented strategies to enhance the supply chain of the aerospace sector. As a consequence, as in 2019, the supplier base of the UK aerospace ecosystem has grown to a level where around 90% of the + 3,000 aerospace companies located in the UK are micro-sized (less than 10 employees) suppliers (United Kingdom 2019b). The latest strategy was launched at the beginning of 2019, a new supply chain competitiveness programme aiming to help small and medium enterprises to become more productive and competitive (United Kingdom 2018).

Another example of supplier development programs is the creation of the AGP. Since its creation in 2010, the AGP has enabled the evolution of the aerospace sector by generating 45% turnover growth of its members and has helped more than 300 companies to achieve world-class levels through supply chain programmes (ADS Group 2019). In particular, as part of the AGP, the UK has developed policies mainly aimed at technology innovation on small and medium-sized enterprises (SMEs), through the National Aerospace Technology Exploitation Programme (NATEP).

Supporting organisations

Development of supporting organisations between private industries, academia and the government is another key enabler for evolution. The ADS Group, the AGP and the ATI are examples of such organisations.

The ADS Group, created in 2009, is a trading organisation aiming to represent and promote the UK aerospace, defence, security and resilience, and space sectors. As in 2019, the ADS Group represents more than 1,000 companies, in which around 950 are SMEs. Such companies provide more than 100,000 direct employees and nearly 4,000 apprentices to the aerospace sector (ADS Group 2019).

The AGP, facilitated by the ADS Group, was formed in 2010, focused on creating a vision and strategies to secure the growth of the aerospace sector for the following decades. Reach for the Skies (AGP 2012), Lifting Off (HM Government 2013), Flying High (AGP 2014), and Means of Ascent (AGP 2016) are published reports containing such strategies. Examples of critical actions are the creation of the UK Aerospace Supply Chain Competitiveness Charter to promote the interchange of technology and growth opportunities within large companies; the creation of the NATEP to support technology innovation on the SMEs; the Aerospace Research Centre (ARC), within the Manufacturing Technology Centre, and the Aerospace Integration Research Centre (AIRC) at Cranfield University aimed at collaboration between the industry and the academia; and the funding of aerospace-related scholarships (Rhodes and Brien 2017). The AGP enables the evolution of the UK aerospace ecosystem mainly by the identification of the growth inhibitors caused by the UK market failure. It encourages the companies, part of the UK aerospace ecosystem, to coexist and increase collaboration to tackle together growth inhibitors, increase exports and high-value jobs. Another way in

which the AGP has enabled the aerospace ecosystem development is by helping with productivity improvement. According to AGP (2016), from 2010 to 2016, the UK aerospace manufacturing productivity increased by 39%. The increment has been driven mainly by generating new skills, the introduction of radical technologies and improved processes.

The ATI was established in 2013 to help the AGP technology strategy to boost the UK aerospace ecosystem as a world leader in technology and innovation by developing strategies and targeting investment (ATI 2018b). This institute has enabled the UK aerospace ecosystem by ensuring an annual investment from the civil and public sectors up to £ 300 million per year in technology until 2026 (ATI 2018a). In 2018, ATI portfolio embraced 214 projects, involving more than 200 companies, reaching a value of £ 2 billion. Besides, it supported the installation of the first Boeing manufacturing facility outside the USA and the Airbus wing integration centre in Filton. Within its main programmes are aircraft of the future, propulsion of the future, aerostructures of the future and smart, connected and more electric aircraft. Previous programmes are aiming to enable the aerospace ecosystem by focusing mainly on fuel efficiency, increased use of electricity and innovative manufacturing processes, such as additive manufacturing (ATI 2018a).

Investment in human capital development

There is robust historical evidence to claim that the development and success of industries based on science in a country is connected to the success of its scientific research (Broadberry and Leunig 2013). Evidence suggests that the leading position of the UK in the aerospace sector has been predominantly a result of the historical institutional expertise and extensive scientific research that has led to the human capital development (House of Commons 2017a). Creation of research centres to link academia and industry, like the ARC and the AIRC, and support of aerospace-related scholarships are examples of actions that have helped the human capital development in the UK.

Examples of activities that the AGP has implemented to enable the aerospace ecosystem are the funding of 500 Aerospace Engineering Master of Science (MSc) bursaries, helping to develop high-quality apprenticeships, the creation of an aerospace employer ownership pilot to cover opportunity areas in skills and the Aerospace Industrial Cadets Programme (AGP 2016).

Geopolitical factors

The aerospace industry is highly globalised and export-oriented and, therefore, so is the UK aerospace ecosystem. Indeed, this sector is unavoidably tied and benefits from geopolitical factors (House of Commons 2017a). In this study, geopolitical factors are considered as those influenced by the relationships with other countries, particularly in terms of trading.

As of 2019, 95% of the UK aerospace production is exported (ADS Group 2019). The UK, as a member of the World Trade Organisation (WTO), signed the Agreement on Trade in Civil Aircraft (ATCA). This trade agreement permits that all exports and imports of civil aerospace parts are exchanged duty-free within the EU and other 20 nations, such as the USA and China (WTO 2019).

In addition to the duty-free agreements, there are the bilateral safety agreements (BASA), which allow mutual airworthiness certification. The main benefit is that traded products require airworthiness certification only by one of the signatory countries (generally from the exporter/manufacturer). The UK, as a member of the European Aviation Safety Agency (EASA), has BASAs with Canada and the USA since 2011, and with Brazil since 2013 (EASA 2019).

Airworthiness certification agreements between the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) have been slightly affected due to the Boeing 737 MAX accidents. This aircraft was grounded worldwide after two crashes caused multiple fatalities, the first one in October 2018 from Lion Air of Indonesia and the second one in March 2019 from Ethiopian Airlines. Evidence of the changes is that the EASA has stated that Boeing 737 MAX aircraft will not fly again European skies until this organism certificates all Boeing design changes, independently from the FAA certification (Konert 2019). However, although airworthiness certification agreements have not been drastically changed yet, a recent study suggests that they must be innovated after the Boeing 737 MAX crashes evidenced their obsoleteness. For instance, Sgobba (2019) indicated that airworthiness authorities should migrate from a rule-based to a risk-based certification process. The first one refers to rules based on the design standards, while the latter refer to rules based on the performance and outcome required.

As in April 2021, the fact that the UK has left the EU on January 31, 2020 (Brexit), geopolitical concerns are still present. However, according to McGuire (2017), the application of tariffs due to Brexit does not represent a potential risk to the UK manufacturing ecosystem, thanks to the fact that the UK, as a member of the WTO, has individually signed the ATCA. The biggest concern is the BASAs and the potential delays that could be caused by the new paperwork and bureaucracy requirements when crossing the border. It is still uncertain if the UK, as a member of the EASA, will still be beneficiated from the current BASAs (House of Commons 2018b). Conversely, international air services do represent potential risk because their governance depends on the Air Service Agreements (ASAs), which are independent of the WTO. Although the UK has ASAs individually with 111 countries, it also depends on ASAs signed between the EU and individual countries. Examples of the latter scenario include some of the UK major partners, such as the USA and Canada (House of Commons 2017b).

Research and development (R&D) public funding

Economic success in the UK is driven by R&D. Innovation is considered as the key enabler for booming the UK economic growth and productivity, and particularly in aerospace has evidenced substantial returns (ATI 2018b).

The UK aerospace ecosystem is highly dependent on R&D government expenditure. This sector receives around 12% of the manufacturing R&D budget (House of Commons 2018b). In the UK, public funding is generally granted to aerospace companies via ATI. Since 2014, this institution has targeted more than £ 1.95billion in funds of over 200 companies (ADS Group 2019). Aircraft of the future, aerostructures of the future, propulsion of the future, smart, connected and more electric aircraft (ATI 2018a), and accelerating ambition (ATI 2019) are the latest strategies to promote technological development. Another example of public funding is the aerospace sector deal, launched in 2018. In this strategy, the UK government has designated £ 125 million for aerospace research and development (House of Commons 2017a).

The UK aerospace ecosystem has also been beneficiated from public funding coming from the EU (Butcher 2018; ADS Group 2017; House of Commons 2018b). For instance, the programme Horizon 2020 was developed to spread R&D grants over EU members through diverse industrial sectors. The UK is the second-largest beneficiary from this program, receiving annually 13.5% of the funding (House of Commons 2019). The UK aerospace ecosystem receives annually nearly £ 100 million from the Horizon 2020 programme (House of Commons 2018b). It is relevant to highlight that this particular funding coming from the EU is at risk due to Brexit. As in February 2020, the future of this funding is still uncertain.

Privatisation of aerospace companies

Although the government funding has been a determinant for the evolution of the UK aerospace sector, the privatisation of public companies has historically been also a key enabler (Broadberry and Leunig 2013; Garside 1998). During the last half-century, firms from the aerospace sector in the UK have fluctuated from being private to public and vice versa. In the 1970s, the nationalisation of aerospace manufacturing firms boomed mainly as a strategy to rescue them from collapsing (Broadberry and Leunig 2013). For instance, Rolls-Royce was nationalised in 1971, and British Aerospace (BAe) surged in 1977 from merging and nationalising British Aircraft Corporation (BAC) and Hawker Siddeley Aviation (HSA). A decade later, once both companies regain strength, they were privatised. Nowadays, the aerospace industry and airlines belong to the private sector.

Strategic alliances of manufacturing firms

Another key factor for the evolution and success of the UK aerospace ecosystem is the association and collaboration of firms not only at national level, but also with European manufacturers (Broadberry and Leunig 2013). Airbus is arguably the best example. It is now the second-largest aerospace company in the world, formed in 1970 by merging European manufacturers aiming at competing with Boeing. Examples of successful strategic alliances at a national level are the creation of BAE Systems in 1999 from merging BAe, and Marconi Electronic Systems; and the BAe, which surged in 1977 from merging BAC and HAS. Previously, BAC was originated from merging Vickers-Armstrongs, English Electric Aviation, Bristol Aircraft Limited and Hunting Aircraft Limited (Broadberry and Leunig 2013).

Other industrial ecosystems

The aim of this part of the research is the identification of other ecosystems that have endorsed the evolution of the UK aerospace ecosystem. Such industrial ecosystems, considered in this part of the research as key enablers, are part of the results from the quantitative analysis presented in the following chapters. From the evolution of the networks of developed aerospace ecosystems, popular products are identified. Popular products are those commodity codes (using the Standard International Trade Classification, SITC, revision 3), apart from the aerospace products, in which the UK has continuously demonstrated a revealed comparative advantage (RCA > 1) from 1992 to 2016. The full list of products is presented in Table 2. Here, codes are grouped in the following industrial ecosystems: automotive ecosystem (code 78), chemical ecosystem (codes 51, 52, 53, 55, 58, 59), machinery ecosystem (codes 71, 72 and 74), pharmaceutical and medicinal ecosystem (code 54), agricultural products ecosystem (codes 00 and 11) and nonagricultural products ecosystem (codes 87 and 89).

Table 2. Popular products in which the UK has continuously demonstrated an RCA > 1 over the last decades.

Industrial ecosystem	Code	Product
Automotive ecosystem	78	Road vehicles (automotive products)
Chemical ecosystem	51	Organic chemicals
	52	Inorganic chemicals
	53	Dyeing, tanning and colouring material
	55	Perfume, cleaning and preparations
	58	Plastics in non-primary forms
	59	Chemical materials and products
Machinery ecosystem	71	Power generating machinery and equipment
	72	Machinery for specialised industries
	74	General industrial machinery
Pharmaceutical and medicinal ecosystem	54	Medicinal and pharmaceutical products
Agricultural products ecosystem	00	Live animals
	11	Beverages
Nonagricultural products ecosystem	87	Instruments and apparatus
	89	Miscellaneous manufactured articles

The products classified by industrial ecosystems are presented and discussed with experts on the UK aerospace ecosystem. After a discussion about the influence of each industrial ecosystem on the growth of the UK aerospace ecosystem, it is decided to consider such industrial ecosystems as following:

- Automotive ecosystem refers to the supply chain developed for the automotive manufacturing sector. The UK automotive ecosystem is considered as a key enabler for the UK exports of industrial goods (SMMT 2019) and a British success story (House of Commons 2019). As in 2018, the automotive industry accounted for 14.4% of all exported goods in the UK, positioning this sector as the UK largest exporter of goods (SMMT 2019).
- Chemical ecosystem includes products such as dyeing, tanning and colouring materials, inorganic chemicals, perfume and cleaning preparations, and plastics in non-primary forms. The UK chemical ecosystem is one of the most successful in the world, and it is a key player in the supply chain of industries, such as the aerospace and automotive industry (House of Commons 2019).
- Machinery ecosystem denotes to the manufacture of general industry machinery, machinery for specialised industries and power generating machinery.
- Pharmaceutical and medicinal ecosystem comprise the capabilities to manufacture all pharmaceutical and medicinal products. The pharmaceutical ecosystem has been considered as one of the most successful manufacturing sectors in the UK, in conjunction with the aerospace sector (Kitson and Michie 2014).

- Agricultural products ecosystem embraces the production of all animals and edible products.
- Nonagricultural products ecosystem refers mainly to the ecosystem required for the production of other goods not included within previous classifications (others apart from the automotive, chemical, machinery, pharmaceutical and medicinal and agricultural products ecosystems presented previously).

In this research, it is assumed that previous ecosystems have endorsed, to a certain extent, the evolution of the aerospace ecosystem in the UK. In particular, it is assumed that elements inherent to those industrial ecosystems, like the required infrastructure, manufacturing capabilities and the supplier base, have fostered the evolution of the aerospace ecosystem.

Key enablers for the development of the Mexican aerospace ecosystem

In this part of the research, the Mexican aerospace ecosystem is used as a case example of an emergent ecosystem.

The beginning of the aerospace industry in Mexico dates back to the early 1900s when, in 1915, an innovative propeller named Anahuac was designed and manufactured in this country (Navarrete 2011). However, along most of the last century, its aerospace ecosystem did not experience significant development. It was until the end of the 1900s and the beginning of 2000s when the government implemented policies to start attracting investment from foreign companies motivating them to relocate their facilities in Mexico. As in 2018, the Mexican aerospace ecosystem embraces more than 300 aerospace-related firms dedicated to production, maintenance, repair and operation (MRO) and research and development (R&D) activities (INEGI 2018; ProMexico 2017).

In Fig. 1, the evolution of the number of companies from 2006 to 2016 is presented by type: manufacturers, MRO and R&D. In the eleven years, the number of companies triplicated. As evidenced, most of the companies belong to the manufacturing sector. The companies are concentrated predominantly close to the USA border, and are grouped in the following five clusters:

- Baja California: it is dedicated to manufacturing processes outsourcing, precision machinery, electric and power systems, and hydraulic and interior systems. This cluster produces the most significant number of exports within the country. More than 70 international companies are represented, such as Honeywell Aerospace, UTC Aerospace Systems, Gulfstream, GKN Aerospace, Triumph Group, LMI Aerospace and Rockwell Collins (ProMexico 2017).
- Queretaro: within the main capabilities of this region are the assembly and manufacture of aeroplanes and helicopter parts, turbines, landing gear and MRO. It has been the region that has grown the most in the last decade, and currently holds the most significant number of R&D entities. It has Bombardier Aerospace and Airbus Helicopters as prime manufacturers; Safran Aircraft Engines, Safran Landing Systems, TechOps and ITP as MRO; Safran Aircraft Engines, Safran Landing Systems, Meggitt Aircraft Braking Systems and Aernnova as tier-1 firms and has more than 15 > tier-1 companies. It also has Horizontec, the only Mexican company that is currently developing, manufacturing and assembling light-sport and experimental aircraft (Torres *et al.* 2019).
- Chihuahua: this cluster is characterised for having strong capabilities on wiring, composite materials and structures. It has the largest wiring plant in the world, Safran Electrical & Power/Labinal Power. Within the leading companies are Cessna, Beechcraft, Textron International, Honeywell Aerospace and EZ Air Interior Limited (a joint venture between Embraer and Zodiac) (Martinez *et al.* 2015).
- Nuevo Leon: MRO is the principal activity in this cluster. It has more than 20 SMEs dedicated to small aircraft (ProMexico 2017). Hawker Beechcraft Services, United Technologies Corporation Aerospace System (UTCAS) and Monterrey Jet Centre are examples of firms located in this region (Martinez *et al.* 2015).
- Sonora: this cluster has more than 50 SMEs dedicated primarily to the production of turbine components. It has companies such as Rolls-Royce, JJ Churchill Ltd, American Precision Assemblers, BAE Systems Products Group, Benchmark Electronics Precision Technologies, UTC Aerospace Systems and Parker Hannifin Aerospace (Martinez *et al.* 2015).

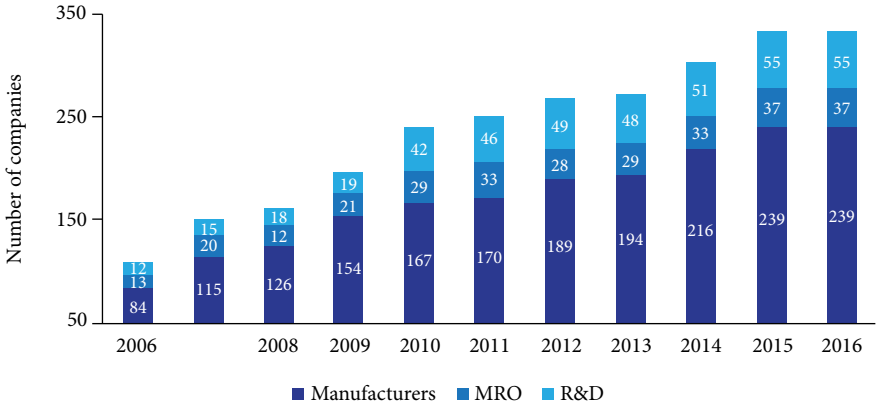


Figure 1. Evolution of aerospace companies in Mexico.

As in 2019, the Mexican aerospace ecosystem is considered as the 12th largest aerospace manufacturer in the world (FEMIA 2019). Since 2009, its aerospace ecosystem has experienced a 14% annual average growth (Muñoz-Sanchez *et al.* 2019). The development has been achieved to some extent by the enablers identified in this research, which are listed in Table 3.

Table 3. Key enablers for the evolution of the Mexican aerospace ecosystem.

From literature review	Geopolitical factors
	Labour
	Investment in human capital development
	Supporting organisations
	Foreign investment
From network analysis	Automotive ecosystem
	Agricultural products ecosystem
	Nonagricultural products

As elaborated for the UK aerospace ecosystem, key enablers for the Mexican aerospace ecosystem are identified through a quantitative analysis and a literature review nurtured and validated with experts. In regards to the literature review, key enablers comprise a summary of the ones suggested by recognised organisations and experts in the Mexican aerospace ecosystem. Since the Mexican manufacturing ecosystem is characterised for hosting foreign companies, the Mexican government has continuously promoted the Mexican aerospace ecosystem to attract investments. As part of the effort, recognised organisations have published official reports containing characteristics of the ecosystem and key enablers that have thrived its evolution. Examples of such organisations include ProMexico, a subdivision of the Ministry of Economy, the Mexican Federation of the Aerospace Industry (FEMIA), the National Centre for Aerospace Technologies (CENTA) and the National Council of Science and Technology (CONACYT). Hence, a summary of key enablers suggested by such recognised organisations is included in this research.

Similarly to the UK aerospace ecosystem analysis, the list of key enablers is divided into two categories: five key enablers from a literature review and three from quantitative analysis. A description of each key enabler is presented next.

Geopolitical factors

Mexico geographical location as a USA neighbour and trade agreements with this country are key enablers that have propelled its attractiveness to foreign manufacturing firms (Meraz-Rodríguez *et al.* 2019; Morsi *et al.* 2018; Padilla and Suarez 2018; Quesada *et al.* 2015). It is positioned as the 9th largest exporter and the 13th largest importer in the world. Thanks to duty-free trading agreements with 45 countries, 93% of imports to this country enter without tariffs (Geiger *et al.* 2016). It is part of the North

American Free Trade Agreement (NAFTA) between Canada and the USA. The leading destinations of its exports are the USA (73%), Canada (5.2%) and Germany (2.1%). Most of its imports come from the USA (51%), China (15%) and Germany (4.2%). Mexico is the first destination of the USA exports (15%) and second in imports (14%), after China (22%) (OEC 2019). Regarding the aerospace ecosystem, around 80% of exports from this sector are sent to the USA, taking advantage of the BASA signed since 2007 (INEGI 2018). It is positioned as the 7th largest aerospace supplier of the USA (Padilla and Suarez 2018).

Labour: low cost and highly-qualified

Mexico economic condition, particularly the relatively low-cost wages compared to the USA, gives this country a comparative advantage to foreign companies when trying to access the USA market (Coffin 2013; Martínez-Romero 2013; Morsi *et al.* 2018; Trimble 2016). As in 2020, the minimum wage in Mexico per hour is US$ 0.82 (Mex$ 15.4) for most of the country, and US$1.23 (Mex$ 23.2) for regions bordering with the USA. Whereas in the USA, the federal minimum wage per hour is US$ 7.25. This economic condition promotes foreign companies to manufacture their products in Mexico and send such products to the USA.

In addition to the wages, nowadays, Mexican labour force is considered as highly-qualified (Coffin 2013; Padilla and Suarez 2018; ProMexico 2017). It is particularly strong in manufacturing capabilities, such as metal-mechanic processes needed for the automotive and aerospace sector (Padilla and Suarez 2018).

Investment in human capital development

In the last decades, the Mexican government has implemented public policies to improve labour skills aiming at enabling the aerospace ecosystem development (Padilla and Suarez 2018; ProMexico 2017). In the recent years, in regards to the number of engineers, Mexico has been considered the country with the highest number in Latin America, and it is positioned within the top ten in the world (Padilla and Suarez 2018).

The CONACYT, founded in 1970, is an example of a public organisation that has enabled human capital development. Since 1971, this organisation has provided more than 450 thousand science and technology-related scholarships (CONACYT 2018).

The motivation of the government catapulted in 2005 when Bombardier officialised its investment to start a manufacturing facility in Queretaro dedicated to the installation of sub-assembly systems, electrical harnesses and carbon fibre structures. To attend Bombardier requirements, the government opened a public university, Aeronautical University of Queretaro (UNAQ), located next to Bombardier facilities. The Mexican government claims that this educational institution promoted the attraction of new foreign investments and enabled the evolution of the aerospace ecosystem (Luna *et al.* 2018b; Luna-Ochoa *et al.* 2016; Meraz-Rodríguez *et al.* 2019; Muñoz-Sanchez et al. 2019). Nowadays, more than twenty educational institutions are offering specialised courses in this sector (ProMexico 2017).

Supporting organisations

Organisations part of the Mexican triple helix, as first proposed in the framework developed by Etzkowitz and Leydesdorff (1995), holding synergy from the academia, private and public sector have been considered as key enablers for the growth of the Mexican manufacturing ecosystem (Guerrero and Urbano 2017), and particularly for the emergence of the aerospace ecosystem (Coffin 2013; Morsi *et al.* 2018; ProMexico 2017).

The CONACYT is an example of a public organisation aiming at developing enhancement policies and promoting technological innovation in this country. Thanks to this organisation, in 2018, the national budget for R&D has increased by 70% compared to the 2001–2006 period (figures for particular sectors are not available) (CONACYT 2018).

Another example is FEMIA. It is a nonprofit organisation established in 2007 between private industries and government aiming at the development of the aerospace ecosystem. This organisation represents more than 110 aerospace companies, including Airbus, Bombardier, General Electric and Safran group (FEMIA 2019). The FEMIA enables the aerospace ecosystem mainly by providing consulting services, such as support with the aerospace certification and the supplier base development.

The CENTA, founded in 2016, is the latest supporting organisation proposed by the FEMIA and developed by the CONACYT and the Ministry of Economy. Nowadays, it is the only R&D institution entirely devoted to the aerospace sector in Mexico

(Muñoz-Sanchez *et al.* 2019). The CENTA enables the aerospace ecosystem in Mexico mainly by providing to the industry aerospace testing laboratories and support for product development. The development of an SME called Horizontec is an example of the efforts of the CENTA to enable the Mexican aerospace ecosystem. Horizontec is a Mexican company, developed in a joint venture with CENTA, capable of designing, manufacturing and testing light-sport aircraft (Torres *et al.* 2019).

ProMexico is an example of a public organisation developed in 2007 dedicated to attracting foreign investments for a wide range of business sectors (Ortiz *et al.* 2014). ProMexico promotes the strengths of the Mexican ecosystem and mainly aims to enable the aerospace ecosystem by attracting foreign direct investment. This organisation analyses the aerospace ecosystem, promotes its strengths, identifies opportunity areas and develops investment road maps (Padilla and Suarez 2018). Examples of reports containing such strategies are the national plan flight Mexico's aerospace industry road map 2014 (Ortiz *et al.* 2014), 2015 (Martinez *et al.* 2015), Mexican aerospace industry: a booming innovation driver (ProMexico 2015), Mexican aerospace industry: flying to new heights (ProMexico 2017) and Mexico: your ally for innovation (Padilla and Suarez 2018). According to ProMexico (2017), this organisation has been a key enabler for increasing the number of aerospace companies in Mexico from around 150 in 2007 to more than 300 in 2016.

Foreign investment

The main economic activity of Mexico is the manufacturing industry, derived predominantly from foreign investments. The manufacturing sector represents around 18% of its gross domestic product (GDP) (Padilla and Suarez 2018). In 2019, Mexico was considered within the top ten in the world in terms of industry capabilities (such as industry size, growth, maturity, profit margin and labour cost). Particularly for the aerospace industry, it has been ranked as the number 35 in the world and second most attractive country for aerospace manufacturing investments in Latin America, just after Chile (PwC 2019). From 2007 until 2016, the Mexican aerospace ecosystem received US$ 3,285 million from foreign investment, where 47% came from the USA, 36% from Canada, 12% from France, 4% from Spain and the rest from other countries (INEGI 2018). According to ProMexico (2018), Mexico is the 3rd largest receiver of aerospace direct foreign investment in the world. As in 2016, it was the 12th largest exporter of aerospace products in the world, holding nearly 2% of world exports (INEGI 2018).

Other industrial ecosystems

Similarly to the UK aerospace ecosystem analysis presented previously, this part of the research aims at the identification of other ecosystems that have endorsed the evolution of the Mexican aerospace ecosystem. The full list of products is presented in Table 4. Here, codes are grouped in the following industrial ecosystems: automotive ecosystem (code 78), machinery ecosystem (codes 71, 76 and 77), agricultural products ecosystem (codes 00, 05 and 11) and nonagricultural products ecosystem (codes 81 and 82).

Table 4. Popular products in which Mexico has continuously demonstrated an RCA >1 over the last decades.

Industrial ecosystem	Code	Product
Automotive products	78	Road vehicles (automotive products)
Machinery	71	Power generating machinery and equipment
	76	Telecommunications and sound recording equipment
	77	Electric machinery and parts
Agricultural products	00	Live animals
	05	Vegetables and fruit
	11	Beverages
Nonagricultural products ecosystem	81	Prefabricated buildings, sanitary, lighting and fixtures
	82	Furniture and parts thereof

As elaborated during the UK aerospace ecosystem analysis, the products classified by industrial ecosystems are then presented and discussed with experts on the Mexican aerospace ecosystem. After a discussion about the influence of each industrial ecosystem

on the growth of the aerospace ecosystem in Mexico, experts decided to exclude the machinery ecosystem as an enabler. Most of the experts suggested that the machinery ecosystem has not considerably influenced the growth of the aerospace ecosystem in this country. Among the main reasons expressed during the discussion is the fact that experts believe that the machinery ecosystem is more a consequence rather than a cause. Experts suggested that the evolution of other industrial ecosystems, such as the automotive ecosystem, have enabled the growth of the machinery ecosystem. Consequently, the discussion concluded that it should be included under the nonagricultural products ecosystem.

Thus, the industrial ecosystems considered as enablers in this part of the research are as follows:

- Automotive ecosystem refers to the supply chain developed for the automotive manufacturing sector. This industrial ecosystem is the most important industrial sector in this country: it is ranked as the 9th largest producer and 4th largest exporter of light vehicles in the world (Padilla and Suarez 2018). Mexico automotive ecosystem hosts 24 final-assembler facilities from companies, such as Audi, Honda, Ford, General Motors, KIA, Mercedes-Benz, Nissan, Toyota and Volkswagen. The Mexican automotive ecosystem supplier base has been considered as a key enabler for the development of the aerospace ecosystem in this country (Martinez *et al.* 2015; ProMexico 2017).
- Agricultural products ecosystem embraces the production of all animals and edible products. Mexico has been particularly good on exporting live animals, vegetables and fruits, sugar, sugar preparations and honey and beverages.
- Nonagricultural products ecosystem refers mainly to the ecosystem required for the production of other goods not included within previous classifications (others apart from the automotive and agricultural products ecosystems presented previously).

In this research, it is assumed that previous ecosystems have endorsed to a certain extent, the evolution of the aerospace ecosystem in Mexico. In particular, it is assumed that elements inherent to those industrial ecosystems, like the required infrastructure, manufacturing capabilities and the supplier base, have fostered the evolution of the aerospace ecosystem.

The next step is the categorisation of the key enablers using the ISM and MICMAC methodologies.

CATEGORISATION OF THE KEY ENABLERS USING ISM AND MICMAC METHODOLOGIES

The process for the categorisation of the key enablers using ISM and MICMAC is described in Fig. 2. Once the key enablers are identified and validated, the first step is the interaction with experts. In this step, the experts are asked to establish contextual relationships via a structural self-interaction matrix (SSIM). The next step is the elaboration of the initial reachability matrix (IRM). In this matrix, experts' opinions are converted into a binary matrix. Then, transitivity is checked, and a Final reachability matrix (FRM) is elaborated.

From the FRM, the driving and dependence power is calculated as part of the MICMAC analysis, and the cause-effect interactions are computed through the levels partition step. The next step is to portray the key enablers in a structural model. To this aim, first a directed graph is developed. In this graph, each key factor is portrayed at a different level according to the levels partition from the previous step. Once the directed graph is developed, all the transitivity links are removed. Finally, the ISM and MICMAC models are generated and validated. A detailed description of each step is presented next.

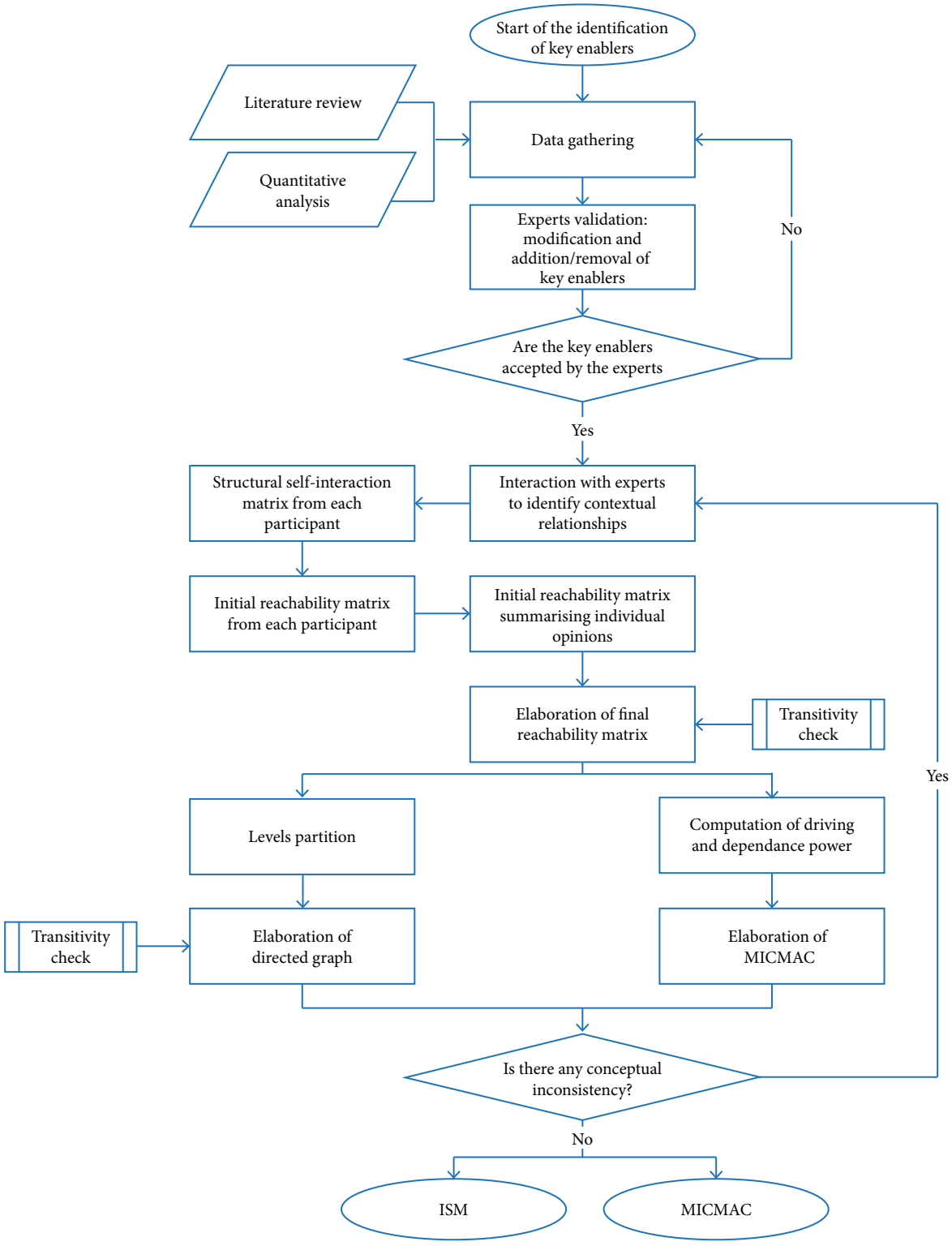


Figure 2. Methodology for the identification and categorisation of key enablers for the evolution of aerospace ecosystems, an ISM and MICMAC approach.

The categorisation of key enablers for the evolution of the UK aerospace ecosystem

The group of experts is selected based on their adherence to the UK aerospace ecosystem and their professional background. The selection criteria aimed to choose experts from both private and public sectors, with vast experience working in the UK aerospace ecosystem. Therefore, the selected group of participants consisted of four experts with more than ten years of working experience in the UK aerospace industry; three of them working in the private sector and one expert working for a public R&D institute (Table 5). Experts' opinions are gathered in a workshop developed during the UK National Manufacturing Debate 2019 hosted by Cranfield University. This is an annual event aiming at enabling continued and long-term growth for the manufacturing industry, by promoting networking and collaboration across manufacturing professionals from different sectors (more information can be found at https://www.cranfield.ac.uk/events/national-manufacturing-debate/national-manufacturing-debate). In the workshop, an explanation of the methodology and a description of each key factor is described to the experts. After a discussion, experts are asked to eliminate the proposed key enablers and to suggest any additional one. Finally, the list of key enablers is updated according to experts' suggestion.

Table 5. Group of experts in the UK aerospace sector used for the ISM-MICMAC analysis.

Sector	Job title	Years of experience
Manufacturing (private sector)	Vice-president	18
Manufacturing (private sector)	Technical Program manager	13
Manufacturing (private sector)	Supplier development manager	10
Research & Development (public sector)	Senior technologist	12

Structural self-interaction matrix (SSIM)

The experts' opinion for the establishment of the cause-effect relationships via SSIM can be gathered mainly by consensus or individual opinion approaches. The main advantage of using the first approach is the collaboration across participants for the achievement of a mutual agreement by sharing diverse perspectives (particularly sharing different points of view that may not be evident for all participants). The main weakness of this approach is that as individuals' expertise, judgement and power to express its arguments can dominate others, it is impossible to assure the correctness of a consensus reached in a group discussion, as suggested by Schuman (2002). On the other hand, the main advantage of using individual opinions approach is the minimisation of the bias in a group discussion caused by an individual's power to express their arguments.

In this research, the individual opinion approach is selected, aiming at trying to reduce the bias that could be generated during a group discussion. To that end, each participant is requested to, using the symbols described in Table 6, individually fill in Table 7. For instance, considering that factor 2, supporting organisations, influences factor 10, machinery ecosystem, the symbol ▲ is used (in this case, factor x is factor 2 and factor y is factor 10). By using this symbol, it is assumed that factor 2 does not get affected by factor 10. A total of four SSIMs are generated.

Table 6. Symbols used for the establishment of the contextual relationships in the SSIM.

▲	Factor x influences factor y
▼	Factor y influences factor x
↔	Mutual influence between both factors
Ø	No influence within both factors

Table 7. Example of an SSIM for the UK aerospace ecosystem filled in by one expert.

Factor	#	1	2	3	4	5	6	7	8	9	10	11	12	13
Supplier development programs	1		↔	▲	▼	↔	▼	Ø	↔	▲	▼	↔	Ø	▼
Supporting organisations	2			▼	▲	↔	▲	Ø	▼	↔	↔	▲	▼	↔
Investment in human capital development	3				↔	↔	▼	↔	Ø	↔	▼	↔	Ø	▲
Geopolitical factors	4					↔	↔	↔	▼	Ø	▼	▼	▲	↔
R&D public funding	5						Ø	▲	▼	↔	▼	▲	Ø	↔
Privatisation of aerospace companies	6							↔	▲	▼	▼	↔	Ø	▲
Strategic alliances of manufacturing firms	7								↔	↔	▼	Ø	▲	↔
Automotive ecosystem	8									▲	▲	▼	↔	Ø
Chemical ecosystem	9										Ø	↔	↔	▼
Machinery ecosystem	10											▲	↔	▼
Pharmaceutical and medicinal ecosystem	11												Ø	▼
Agricultural products ecosystem	12													Ø
Nonagricultural products ecosystem	13													

Initial reachability matrix (IRM)

Subsequently, the IRM summarising independent opinions is elaborated. To this aim, each SSIM is converted into an IRM. Thus, four IRM matrices are generated. Each IRM is produced by converting each SSIM into a binary matrix, according to the rules from Table 8. For instance, if factor 2 affects factor 10, but factor 10 does not affect factor 2, described by using ▲ in the cell (2,10), the value of cell (2,10) in the IRM is 1 and 0 for cell (10,2). As they are four participants, a value of 1 is assumed when two or more individual IRMs have a value of 1 and a value of 0 for all the others.

The final IRM is presented in Table 9. This table summarises the expert's opinion expressing pairwise relationships using binary language. A value of 1 indicates a causality relation, while a value 0 indicates no relationship between factors. For instance, cell (3,1) has a value of 0, while cell (1,3) has a value of 1. The former value indicates that factor 3 does not affect factor 1. The latter indicates that factor 1 causes factor 3. The next step is the elaboration of the FRM.

Table 8. Set of rules used to convert the SSIM into a binary matrix (IRM).

▲	1 for (x, y) and 0 for (y, x)
▼	0 for (x, y) and 1 for (y, x)
↔	Both entries become 1
Ø	Both entries become 0

Table 9. Initial reachability matrix for the UK aerospace ecosystem.

Factor	#	1	2	3	4	5	6	7	8	9	10	11	12	13
Supplier development programs	1	1	1	0	1	1	1	1	0	0	0	1	0	0
Supporting organisations	2	1	1	1	0	0	0	1	0	0	1	1	0	0
Investment in human capital development	3	1	0	1	1	1	0	1	0	0	0	0	1	0
Geopolitical factors	4	1	0	1	1	0	0	1	0	0	0	1	0	0
R&D public funding	5	0	1	1	0	1	0	0	0	0	1	0	0	1
Privatisation of aerospace companies	6	0	0	0	0	1	1	0	0	0	0	0	0	0
Strategic alliances of manufacturing firms	7	1	1	0	1	1	1	1	0	0	0	0	0	0
Automotive ecosystem	8	0	1	1	0	1	0	0	1	0	0	0	0	0
Chemical ecosystem	9	0	0	1	0	0	0	0	0	1	0	0	0	0
Machinery ecosystem	10	0	0	1	0	0	0	0	1	0	1	0	0	0
Pharmaceutical and medicinal ecosystem	11	0	1	0	0	1	0	0	0	1	1	1	1	0
Agricultural products ecosystem	12	0	0	0	0	0	0	0	0	0	0	1	1	0
Nonagricultural products ecosystem	13	0	0	0	0	0	0	0	0	1	0	1	0	1

Final reachability matrix (FRM)

The FRM adds more cause-effect relations by adding transitivity to the final IRM (Table 9). In mathematics, transitivity between three elements exists when a mutual relationship is derived from one indirect connection. For instance, if x is related to y, and y is related to z; consequently x and z have a transitive relationship. Thus, the FRM for the UK aerospace ecosystem, presented in Table 10, is elaborated indicating transitivity relations with a 1*.

Besides, the driving power and dependence power are computed as part of the MICMAC analysis. The first one is the total amount of factors that are influenced by this metric, it is obtained by adding all the 1s of each row. The latter is the number of factors that might affect this metric, it is obtained by adding all the 1s of each column. For instance, the key enabler #1, supplier development programs, influences 12 factors (11 other factors plus the factor itself) and it is influenced by ten factors (nine other factors plus the factor itself).

Table 10. Final reachability matrix including transitivity for the UK aerospace ecosystem.

Factor	#	1	2	3	4	5	6	7	8	9	10	11	12	13	Driving power
Supplier development programs	1	1	1	1*	1	1	1	1	0	1*	1*	1	1*	1*	12
Supporting organisations	2	1	1	1	1*	1*	1*	1	1*	1*	1	1	1*	0	12
Investment in human capital development	3	1	1*	1	1	1	1*	1	0	0	1*	1*	1	1*	11
Geopolitical factors	4	1	1*	1	1	1*	1*	1	0	1*	1*	1	1*	0	11
R&D public funding	5	1*	1	1	1*	1	0	1*	1*	1*	1	1*	1*	1	12
Privatisation of aerospace companies	6	0	1*	1*	0	1	1	0	0	0	1*	0	0	1*	6
Strategic alliances of manufacturing firms	7	1	1	1*	1	1	1	1	0	0	1*	1*	0	1*	10
Automotive ecosystem	8	1*	1	1	1*	1	0	1*	1	0	1*	1*	1*	1*	11
Chemical ecosystem	9	1*	0	1	1*	1*	0	1*	0	1	0	0	1*	0	7
Machinery ecosystem	10	1*	1*	1	1*	1*	0	1*	1	0	1	0	1*	0	9
Pharmaceutical and medicinal ecosystem	11	1*	1	1*	0	1	0	1*	1*	1	1	1	1	1*	11
Agricultural products ecosystem	12	0	1*	0	0	1*	0	0	0	1*	1*	1	1	0	6
Nonagricultural products ecosystem	13	0	1*	1*	0	1*	0	0	0	1	1*	1	1*	1	8
Dependence power		10	12	12	9	13	6	10	5	8	12	10	11	8	

Levels partition

The next step is the partition of the FRM into different levels. A summary of the level partitions is presented in Table 11. This table indicates the pairwise relationships and the structural level in the ISM. The process starts by assessing the reachability, antecedent and intersection sets for each factor. The reachability set is defined by identifying all the other factors that might be achieved thanks to the assessed factor. It is obtained by identifying all the 1 and 1* across the entire row of each factor from the FRM table. For instance, factor 5 affects 12 factors (11 other factors plus itself — 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12 and 13). The antecedent set is acquired by finding all the other factors that may help to achieve the evaluated factor. This set is found by getting all the 1 and 1* across each factor column. For instance, factor 5 gets affected by 13 factors (12 other factors plus itself — 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13). The intersection set for each factor is obtained by identifying all the other factors that are part of both sets, the reachability and antecedent sets. For instance, 12 factors are shared by the reachability and antecedent set of factor 5 (11 other factors plus itself — 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12 and 13). Then, the first level is obtained by identifying all the factors where the reachability and intersection sets include the same factors. The process continues for the following level. Here, the factors from the previous level are excluded, and then the reachability, antecedent and intersection sets are calculated again. The same process

is repeated until every factor is classified into a level. Each level is positioned following a top-bottom order, meaning that level 1 is positioned at the top while the last level is positioned at the base of the ISM (Rana *et al*. 2019).

Table 11. Summary of levels partition for the UK's aerospace ecosystem.

Factor	Reachability set	Antecedents set	Intersection set	Level
5	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13	1
10	1, 2, 3, 4, 5, 7, 8, 10, 12	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13	1, 2, 3, 4, 5, 7, 8, 10, 12	1
12	2, 5, 9, 10, 11, 12	1, 2, 3, 4, 5, 8, 9, 10, 11, 12, 13	2, 5, 9, 10, 11, 12	1
6	6	1, 2, 3, 4, 6, 7	6	2
1	1, 2, 3, 4, 7, 9, 11	1, 2, 3, 4, 7, 8, 9, 11	1, 2, 3, 4, 7, 9, 11	3
3	1, 2, 3, 4, 7, 11	1, 2, 3, 4, 7, 8, 9, 11, 13	1, 2, 3, 4, 7, 11	3
7	1, 2, 3, 4, 7, 11	1, 2, 3, 4, 7, 8, 9, 11	1, 2, 3, 4, 7, 11	3
9	9	2, 4, 9, 11, 13	9	4
2	2, 11	2, 4, 8, 11, 13	2, 11	5
11	2, 11	2, 4, 8, 11, 13	2, 11	5
4	4	4	4	6
8	8	8	8	6
13	13	13	13	6

Interpretative structural modelling for the UK aerospace ecosystem

The next step is the development of the directed graphs by using the levels partitions from the previous step. The outcome of the level partition from the previous step resulted in a 6-level model. Each level contains all the factors indicated in Table 11. For instance, factors 5, 10 and 12 are categorised as level one. Thus, such factors are positioned at the top of the model. This level is characterised by having the factors that do not help to achieve any others. The next level has only one factor, number 6. Thus, it is positioned just below the top level. The process continues until the last level. The links between the factors are generated from all the 1 and 1* from the FRM. Finally, the ISM model, Fig. 3, is generated after removing the transitivity links and replacing numbers by statements.

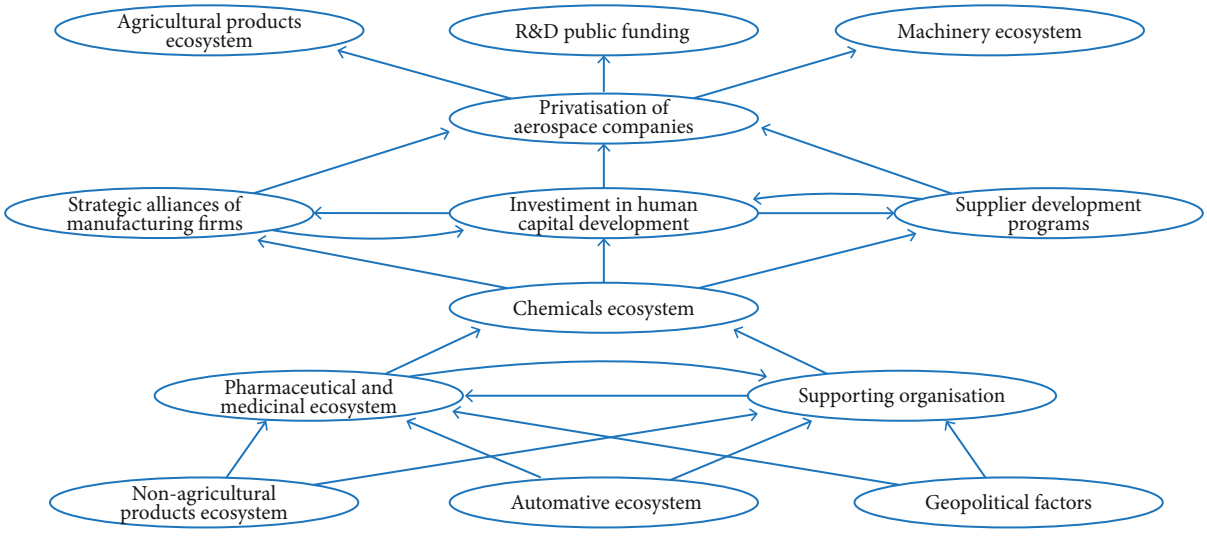


Figure 3. An interpretative structural model for the UK aerospace ecosystem.

A MICMAC analysis for the UK aerospace ecosystem

Within the MICMAC analysis, each factor is classified as autonomous, linkage, dependent or driver. Autonomous are those factors that are more disconnected, as they are considered to have the least influence to and from others. Factors are classified as linkage when any action related to them drives an effect on them and others. Dependent factors got the most influence from others, and driver factors are considered as the key enablers to other factors (Raj *et al*. 2008). Results are presented in Fig. 4.

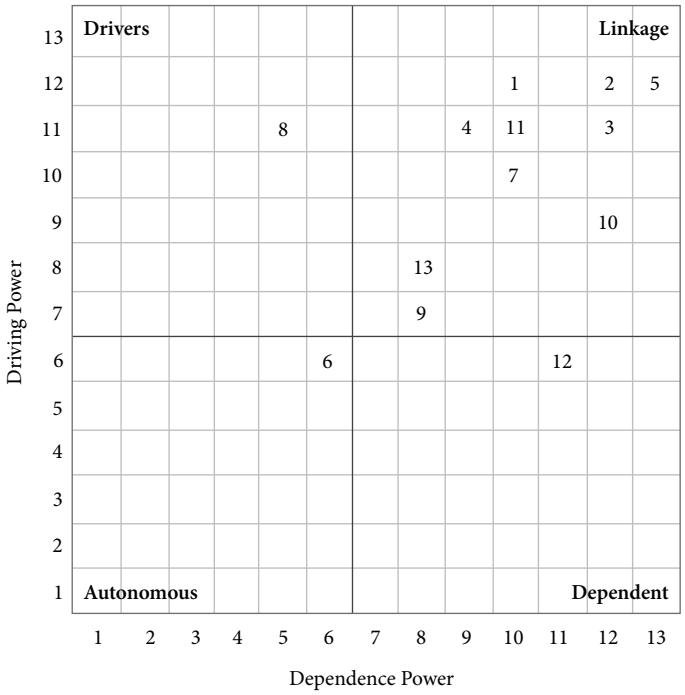


Figure 4. A MICMAC model for the UK aerospace ecosystem.

Interpretation of results of the categorisation of the key enablers that have fostered the UK aerospace ecosystem evolution

The analysis resulted in a six level ISM model, where each level represents the hierarchy of the key enablers. The bottom level, level 6, according to Table 11, is considered as the base of the model. This level is characterised for having the key enablers that trigger all the others. Thus, according to the analysis elaborated in this research, geopolitical factors, the automotive ecosystem and nonagricultural products ecosystem are considered as the key triggers for the evolution of the UK aerospace ecosystem. Evidence suggests that the UK aerospace ecosystem is tied-up to the geopolitical factors (House of Commons 2017a), driven by free trade agreements with other nations, 95% of the UK aerospace production is exported (ADS Group 2019). The UK automotive ecosystem is considered within the most important in the UK good portfolio, as this sector trades is the one that exports the most (SMMT 2019). The nonagricultural products ecosystem embraces the infrastructure and supplier base developed for other manufactured products (others apart from the automotive, chemical, machinery, pharmaceutical and medicinal, and agricultural products ecosystems).

The next level in the ISM model, level 5, includes pharmaceutical and medicinal ecosystem, considered as one of the most successful manufacturing sectors in the UK (Kitson and Michie 2014), and the development of supporting organisations between private industries, academia and the government. The next level is the chemical ecosystem. The UK chemical ecosystem is regarded as one of the most successful in the world and a key player in the supply chain of industries, such as the aerospace and automotive industry (House of Commons 2019). The fourth level includes the following key enablers: strategic alliances and of

manufacturing firms, investment in human capital development and supplier development programs. The fifth level only has privatisation of aerospace companies. Finally, the top level holds R&D public funding, the agricultural products and machinery ecosystems. According to the ISM methodology, this level contains the less influencer enablers as they do not trigger other factors.

The MICMAC methodology is also used in this research to categorise the thirteen key enablers. This methodology suggests that each enabler could be classified as autonomous, linkage, dependent or driver, depending on the level of influence to and from others. Results evidence that most of the factors fall under the linkage classification: supplier development programs, supporting organisations, investment in human capital development, geopolitical factors, R&D public funding, strategic alliances of manufacturing firms and chemical, machinery, pharmaceutical and medicinal, and nonagricultural products ecosystems. This category is characterised for having highly dependent and influent enablers as any action related to them drives an effect on them and others. The other categories embrace one key enabler each. Privatisation of aerospace companies is categorised as the most neutral factor, as is the only one with weak driving and dependence power. Agricultural products ecosystem is classified as the most dependable and less influencer factor. The automotive ecosystem is the enabler considered with the strongest driving power and weakest dependence power, as is the only one laying under driver classification.

The rationality of results on the categorisation of the key enablers, depicted in the ISM and MICMAC models, is validated using experts' judgement. Overall, results are expected to some extent, with some exceptions. For instance, one of the main findings is that the automotive ecosystem is categorised as the enabler with the strongest driving power and as part of the base for enabling all others. This finding is very much expected, as the UK automotive ecosystem is considered within the most important in the UK good portfolio, and its ecosystem, such as the supplier base, has helped the growth of the aerospace ecosystem. Another expected finding is that geopolitical factors, supporting organisations and pharmaceutical and medicinal ecosystem, are considered within the base for enabling all others, as illustrated in the ISM model (Fig. 3). Also, the categorisation of agricultural products ecosystem as the most dependable and among the fewer influencer factors is an expected result. This may be because its development depends on other factors, such as the geographical location of the country. In contrast, there are a couple of key enablers that their categorisation is not as expected. For instance, it is not expected that R&D public funding is within the least influencers, while nonagricultural products ecosystem is considered among the most influencers. Research and development public funding is expected to be among the most influencers, as the aerospace industry is highly dependent on technological developments triggered by R&D investments. One of the reasons behind this result may be because, nowadays, an important R&D investment comes from the private sector. In regards to the categorisation of most of the key enablers as linkage factors, this result is expected as it evidences a balanced ecosystem with interconnected components, which is a characteristic of a country with a developed economy.

The categorisation of key enablers for the evolution of the Mexican aerospace ecosystem

The categorisation of the key enablers for the evolution of the Mexican aerospace ecosystem is elaborated following nearly the same methodology as for the UK analysis. The only difference is the way in which experts' opinion is gathered. Here, individual meetings were held with each participant in which a description of the key factors was presented. The reason for taking the approach of individual meetings lies behind experts' availability. The group of participants consisted on four experts in the aerospace sector; all of them are Mexican nationals with more than ten years of experience in the aerospace sector and working in top-positions in recognised aerospace organisations (Table 12). A professional working as vice-president of a leading aerospace company and for the national association of aerospace industries. A researcher from the highest-ranked university in Mexico. An individual working as director of an aerospace research centre. A participant working for the government, focusing on developing policies to enhance the aerospace sector.

Table 12. Group of experts in the Mexican aerospace sector used for the ISM-MICMAC analysis.

Sector	Job title	Years of experience
Manufacturing (private sector)	Vice-president	20
Research and development (public sector)	Director	25
Research and development (public sector)	Director	10
Academia	Professor and researcher	13

As elaborated for the UK, experts' opinion is collected via SSIM (Table 13).

Table 13. Example of an SSIM for the Mexican aerospace ecosystem filled by an expert.

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1		Ø	↔	▼	▲	▲	▲	▲
Labour: low cost and highly-qualified	2			Ø	Ø	▲	Ø	▼	▼
Investment in human capital development	3				↔	↔	↔	Ø	Ø
Supporting organisations	4					↔	Ø	▲	Ø
Foreign investment	5						▼	↔	↔
Automotive ecosystem	6							Ø	↔
Agricultural products ecosystem	7								▼
Nonagricultural products ecosystem	8								

Interpretive structural modelling for the Mexican aerospace ecosystem

Finally, the ISM model for the Mexican ecosystem is generated (Fig. 5). In contrast with the UK aerospace ecosystem, the ISM model for the Mexican model resulted in a smaller model with only four levels. It is relevant to highlight that the two factors considered as the base for enabling all others, geopolitical factors (factor 1) and the automotive ecosystem (factor 6), are also part of the base of the UK ISM model.

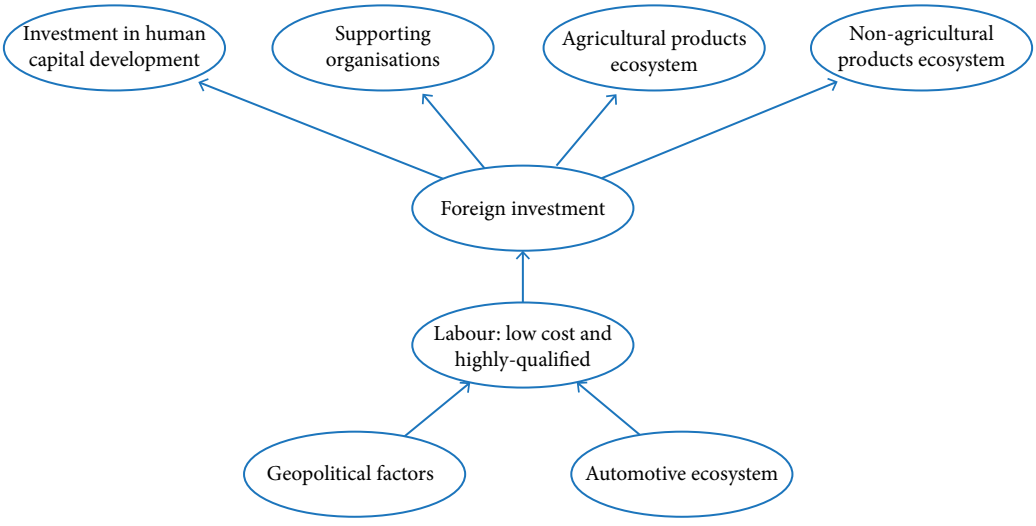


Figure 5. An interpretive structural model for the Mexican aerospace ecosystem.

A MICMAC analysis for the Mexican aerospace ecosystem

In addition to the ISM methodology, the MICMAC approach is elaborated. Here, each factor is classified as autonomous, linkage, dependent or driver. Results, presented in Fig. 6, indicate a contrasting categorisation compared to the UK MICMAC model. Results indicate that, contrary to the UK, there is no factor under the linkage category. On the other hand, the automotive ecosystem (factor 6) is categorised in a similar way: it is considered as a driver for enabling all the others. Results are further discussed.

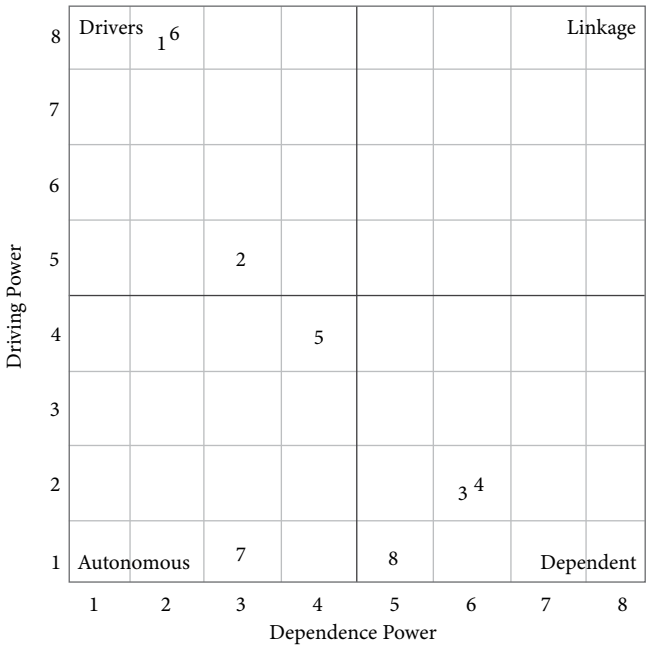


Figure 6. A MICMAC model for the Mexican aerospace ecosystem.

Interpretation of results of the categorisation of the key enablers that have fostered the Mexican aerospace ecosystem evolution

The analysis of the Mexican aerospace ecosystem resulted in an ISM model with four levels. The bottom level is considered as the base of the model, as it embraces the key enablers that foster all the others. Thus, according to the analysis elaborated in this research, geopolitical factors and the automotive ecosystem are considered as the key triggers for the evolution of the Mexican aerospace ecosystem. The next level in the ISM model, level 3, includes labour: low cost and highly-qualified. The following level holds foreign investment. Finally, the top-level embraces investment in human capital development, supporting organisations, agricultural products ecosystem and nonagricultural products ecosystem. Previous enablers are considered as the fewer influencer enablers as they do not trigger other factors.

The MICMAC methodology is also used in this research to categorise the eight key enablers of the Mexican aerospace ecosystem. Results evidence that most of the factors fall under the driver and dependent classification. Such results evidence an ecosystem characterised for having a lack of interconnected elements. In practical terms, it could reflect an imbalanced ecosystem typified by giving more strength to particular enablers, which is opposite to the findings from the developed aerospace ecosystem.

In addition, geopolitical factors, the automotive ecosystem and low cost and highly-qualified labour are considered as the enablers with the strongest driving power and weakest dependence power. It is relevant to highlight that, from previous enablers, the only one in common with the UK model is the automotive ecosystem. The previous finding reflects that the automotive ecosystem is considered as the most influential key enabler for the growth of both a developed and an emergent aerospace ecosystem.

On the other hand, investment in human capital development, supporting organisations and nonagricultural products ecosystem are the most dependent and fewer influencer factors for the growth of the Mexican aerospace ecosystem.

Finally, foreign investment and the agricultural products ecosystem are the most neutral factors for the development of the Mexican aerospace ecosystem, as they have been categorised with a weak driving and dependence power.

The rationality of results on the categorisation of the key enablers for the growth of the Mexican aerospace ecosystem, depicted in the ISM and MICMAC models, is validated using experts' judgement. Overall, results are expected to some extent. For instance,

one of the main findings is that the categorisation of the enablers suggests that geopolitical factors, the automotive ecosystem and low cost and highly-qualified labour are among the base for enabling all others and with the strongest driving power. This result is very much expected as Mexico has been historically beneficiated from having as neighbour one of the most important economies in the world, meaning the USA. Certainly, the inherent conditions of Mexico as a developing economy, in conjunction with its geographical location, have fostered the growth not only of the aerospace ecosystem but of other industrial ecosystems, such as the automotive one. Consequently, it is also expected that foreign investment is influenced by previous enablers. Indeed, foreign companies have invested by opening manufacturing facilities in Mexico aiming at being closer (and with less operational costs) to their most important market, the USA. In regards to investment in human capital development and supporting organisations enablers, experts suggest that their categorisation among the fewer influencers is rational because, although they have fostered the aerospace ecosystem progression, they haven't helped with the required extent. In particular, expert's suggestions emphasise that strengthening of supporting organisations is imperative, as such organisations should be responsible for triggering the strategies that the Mexican aerospace ecosystem needs to grow. Experts claim that the existing supporting organisations promote mainly foreign investments rather than developing long-term strategies founded on R&D progression. On the other hand, the lack of enablers under the linkage category in the Mexican ecosystem may indicate an imbalanced ecosystem, based on the achievement of individual components rather than the interdependence of its components. Experts suggest that such results are coherent as Mexico, as a developing economy, is characterised for having a high level of inequalities.

KEY FINDINGS AND DISCUSSION

In this research, the key factors that have enabled the aerospace ecosystem evolution were analysed from two different perspectives: from a developed aerospace ecosystem, the UK, and an emergent one, Mexico. The key findings are summarised next:

- A developed aerospace ecosystem, the UK, and an emergent aerospace ecosystem, Mexico, both consider similar key enablers for the evolution of their aerospace ecosystems. Most of the enablers found for the UK ecosystem were also found as enablers for the Mexican aerospace ecosystem. On the other hand, there are some differences. For instance, low cost and highly qualified labour and foreign investments are factors found in the emergent ecosystem that are not found in the advanced one. Both are inherent characteristics of a developing economy, so it is congruent that they are not considered as key enablers for a developed aerospace ecosystem with a developed economy. Moreover, pharmaceutical and medicinal ecosystem, strategic alliances of manufacturing firms, privatisation of aerospace companies, R&D public funding and the machinery ecosystem are part of the UK ecosystem that are not part of the Mexican ecosystem. Such results motivate to suggest that, although Mexico is going in the right direction, as evidenced by having similar key enablers as a developed ecosystem, Mexico perhaps is lacking critical enablers. In regards to the pharmaceutical and medicinal ecosystem in Mexico, this sector has been recently considered as an emerging one (Meraz-Rodríguez *et al.* 2019; Padilla and Suarez 2018). In regards to strategic alliances of manufacturing firms and privatisation of aerospace companies, evidence suggests that the Mexican aerospace ecosystem is at least two steps far from this achievement. This is because, as in 2019, both enablers are not applicable to the Mexican aerospace ecosystem as there is not any Mexican public aerospace company. Thus, the Mexican aerospace ecosystem possible needs to develop as a first step a public aerospace company. Successful examples that the Mexican ecosystem could follow are Embraer, the Brazilian aerospace manufacturer founded in 1969 as a public company but denationalised in 1994, and Bombardier, the Canadian public aerospace manufacturer, also founded in 1969 (Yamashita 2009).
- The automotive ecosystem and geopolitical factors have been considered by both ecosystems as the base for enabling the aerospace ecosystem evolution. In regards to the UK ecosystem, the geopolitical factors refer in particular to the trade agreements of the UK with other countries, such as the ATCA with the EU and other 20 countries, and the BASAs with the USA, Canada and Brazil. In regards to the Mexican ecosystem, Mexican geopolitical condition motivates foreign manufacturing firms to locate production facilities in Mexico and send duty-free products to the USA. Although the Mexican economy is considered as a developing one, it is positioned within the top-ten exporters

in the world thanks mostly to its geographical position and free trade agreements with the USA. Mexico is part of the NAFTA and has BASA with the USA. The automotive ecosystem is considered among the most significant industrial sectors for both countries. Evidence suggests that it is considered the most important industrial sector in Mexico (Padilla and Suarez 2018), and it represents the UK largest sector of exported goods (SMMT 2019). Such results inspire to suggest that perhaps Mexico partially has already the infrastructure required to enable its aerospace ecosystem, as the automotive ecosystem infrastructure is considered as a driving force behind the exports of industrial goods in a developed ecosystem (SMMT 2019).

- The categorisation of some of the key enablers differs among developed and emergent aerospace ecosystems. For instance, contrary to the UK aerospace ecosystem, in the Mexican ecosystem, the supporting organisations key enabler is considered among the least influence factors. Evidence suggests that the UK ecosystem has created robust supporting organisations aiming at the development of the aerospace ecosystem. Such organisations have been essential for the elaboration and implementation of enhancement policies. Moreover, another key finding falls out from the validation with experts on the Mexican aerospace ecosystem. Expert's suggestions emphasise that strengthening of supporting organisations is imperative, as such organisations should be responsible for triggering the strategies that the Mexican aerospace ecosystem needs to grow. Expert's claim that most of the existing supporting organisations have the attraction of foreign investments as their main strategy, rather than developing long-term strategies founded on R&D progression.
- Developed aerospace ecosystems denote a more balanced ecosystem than emergent ones. The previous finding is evidenced in the MICMAC analysis: while most of the factors of the developed ecosystem fall under the linkage category, there is not any factor of the emergent ecosystem under this category. The fact that most of the elements of the developed ecosystem fall under the linkage classification denote an ecosystem characterised for having higher interconnected elements. Meaning that any action of these factors has an impact on the entire ecosystem. On the other hand, the lack of enablers under the linkage category in the Mexican ecosystem may indicate an imbalanced ecosystem, which is based on the achievement of individual components rather than the interdependence of its components.

The ISM and MICMAC analysis depict more balanced models for the UK than Mexico. Previous findings could lead to the conclusion that, if a developing aerospace ecosystem wants to improve its aerospace ecosystem, perhaps needs to develop and prioritise more factors as a developed one, like the UK.

LIMITATIONS OF THE STUDY

After a literature review, it is concluded that, although there is extensive information published on the aerospace sector, there is not a unique report containing all the key enablers for the evolution of the UK or the Mexican aerospace ecosystems. Consequently, in this research, this gap is filled to some extent. In this research, a total of 13 key enablers for the development of the UK aerospace ecosystem and 8 for the Mexican one is considered. This study proposes a list of key enablers intending to contain relevant key enablers suggested by recognised organisations and experts. It is assumed that the list of key enablers proposed in this research is not fully comprehensive, but is sufficient to some extent for the elaboration of enhancement proposals.

AUTHORS' CONTRIBUTION

Conceptualization: Salonitis K, Brintrup A and Luna Andrade JJ; **Methodology:** Salonitis K; **Formal Analysis:** Luna Andrade JJ; **Writing – Original Draft:** Luna Andrade JJ; **Writing – Review and Editing:** Salonitis K, Brintrup A and Luna Andrade JJ; **Supervision:** Salonitis K and Brintrup A.

DATA AVAILABILITY STATEMENT

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