CRANFIELD UNIVERSITY

José Junior Luna Andrade

Analysis of the evolution of aerospace manufacturing ecosystems

School of Aerospace, Transport and Manufacturing

Doctor of Philosophy (PhD)
Academic Year: 2016 - 2020

Supervisor: Prof Konstantinos Salonitis
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Abstract

The aerospace manufacturing industry is predicted to continue growing. Understanding its evolution is thus essential to prepare optimal conditions to nurture its growth. This research aims to help the growth of emerging aerospace ecosystems by identifying evolution patterns and categorising key enablers that have encouraged the growth of developed ones. The term aerospace ecosystem is used to embrace all the business activities and infrastructure that are related to the entire aerospace's supply chain in a specific country.

Inspired by studies that have successfully combined economics and network science, in this research, bipartite country-product networks are developed based on trade data over 25 years. The United Kingdom (UK), the United States of America, France, Germany, Canada and Brazil's are first analysed as evidence suggests that their aerospace ecosystems are within the most developed in the world. Then, China and Mexico's networks are analysed and compared with developed ones, as these countries have evidenced emergent aerospace ecosystems. Results reveal that developed ecosystems tend to become more analogous, as countries lean towards having a revealed comparative advantage (RCA) in the same group of products. Further analysis shows that manufactured products have a stronger correlation to an aerospace ecosystem than primary products; and in particular, the automotive sector shows the highest correlation with positive aerospace sector evolution.

Key enablers related to the growth of the UK and Mexico's aerospace ecosystems are identified and categorised using interpretive structural modelling (ISM) and cross-impact matrix multiplication applied to classification (MICMAC) methodologies. Results evidence relevant differences in the categorisation of key enablers among a developed and emergent aerospace ecosystems. On the other hand, it was identified that geopolitical factors and the automotive ecosystem are underpinning enablers for both aerospace ecosystem's evolution.

The final aim is that results of this research could be implemented on emerging aerospace ecosystems by emulating the patterns and key enablers that have characterised the evolution of developed aerospace ecosystems.

Keywords:

Network science; bipartite networks; nestedness; comparative advantage; interpretive structural modelling (ISM); cross-impact matrix multiplication applied to classification (MICMAC); aerospace manufacturing; industrial ecosystem.

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Table of contents

List of figures

List of tables

List of abbreviations

AGP	Aerospace growth partnership
AHP	Analytical hierarchy process
AIRC	Aerospace Integration Research Centre
AMRC	The University of Sheffield advanced manufacturing research centre
ANP	Analytic network process
ARC	Aerospace research centre
ASAs	Air service agreements
ATCA	Agreement on trade in civil aircraft
ATI	Aerospace technology institute
BAC	British aircraft corporation
BAe	British aerospace
BASA	Bilateral safety agreements
BIS	The department for business, innovation and skills
BR	Brualdi and Sanderson
BRA	Brazil
CAN	Canada
CENTA	The national centre for aerospace technologies
CHN	China
CONACYT	The national council of science and technology
CTA	Technical centre of aeronautics
DEU	Germany
EASA	European aviation safety agency
ELECTRE	Elimination and choice expressing reality
FEMIA	Federation of the aerospace industry
FRA	France
FRM	Final reachability matrix
G1	Group 1
G2	Group 2
G3	Group 3
GDP	Gross domestic product
GP	Goal programming

HS	Harmonised system
HSA	Hawker Siddeley aviation
IATA	International air transport association
IRM	Initial reachability matrix
ISM	Interpretive structural modelling
ITA	Institute for aerospace technology
MAER	Ministry of aeronautics
MEX	Mexico
MICMAC	Cross-impact matrix multiplication applied to classification
MODM	Multiple objective decision-making
MOLP	Multiple objective linear programming
MRO	Maintenance, repair and operations
NAFTA	North American free trade agreement
NATEP	National aerospace technology exploitation programme
NODF	Nested overlap and decreasing fill
PP	Row-column proportional
PROMETHEE	Preference ranking organisation method for enrichment of evaluations
R&D	Research and design
RCA	Revealed comparative advantage
SAR	Special administrative region of China
SEM	Structural equation modelling
SEMOPS	Sequential multiple objective problems solving
SIMOLP	Simplified interactive multiple objective linear programming
SITC	Standard international trade classification
SMEs	Small and medium-sized enterprises
SSIM	Structural self-interaction matrix
STEM	Step method
SWT	Surrogate worth trade-off
T	Matrix temperature
TISM	Total interpretive structural modelling
TOPSIS	Technique for the order of preference by similarity to an ideal solution
UK	The United Kingdom

UKTPO	The UK trade policy observatory
UN	United nations
UNAQ	Aeronautical university of Querétaro
USA	The United States of America
VIKOR	Multi-criteria optimisation and compromise solution
WTO	World trade organisation

List of publications

Journal papers:

- Jose Jr. Luna A., Alexandra Brintrup, and Konstantinos Salonitis. 2020. "Analysing the Evolution of Aerospace Ecosystem Development." PLoS ONE 15 (4): 1–25. https://doi.org/10.1371/journal.pone.0231985.

Under review:

- Jose Jr. Luna A., Konstantinos Salonitis and Alexandra Brintrup. 2020. "Key enablers for the evolution of aerospace manufacturing ecosystems: the UK and Mexico analysis using ISM-MICMAC methodologies". International Journal of Production Research.

Conference papers:

- Jose Jr. Luna A., Sri Addepalli, Konstantinos Salonitis, and Harris Makatsoris. 2018. "Assessment of an Emerging Aerospace Manufacturing Cluster and Its Dependence on the Mature Global Clusters," Procedia Manufacturing, 19 (November): 26–33.

- Jose Jr. Luna A., Alexandra Brintrup, and Konstantinos Salonitis. 2018. "Monitoring the Evolution of Aerospace Ecosystems by Applying Network Science." In International Conference on Operations and Supply Chain Management. Cranfield University, United Kingdom.

Chapter 1 - Introduction

1.1 The aerospace ecosystem landscape

The aerospace ecosystem is growing. In 2018, results from all commercial airlines worldwide, published by the International Air Transport Association (IATA) exhibited that the passenger traffic grew by 7.4%. The increase is still dominated by North America and Europe (12.8%), followed by the Asia-Pacific region (9.5%), Latin America (7%), Africa (6.1%) and Middle East (5%) (IATA, 2019). Over the next twenty years, passenger traffic figures are projected to double up. In 2015, the estimation is that a fleet of around 26,000 aeroplanes was in service (IATA, 2016a). By 2034, the forecast is that this number will grow to reach more than 37,500 aeroplanes (Leahy, 2014; Cone, 2016; IATA, 2016b).

The aerospace ecosystem is evolving. In the following years, the aerospace industry is predicted for a reconfiguration (IATA, 2017). The most substantial market demand is expected to swing to the Asia-Pacific region, overtaking America and Europe's position (Boeing, 2017; IATA, 2018; Lineberger and Hussain, 2018).

A few key players share most of the aerospace manufacturing revenues worldwide. The market share of aerospace and defence companies based on 2018's revenues is presented in Figure 1. In that year, 20 companies held around 75% of the revenues from the civil and defence market (PwC, 2019b). Boeing and Airbus remained with the largest share by holding together 23% of the total (PwC, 2019b). Mostly, revenues were absorbed by the North America and Europe region. North America, predominantly the USA, possessed more than 50% of the market share (IATA, 2019). Europe embraced around one-quarter of the market, with the UK, France and Germany as the key players (Lineberger, 2019).

The aircraft market is also dominated by a small number of key players. The large aircraft[1] market is dominated by Boeing and Airbus (Rhodes, Hough and Ward, 2017). Nowadays, these are the only companies worldwide capable of designing, producing and selling commercial single and twin-aisle aircraft. In contrast, the small aircraft[1] market is more segmented. In addition to Boeing and Airbus, more companies like Bombardier, Embraer, Comac, Irkut Corporation and Mitsubishi Aircraft Corporation are part of the largest manufacturers' portfolio (House of Commons on Exiting the European Union Committee, 2017a; Lineberger and Hussain, 2018).

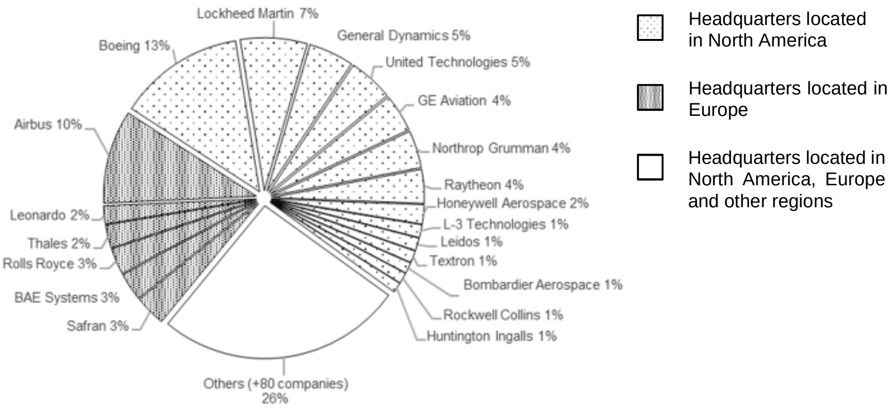


Figure 1. Market share of aerospace and defence companies based on 2018's revenues

Concerning the defence sector, it is driven mainly by geopolitical factors and the budget that each country's government assigns. The USA is by far the country that spends the most on this sector — followed by countries like China, Russia, Saudi Arabia, France, the UK, India, Germany, Japan and South Korea (Captain, Hussain and Hanley, 2017; Lineberger, 2019).

[1] The Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) define a large aircraft as any aircraft with at least 12,500 pounds of take-off weight. Small aircrafts are those with less than 12,500 pounds of take-off weight.

The aerospace manufacturing supply chain is highly globalised. Components are manufactured and assembled in different locations worldwide. For instance, the production of all the components required for the Boeing 787 is distributed within more than 300 companies, with production over 5,000 facilities around the world (Turkina, Assche and Kali, 2016). Figure 2, adapted from (Luna *et al.*, 2018) with data from (Koster, Uhmeyer and Soin, 2013), depicts the supply chain structure of Boeing 787. The final assembly takes place in the USA, either in the Boeing Everett Factory, Washington, or Boeing South Carolina; it assembles structures, coming from other Boeing's manufacturing facilities and systems coming from tier 1 suppliers. According to the position in the market, the main mature aerospace manufacturing clusters are located in USA, Canada, Brazil, France, Germany, the United Kingdom, Spain and Japan. The main emerging aerospace clusters are located in Mexico, China, India, Malaysia, UAE and Singapore (Stewart, 2015; Paone and Sasanelli, 2016; Turkina, Assche and Kali, 2016; Luna *et al.*, 2018; PwC, 2019a).

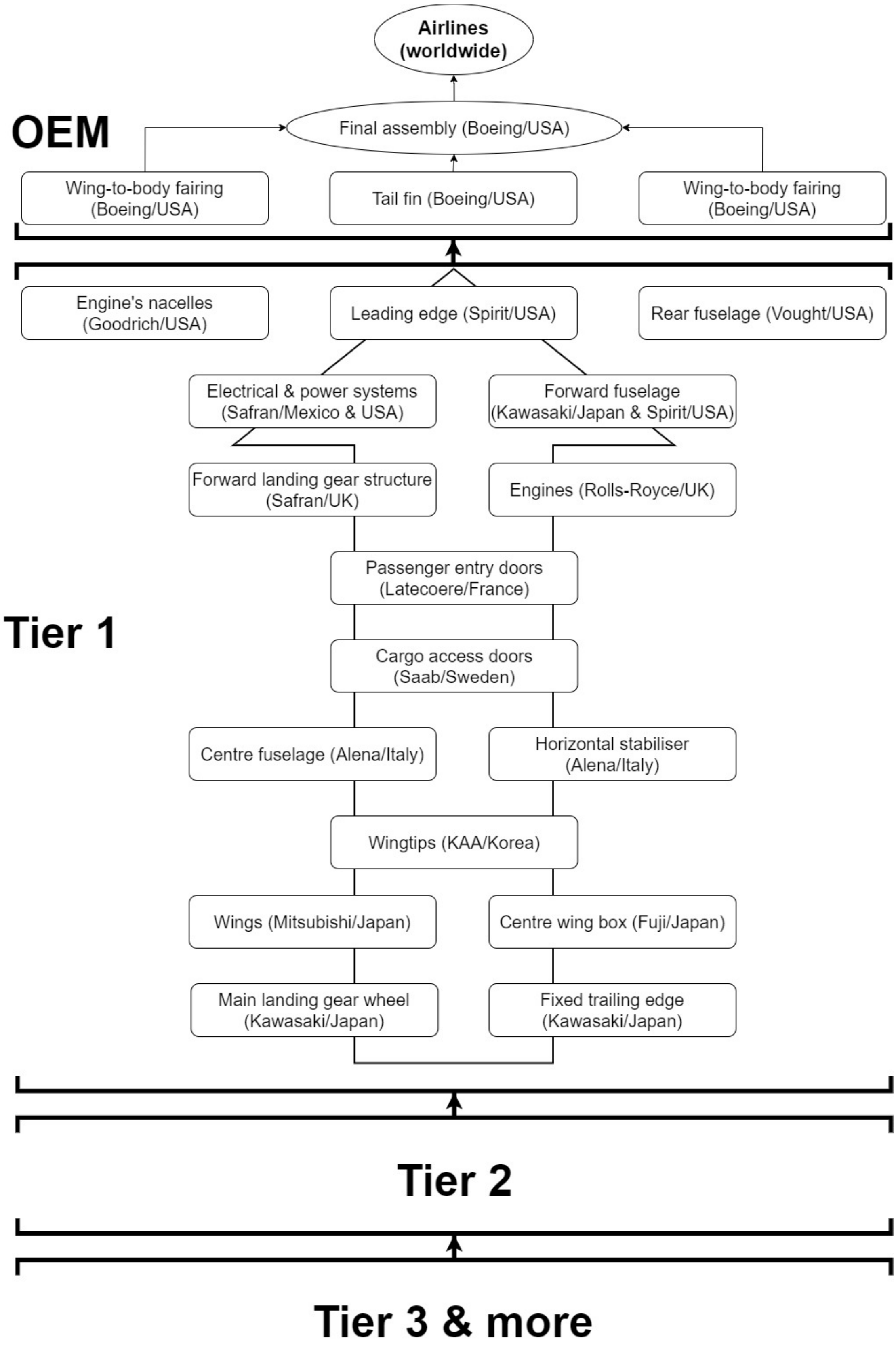


Figure 2. Supply chain structure for the production of the Boeing 787

1.2 Ecosystem approach

Scientists have analysed and tried to explain the behaviour of industrial systems by applying an ecosystem approach, analogously from biological systems. The term *ecosystem* has been applied in different contexts since its first appearance. It was first introduced in 1935 by a British ecologist named A.G. Tansley, where he defined an ecosystem as a biological system located in a particular physical environment integrated by interactive and interdependent organisms (Tansley, 1935). Many years later, in 1993, James F. Moore, an American business strategist, adopted for the first time this biological approach to business theory by introducing the concept of a business ecosystem. Moore defined a *business ecosystem* as a sustainable economic community integrated by evolving and adapting self-organised organisations and individuals that interact with each other to survive (Moore, 1993).

In this research, the term *ecosystem* is used to take a holistic approach by embracing all the business activities and their supply networks that coexist in a specific country. The term *aerospace ecosystem* is used to consider all the businesses in a country, and the required infrastructure, that is part of the entire aerospace supply chain – such as manufacturing, maintenance, repair and operations (MRO), research and design (R&D), supporting organisations, etc. The term *aerospace manufacturing ecosystems* is used to embrace all the industries that coexist in a country and that are particularly dedicated to the manufacture of aerospace's related parts and equipment.

For the classification of *developed* and *emergent* aerospace ecosystems, a widely used metric called *revealed comparative advantage (RCA)* is taken as a reference. This metric is based on comparing the exports of a specific country with the exports of the rest of the world in a particular product and the entire portfolio (French, 2017). A value of RCA>1 means that the country has developed a comparative advantage on exporting the product. In this research, the term *developed ecosystems* is used to denote those ecosystems with an RCA>1 on a particular product. The term *emergent* is used for those ecosystems with an RCA<1 and that have evidenced improvement or intentions to improve.

1.3 Challenges in the global aerospace ecosystem and research programme questions

Contrary to the increasing market demand, the aerospace manufacturing ecosystem has not been able to react as needed. Evidence suggests that one of the main challenges for the global aerospace ecosystem is the insufficient production capacity and production rates required to fulfil the rise in demand (Lineberger, 2019).

During the last years, aerospace manufacturers have experienced an increasing number of customer orders' backlogs (Gale, 2014; Leahy, 2014; Anselmo, 2015; Boeing, 2015; Bombardier, 2015; Hollinger, 2015; Powley, 2015; Weber, 2016). By 2004, the commercial aeroplane backlog consisted of about 2,500 aeroplanes from two prime manufacturers, with 49 major customers, representing more than four years of production. By 2015, the commercial aeroplane backlog raised to more than 13,000 aeroplanes from 5 prime manufacturers, with more than 200 major customers, representing more than nine years of backlog (Deloitte Touche Tohmatsu Limited, 2016). In 2018, aeroplane manufacturers reported a record high commercial aeroplane backlog of more than 14,000 units (Lineberger, 2019).

Market demand is pushing manufacturers to adopt new manufacturing practices to enhance their manufacturing capabilities (Lineberger, 2019). For instance, Boeing announced in 2014, that in response to strong commercial aeroplane demand from customers worldwide and the need to replace older aeroplanes, they needed to increase the 737 production rate from 42 to 52 aeroplanes per month by 2018 (Tischler, 2014). Improved efficiencies achieved through manufacturing innovation are helping Boeing to raise its production rates (Trefis, 2013). Likewise, Airbus planned to raise A320 production rates from 42 aeroplanes a month to 50 units, also by 2018 (Weber, 2016). To achieve this, Airbus implemented a new production organisation in 2013 to manage the industrial activities required to meet continued strong demand, while also achieving higher performance levels across the company's series and development programmes (Airbus, 2016). Besides, Airbus also created a new

Operational Excellence Centre of Competence to define and deploy Airbus' industrial strategy, to support their long-term "Vision 2020" and to ensure "best-in-class" industrial standards for the company (Airbus, 2016).

Another challenge that the aerospace manufacturing companies are facing is the introduction of new players to the aerospace manufacturing ecosystem, like emergent clusters in low-cost countries, such as Mexico (Flores, Villarreal and Flores, 2016; McGuire, 2017; Luna *et al.*, 2018). These new entrants are conditioning the current aerospace manufacturers and leading a reconfiguration of the aerospace ecosystem (Martínez-Romero, 2013; Tischler, 2014; Powley, 2015). For instance, aerospace companies are following internationalisation strategies of their manufacturing plants in new clusters, helping with this the emerging of new aerospace clusters. Within the main reasons behind the creation of new aerospace manufacturing ecosystems are the potential low labour and operating costs, an increase of production capacity, an expansion of their market access, and an increase in market share, as it helps to meet industrial offset obligations derived from political reasons. It is relevant to remember that as the aerospace industry is not mass production, the transportation cost is not considered as an impediment for its internationalisation (Bédier, Vancauwenberghe and Van Sintern, 2008; AeroStrategy, 2009; Martínez-Romero, 2013).

As in June 2020, the world is facing an unprecedented public health emergency caused by the virus COVID-19. The virus, which started to spread in an uncontrollable way around the world at the beginning of 2020, has affected all types of industrial ecosystems. In the short term, the impact on the aerospace ecosystem has already caused consequences that will take years to solve. Abrupt reduction on passenger travels decreased production rates caused by reduced demand, and deferred customers deliveries are among the main 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 IATA forecasts for 2020 a drop in global airline passenger revenues by around 55% (equivalent to more than $300 billion), compared to 2019 (IATA, 2020). The mid and long-term consequences are still unmeasurable. According to (Lineberger, 2020), the 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 (Lineberger, 2020).

To sum up, evidence suggests that there are three main challenges that the global aerospace ecosystem is facing:

- Market trends (forecast increase and shifting towards Asia-Pacific region, unknown long-term effects on demand due to COVID-19 pandemic)
- Insufficient manufacturing capacity (evidenced by all-time high backlogs and potential increased production challenges)
- Development of new aerospace manufacturing ecosystems (like China and Mexico)

Previous challenges motivate this research to raise the following research questions:

- Which countries have developed the most prominent ecosystems on exporting aerospace products over the last years?
- What patterns have characterised the evolution?
- Which other industries have nourished the growth of aerospace ecosystems?
- Which key enablers have promoted the evolution of aerospace ecosystems?

The challenges and the research questions described in this section guided to the definition of the aim and objectives of this research. In the next sections, further discussion is presented.

1.4 Aim and objectives

The challenges that the aerospace ecosystem is facing are leading to a reconfiguration. During the last decades, a number of aerospace ecosystems have emerged aiming at coping with the forecast and production requirements. The emergence of new aerospace ecosystems has been driven mainly by enhancement strategies developed by the public sector of each country. However, most of the implemented strategies are characterised for not having scientific foundations. Moreover, the literature review elaborated as part of this research programme evidenced a lack of reports that have analysed in detail what other ecosystems have done for the enhancement of their aerospace ecosystems.

The aim of this research is elaborated based on the idea that enhancement strategies should be founded on a proven point of reference. Thus, this research aims at the identification to some extent of the point of reference against which emergent ecosystems should base their enhancement strategies. Such point of reference is expected to be found by analysing the evolution of developed ecosystems. Understanding the evolution of developed aerospace ecosystems is thus essential to prepare optimal conditions to nurture the growth of new aerospace ecosystems.

Therefore, **this research programme aims to help the growth of emerging aerospace ecosystems by identifying evolution patterns and categorising key enablers that have encouraged the growth of developed ones.**

The following objectives are required to achieve the aim and to answer the research questions of the research programme:

1) Identification of patterns that have characterised the evolution of aerospace ecosystems.
2) Identification of other industries that have nourished the growth of aerospace ecosystems.

3) Identification and categorisation of key enablers that have fostered the improvement of aerospace ecosystems.

At the end of the research, a number of suggestions are elaborated. The ultimate goal of this research is that such suggestions can be used by any country as the foundation for the emergence and development of their aerospace ecosystems.

The next section includes a description of the process to achieve the defined aim and objectives.

1.5 Thesis structure

The process to achieve the aim and objectives of this research programme are depicted in Figure 3. The research is divided into two main phases: the first one is a quantitative analysis to achieve objectives 1 and 2, and the second one is a qualitative analysis to reach objective 3. As part of the qualitative analysis, exports data from 1992 to 2016 is collected. Then, a computation of the RCA of aerospace products is elaborated for the identification of the countries that have developed the most prominent ecosystems. From the previous analysis, groups of countries of developed and emergent aerospace ecosystems are selected. Subsequently, also using the exports data, bipartite country-products networks for the chosen countries are developed. Then, network science is used for the identification of evolution patterns and other industries that have nourished the growth of aerospace ecosystems. As part of the qualitative analysis, the key enablers are identified and then categorised using ISM and MICMAC methods.

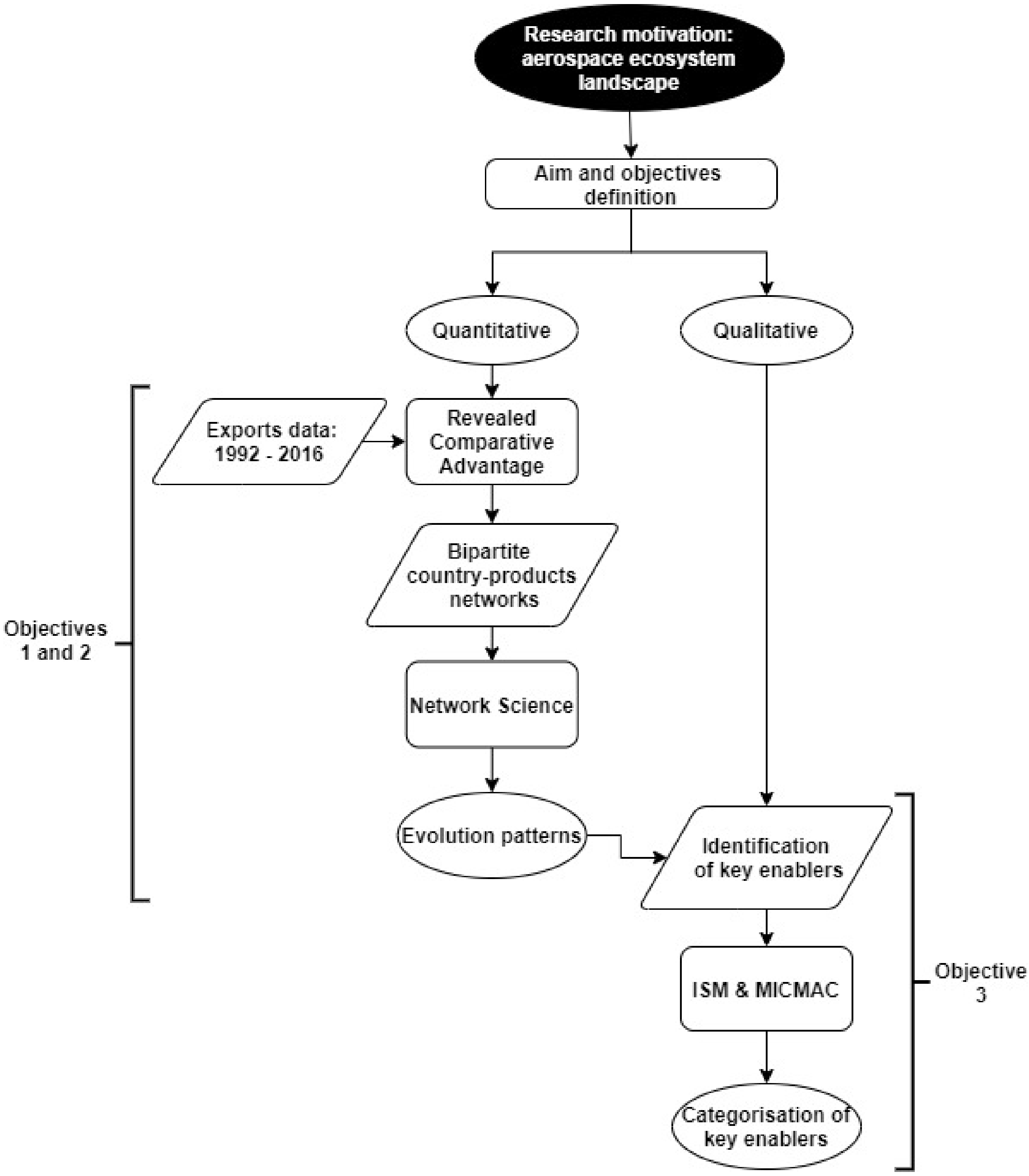


Figure 3. The process to reach the aim and objectives of the research programme

The research presented in this thesis is organised as follows:

- Chapter 1: this chapter includes research motivation, the aim and objectives of the research.
- Chapter 2: in this chapter, a literature review is divided into three parts. In the first part, the available methods for analysing industrial ecosystems

are presented. Then, a detailed review of the applications of network science in scientific studies is included. In the second part, a literature review of methods for categorising key enablers is presented. Here, a detailed review of ISM and MICMAC methods is also depicted. Finally, in the third part, the key enablers that have fostered the evolution of the UK and Mexico's aerospace ecosystem are described.

– Chapter 3: this chapter contains a description of the research methodology followed among all the research programme presented in this thesis. The philosophical positions are also introduced here.
– Chapter 4: in this part of the thesis, the first two objectives are covered from the developed aerospace ecosystems perspective: the UK, the USA, France, Germany, Canada and Brazil's aerospace ecosystems. The quantitative analysis using network science is described. Here, a detailed description of the process to elaborate and analyse the bipartite country-products networks is included.
– Chapter 5: in this part of the thesis, the last objective is covered from the developed aerospace ecosystems perspective: the UK. The process for the categorisation of the key enablers using ISM and MICMAC methods is described, and results are discussed.
– Chapter 6: in this chapter, a case example of emergent aerospace ecosystems is presented: China and Mexico. A quantitative and qualitative analysis similar to the developed ecosystems is elaborated.
– Chapter 7: the last chapter summarises the significant findings to help emergent manufacturing aerospace ecosystems to grow and develop, based on the patterns and key enablers that have characterised the evolution of developed aerospace ecosystems

Chapter 2 - Literature review

The aim of the literature review presented in this chapter is the identification of the most suitable methods needed for addressing the aim and objectives of this research.

The literature review is presented in three main topics:

- The available methods for analysing industrial ecosystems
- The available methods for categorisation of key enablers
- The key enablers for the growth of the UK and Mexico's aerospace ecosystem.

According to (Booth, Sutton and Papaioannou, 2012), the study of the existent literature during a research journey can be categorised based on the *SALSA* (search, appraisal, synthesis and analysis) framework. *SALSA* framework categorises the types of literature reviews depending on the methods used alongside the search, appraisal, synthesis and analysis (see *Table 1 Main review types characterized by methods used,* pages 94 and 95, (Grant and Booth, 2009)). Based on this classification, the type of review in this research is a structured *literature review*. A structured *literature review* is appropriate for the aim of this research as it applies systematic approaches for the examination of recent or current literature (Booth, Sutton and Papaioannou, 2012).

The *search* of the literature is conducted mainly across *google scholar* database. This database is selected as recent studies have categorised this database as one of the most complete currently existing. A study developed by (Khabsa and Giles, 2014) reveals that *google scholar* database contains nearly 90% of the academic literature available on the web; (Martín-Martín *et al.*, 2018) elaborated a systematic comparison between *google scholar, web of science and Scopus* using citations in more than 250 different subjects, concluding that *google scholar* has the most coverage and consider this as a superset of the two other databases.

The literature's *appraisal* is focused on evaluating the internal validity, reliability and applicability (Booth, Sutton and Papaioannou, 2012), intended to reduce the selection bias. The period covered during the search process is limited to the past 25 years.

The literature's *synthesis* and *analysis* are presented using a *narrative* approach. One advantage of this approach is that it can be used to accommodate different type of studies in multiple grouping, to compare individual studies and to identify patterns amongst comprised studies (Booth, Sutton and Papaioannou, 2012).

In the following chapters, the *synthesis* and *analysis* of the existent literature on methods for analysing industrial ecosystems and categorisation of key enablers are presented in a *narrative* form.

2.1 Methods for analysing industrial ecosystems

The literature review presented in this section intends to find the available methods and identify the newest research trends for analysing industrial ecosystems.

In the literature, there are many available techniques and methods for ecosystems' analysis. A systematic literature review, elaborated by (Oliveira, Lima and Montevechi, 2016), includes a summary and comparison of the most popular techniques used for supply network analyses. This research, which results are summarised in Figure 4, included 14 databases (such as Emerald Insight, Sage Crossref, Scopus, IEEE Xplore, ScienceDirect, Springer Link, Web of Science, and Wiley Online Library), the keywords "Supply Chain" and "Simulation", and a time frame from 1992 to 2014.

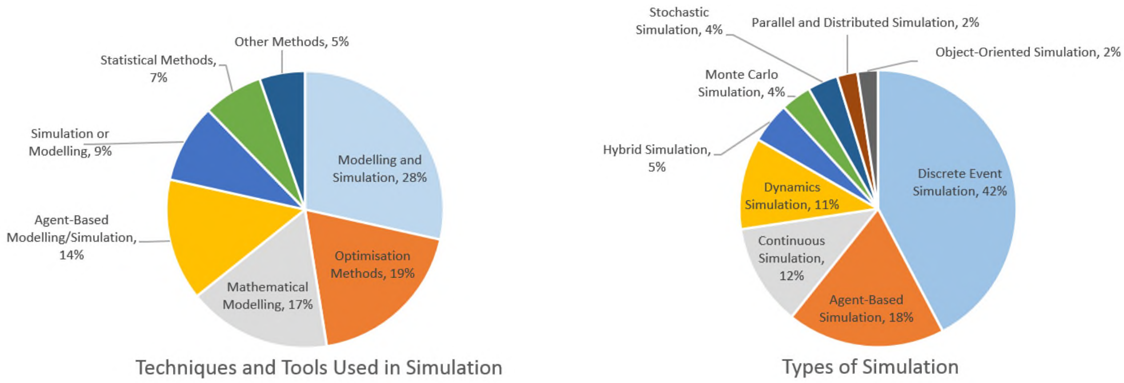


Figure 4. Techniques, tools and types of simulation for ecosystems analysis

As shown in Figure 4, a combination of modelling and simulation techniques is one of the most popular options with 28%. This assumes that the modelling is performed first, and then the use of a simulation model to evaluate diverse scenarios. The second category most used is the application of Optimisation Methods (19%). These methods include mainly *particle swarm, multi-objective programming, mixed integer programming, genetic algorithms, simulated annealing, neural networks, and data envelopment analysis*. Another important outcome of the systematic literature review performed by Oliveira et al. (2016) is the main computational tools, which are: *Arena, Matlab, Java, iThink, Anylogic, C++, Extendsim, Promodel, Simprocess and MS Excel*.

In regards to the types of simulation, *Discrete Event simulation* appears to be the most preferred, followed by *Agent-Based Simulation*, *continuous simulation* and *dynamics simulation*. Table 1 includes a brief definition of the main types of modelling and simulation techniques and their main applications.

Table 1. Types of simulation and main applications used for ecosystems analysis

Type of simulation	Main application
Discrete Event Simulation (DES): is used to analyse a system through the interaction of individually separated events that occur at a particular time, not continuously. When the supply chain is relatively complex, the literature suggests that DES has several limitations (Carson II, 2004; Oliveira, Lima and Montevechi, 2016)	Production and transportation processes (Sun *et al.*, 2016).
Agent-Based Modelling (ABM)/Simulation: is mainly applied to analyse complex systems by using individual or collective autonomous entities, called agents, which dynamically interact with each other following defined rules (Batool and Niazi, 2017).	Optimisation and reconfiguration (Batool and Niazi, 2017)
System Dynamics: is a simulation used to analyse discrete or continuous time-variable interactions of objects in complex systems, using casual loop diagrams. (MIT, 1997; Ossimitz and Mrotzek, 2008; Campuzano and Mula, 2011; Ramírez *et al.*, 2016). The main objective is to understand the structural variables that activate the performance of a complex system (Campuzano and Mula, 2011).	Planning strategies for resources; capacity increase analysis; flexibility in a multi-tier in a supply network; Inventory trends; Cost-reduction (Ramírez *et al.*, 2016)
Stochastic Simulation: is a type of simulation that uses random numbers, according to a given probabilistic pattern for each variable, to investigate a wide range of uncertain situations. It is mainly used to experiment with the potential outputs generated by changes in a system (Chelst and Canbolat, 2011). This type of simulation can be used as part of DES or ABM.	Reliability. Six Sigma applications. To provide the probability of various failure events (Raychaudhuri, 2008; Oliveira, Lima and Montevechi, 2016).
Monte Carlo Simulation: also called 'what-if' analysis, is a mathematical technique that uses repeated random sampling for evaluating uncertain scenarios and providing probabilistic analysis of different situations. It is used to investigate all the potential outputs associated with input variables (Raychaudhuri, 2008). This type of simulation can be used as part of DES or ABM.	Reliability. Six Sigma applications. To provide the probability of various failure events (Raychaudhuri, 2008; Oliveira, Lima and Montevechi, 2016).
Network Science: this methodology uses network science to approach an ecosystem as connected individual components interacting within them, by following local rules without central control (Mitchell, 2006; Brintrup, Wang and Tiwari, 2017).	Mainly used to analyse the topology and structure of different types of networks. (Newman, 2010)

After evaluating the available methods presented in Table 1, it is concluded that *ABM* and *Network science* are suitable for the aim of this research. Both methodologies are mainly used to analyse complex systems and potential reconfigurations. ABM is more suitable when the system under analysis comprises dynamically interacting components (agents) following predefined rules. On the other hand, network science is more preferred for analysing the structure of systems containing static components - it has gained interest among scientists as it is a powerful approach for representing and analysing industrial ecosystems (Borgatti and Li, 2009; Newman, 2010; Holme and Saramäki, 2012; Brandes *et al.*, 2013; Mariani *et al.*, 2019). In addition, network science has been successfully applied to develop economic theories and predict evolution, based on the identification of patterns in the evolution of country-products networks. Thus, network science is selected as the methodology for this research. The next chapter presents a *literature review* of network science.

2.1.1 Network science

Many objects and systems from different nature (such as physical, biological or social sciences) can be represented by *networks*. A *network* can be simply defined as a collection of points (nodes or vertices) connected together by lines (edges). The study of the pattern of connections between the components of a system has given scientists the ability to understand how the corresponding systems work (Newman, 2010). To this aim, scientists have developed a wide variety of tools to understand networks' structure and to simulate potential reconfigurations. Such tools and methods have driven the emergence of a science, called *network science*.

Network Science is defined as the "the study of the collection, management, analysis, interpretation and presentation of relational data" (Brandes *et al.*, 2013). The beginning of the XXI century has ignited the application of network science as a powerful approach for representing and analysing industrial ecosystems (Borgatti and Li, 2009; Newman, 2010; Holme and Saramäki, 2012; Brandes *et al.*, 2013; Mariani *et al.*, 2019). Some studies have successfully applied network science to develop economic theories and predict evolution, based on analysing the pattern of connections between country-products networks. One of the first attempts was in the XIX century, when (Ricardo, 1817) claimed for the first time that countries benefitted mainly by specialising on products on which they have demonstrated a comparative advantage. More recently, (Imbs and Wacziarg, 2003) claimed that developing countries tend to have high product diversification, while developed countries tend to specialise in niche products. However, a few years later, (Hidalgo *et al.*, 2007; Hidalgo and Hausmann, 2009; Tacchella *et al.*, 2012) used historical international trade data to predict countries' product diversification, and reported that developed countries are highly diversified and have numerous amount of products with an RCA>1. They also highlighted that developing economies have historically developed a comparative advantage only on products that are also exported by countries with high product diversification. (Caldarelli *et al.*, 2012; Tacchella *et al.*, 2012) introduced an alternative methodology to Hidalgo and Haussmann for analysing countries' export flows and product diversification. Based on biased Markov chains, they ranked countries in a conceptually consistent approach and revealed a non-linear interaction among the catalogue diversification and the universality of products of a country. More recently, Hartmann et al. (2017) used multivariate regression analysis on the country-products networks to demonstrate that levels of income equality in a country are related to the complexity of their exported products.

Along the same line, there is a subset of studies that have used network science for a particular business ecosystem. For instance, (Saavedra, Reed-Tsochas and Uzzi, 2008) used trade data of the garment industry to analyse its disassembly process and to test a model of declining networks. (Kito *et al.*, 2014) used a database of around 40,000 firms of the automotive industry to analyse the topology of Toyota's supply chain. They claim that the tier structure of Toyota's supply chain creates a complexly woven network, rather than a pyramidal structure as previously theorised. (Brintrup, Ledwoch and Barros, 2015) proposed a framework to analyse the topological robustness of manufacturing industry and validated it using a dataset from the automotive industry. They evidenced that network science can be applied to study structural interdependencies of large-scale data. (Sun *et al.*, 2016) combined agent-based model, discrete event modelling and network science to simulate the evolution of the consumption-driving supply chain system of the automotive industry in China. (Brintrup, Wang and Tiwari, 2017) analysed the structure of the aerospace industry using Airbus' supply chain consisting of 544 companies with more than 1,600 interactions between them. Here, authors demonstrated that the large-scale dataset analysed is a supply network formed by communities connected by interconnected hub firms. They also evidenced that network science can be applied to identify crucial firms within a network, and that is useful mainly to propagating information. (Guffarth and Barber, 2014) analysed the network evolution of the European aerospace ecosystem using data from the European Framework Programmes and on Airbus suppliers. They investigated the spatial structure of the European aerospace R&D collaboration network, the topological structure, the individual elements of the network and an evaluation of the Airbus's invention and production networks. Among their findings is that these type of networks are formed by well-connected hubs, and that the regional hub structure is emulated in topology of the European aerospace R&D collaboration network. Also, they claim that only successful firms are the ones capable to form a vast amount of ties. (Turkina, Assche and Kali, 2016) also analysed the evolution of the aerospace ecosystem by using a dataset consisting of firm linkages within 52 aerospace clusters in North America and Europe. To analyse the evolution and dynamics of the topological structure, they divided the dataset into three periods: 2002-2005, 2006-2009 and 2010-2014. They evidenced that the topology of networks have evolved across the different periods, and that clusters have increasingly specialised in value chain stages over time.

In tandem, motivated by studies in ecology, scientists have analysed nestedness patterns in networks across a variety of fields. The concept of nestedness originated in ecology and was introduced to describe patterns in two types of *bipartite*[2] *networks*: mutualistic interaction patterns between species-species networks, and distribution patterns across species-habitat networks. Mutualistic

[2] A bipartite network is characterised for being partitioned into two classes without ties within classes (Borgatti and LI, 2009).

interaction patterns are found in networks where two different species interact and beneficiate reciprocally. The interaction between insects and plants, when insects feed and pollinate from plants at the same time, are examples of mutualistic networks (Bascompte *et al.*, 2003; Jordano, Bascompte and Olesen, 2006). The pattern found within these networks is that most common interactions occur between generalist insects and plants, and between specialists with generalists, but not between specialists with specialists. Here, generalist insects refer to those feeding on multiple plants and generalist plants to those having many pollinators/feeders, while specialists are insects feeding on a small number of plants and plants having few pollinators/feeders. The second type of networks was individually conceived in biogeography by (Hultén, 1937; Darlington, 1957; Daubenmire, 1975) to describe distribution patterns of species across isolated habitats. Examples include the distribution of species within islands. Here, the distribution pattern found is that generalist islands congregate a vast number of species, while specialist islands host proper subsets of species existing in generalist islands. The pattern also suggests that rare species are most likely to exist in generalist islands rather than in specialist ones.

After being unveiled in ecology, nestedness patterns have been discovered across networks of different nature. For instance, patterns found in inter-organisational networks. (Saavedra, Reed-Tsochas and Uzzi, 2009) developed a model to reproduce the structure of manufacturer-contractor interactions, in which they found that these type of networks depict a similar pattern than the mutualistic interaction patterns between species-species networks. Nestedness patterns have also been found in supply chain networks by (Brintrup *et al.*, 2012). Here, authors analysed a large dataset of the automotive industry, particularly from the Toyota Motor Company and the Ford Motor Group, to demonstrate that supply networks of this industry depict nestedness patterns. They showed that generalist companies are the only ones producing specialist products and that specialists companies compete practically utterly in the generalist products market. Another study of nestedness patterns in supply chains is presented in (Brintrup, Barros and Tiwari, 2018). Here, they analysed the supplier-product distribution and supplier-manufacturer relations in the global automotive industry.

They claim that specialist suppliers produce proper subsets of what generalist suppliers produce and that specialist products are only produced by generalist suppliers. Also, they found that specialist manufacturers procure from generalist suppliers, and specialist suppliers typically supply to generalist manufacturers.

Another type of networks in which nestedness patterns have been found is in trade networks. For instance, (Bustos *et al.*, 2012) developed country-products networks using trade data from 1985 to 2009, connecting 114 countries to 772 different products. Here, they developed a model to predict the evolution of business ecosystems by analysing the dynamics of nestedness, positing that nestedness arises when an industrial ecosystem has a core set of interactions attached to the rest of the community. (Tacchella *et al.*, 2012) used trading data of around 200 countries and 1200 products to introduce a new metric to assess the competitiveness of a country and the complexity of its product portfolio. (König, Tessone and Zenou, 2014) developed a dynamic network formation model to examine the topological structure and nestedness in real-world networks. They empirically tested their model using two different types of networks, the banking network and trade network between countries. (Saracco *et al.*, 2016) analysed the evolution of country-products networks, using trade data from 1995 to 2010, aiming at the identification of early symptoms of the 2007-2008 financial crisis. They evidenced that the structure of the network started to experience significant changes since 2003, and suggested that the most critical early signs are found in the macro-sectors evaluated on developing countries. More recently, (Alves *et al.*, 2019) developed multi-layer networks also using international trade to reveal variations of country-based and transaction-based nestedness over time. Here, the authors argued that multi-layer networks could better depict the economic interactions involved in the worldwide production network and global value chain.

Although the analysis of networks using network science approach has been growing in the last years, it could be alleged that this approach is still in its infancy compared to other fields (Brintrup and Ledwoch, 2018). Moreover, while most studies that use economics and network science-based methodologies have thus far focussed on the macro-economic space, few studies have combined and applied such methodologies to understand the evolution of particular ecosystems. In this research, this gap will be approached to some extent by developing an analytical approach for a particular industry, namely the aerospace ecosystem.

2.2 Methods for categorisation of key enablers

This section aims at the identification of the available tools for the *categorisation of key enablers.*

In the literature, the discipline of *multiple criteria decision-making (MCDM)* has developed a vast range of methodologies for categorising preferences and for calculating the relative weights of the criteria available (Tzeng and Huang, 2011). Hwang and Yoon (1981) proposed a categorisation of MCDM methodologies depending on the phase, the aim and the data availability of the problem intended to solve. They proposed the following two categories:

- *Multiple objective decision-making (MODM)* methods are appropriate during the planning phase, aiming at the identification of the optimal solution (from conflicting potential solutions) obtained by multiple interactions of the specified limitations. These kinds of problems are typically solved using computer-aided programming. Examples of available methods are L-P metric methods, utility function, bounded objectives, goal programming (GP), goal attainment, multiple objective linear programming (MOLP), multiple criteria simplex, Geoffrion, simplified interactive multiple objective linear programming (SIMOLP), Zionts, step method (STEM), surrogate worth trade-off (SWT), sequential multiple objective problem solving (SEMOPS), satisfactory goals and game-theoretic technique (Sadjadi, Habibian and Khaledi, 2008).
- *Multiple attribute decision-making (MADM)* methods are particularly appropriate during the evaluation phase, aiming at the categorisation of the available alternatives and defined preferences. Available methods to solve these problems include analytical hierarchy process (AHP), analytic network

process (ANP), simple additive weighting method, technique for order of preference by similarity to ideal solution (TOPSIS), multi-criteria optimisation and compromise solution (VIKOR), elimination and choice expressing reality (ELECTRE), preference ranking organisation method for enrichment of evaluations (PROMETHEE), Gray relation model, fuzzy integral technique, the interpretive structural modelling (ISM) method and the ‘cross-impact matrix multiplication applied to classification (MICMAC). A complete description and application examples of each method is out of the scope of this research. A full review can be found in (Yoon and Hwang, 1995) and (Tzeng and Huang, 2011).

As part of the aim of this research is the identification and categorisation of the key enablers for the evolution of aerospace ecosystems, the type of problem is under the evaluation phase rather than in the planning phase. Thus, a MADM method is selected.

After scrutinising the available options within the MADM methods, a combination of ISM and MICMAC is chosen because both methodologies are well established and widely applied approaches for the identification of relationships and categorisation of key factors, to subsequently portray them via a structural model. A literature review of both methodologies is presented next.

2.2.1 ISM – MICMAC

The ISM, proposed by (Warfield, 1974), is a methodology based on discrete mathematics and graph theory that is 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 is 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 *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, Shankar and Suhaib, 2008).

ISM 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) combine 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 continuous improvement initiatives in small and medium enterprises in the United Arab Emirates.

ISM and MICMAC have also been used together for performance evaluation subjects: (Pathak, Thakur and Rahman, 2019) propose a framework to evaluate freight transportation's sustainability performance. Here, authors combine Total Interpretive Structural Modelling (TISM), MICMAC and other methodologies for the identification and categorisation of critical success factors. TISM 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 together to help the development of policies by the private and public sector. For instance, (Kapse *et al.*, 2018) identify and classify 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) applies 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) develop 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.

2.3 Key enablers for the growth of the UK and Mexico's aerospace ecosystems

In this research, key enablers are defined as any policies and/or characteristics inherent to a country's ecosystem 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 (a detailed list of sources is included in the following sections). The other source is the outcome of the *quantitative analysis* presented in subsequent chapters. Additionally, once the key enablers are identified, they are validated and nurtured with experts on the aerospace sector.

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

2.3.1 Key enablers for the development of the UK's aerospace ecosystem

The aim of this part of the research is the identification and categorisation of key enablers that have fostered the evolution of a developed aerospace ecosystem, taking the UK's aerospace ecosystem as a case example. This country is selected as its aerospace ecosystem has demonstrated an RCA>1 of aerospace exports continuously during the last decades.

The identification of key enablers is through qualitative and quantitative analysis. The former is mainly based on a literature review. In the latter one, key enablers are obtained via country-products network analysis elaborated for a group of developed aerospace ecosystems.

From the literature review, 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 (which are detailed in the following sections). Since the 'UK European Union Membership Referendum' held on 23 June 2016, the UK's government has analysed impact assessments when leaving the EU coming from different UK's economy sectors (House of Commons on Exiting the European Union Committee, 2017a). Notably, the UK's government has pursued recommendations from civil and public organisations from the UK's 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.

2.3.1.1 The UK's aerospace ecosystem landscape

The UK's aerospace ecosystem is considered as 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's 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's aerospace ecosystem is characterised for being a world leader in developing new technologies and having expertise across all aircraft's components, such as aerostructures, propulsion, systems, interiors and maintenance and repair operations (Department for Business Energy and Industrial Strategy, 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) (ATI, 2018a; Business Energy and Industrial Strategy Committee, 2018a). All Airbus aircraft's wings are manufactured in Bristol and North Wales, UK. Bombardier also manufactures wings in Northern Ireland. Fifty per cent of the UK's 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% (Department for International Trade, 2019b).

The key enablers for the evolution of the UK's aerospace ecosystem are listed in Table 2. A total of 13 key enablers are identified: seven resulted from the literature review and six from the quantitative analysis. A description of all the key enablers is presented in the next sections.

Table 2. Key enablers for the evolution of the UK's 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
	Chemicals ecosystem
	Machinery ecosystem
	Pharmaceutical and medicinal ecosystem
	Agricultural products ecosystem
	Non-agricultural products ecosystem

2.3.1.2 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's 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's aerospace ecosystem has grown up to a level where around 90% of the +3,000 aerospace companies located in the UK, are micro-sized[3] suppliers (Department for International Trade, 2019a). The latest strategy was launched at the beginning of 2019, a new 'Supply Chain Competitiveness programme', aiming to help small and medium

[3] Micro, small and medium-sized enterprises (SMEs) can be categorised according to the headcount as: *micro with* less than 10, *small* with less than 50, and *medium with* less than 250 employees (European Commission, 2016)

enterprises to become more productive and competitive (Department for Business Energy and Industrial Strategy, 2018).

Another example of supplier development programs is the creation of the Aerospace Growth Partnership (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 SMEs, through the National Aerospace Technology Exploitation Programme (NATEP).

2.3.1.3 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's 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* (AGP, 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, Hough and Ward, 2017). The AGP enables the evolution of the UK's aerospace ecosystem mainly by the identification of the growth inhibitors caused by the UK's market failure. It encourages the companies, part of the UK's 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's 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's technology strategy to boost the UK's aerospace ecosystem as a world leader in technology and innovation by developing strategies and targeting investment (ATI, 2018b). This institute has enabled the UK's aerospace ecosystem by ensuring an annual investment from the civil and public sector up to £300m per year in technology until 2026 (ATI, 2018a). In 2018, ATI´s portfolio embraced 214 projects, involving more than 200 companies, reaching a value of £2bn. Besides, it supported the installation of the first Boeing's 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).

2.3.1.4 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 on Exiting the European Union Committee, 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 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).

2.3.1.5 Geopolitical factors

The aerospace industry is highly globalised and export-oriented and, therefore, so is the UK's aerospace ecosystem. Indeed, this sector is unavoidably tied and benefits from geopolitical factors (House of Commons on Exiting the European Union Committee, 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's 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 EASA and the 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's design changes, independently from the FAA certification (Konert, 2019). However, although airworthiness certification agreements have not been drastically changed yet, recent studies suggest that they must be innovated after the Boeing 737 MAX crashes evidenced their obsoleteness. For instance, (Sgobba, 2019) suggests 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 ones refer to rules based on the performance and outcome required.

As in February 2020, 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´s 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 (Business Energy and Industrial Strategy Committee, 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´s major partners such as the USA and Canada (House of Commons on Exiting the European Union Committee, 2017b).

2.3.1.6 Research and design (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's economic growth and productivity, and particularly in aerospace has evidenced substantial returns (ATI, 2018b).

The UK's aerospace ecosystem is highly dependent on R&D government's expenditure. This sector receives around 12% of the manufacturing R&D budget (Business Energy and Industrial Strategy Committee, 2018b). In the UK, public funding is generally granted to aerospace companies via the ATI. Since 2014, this institution has targeted more than £1.95 bn 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's government has designated £125 million for aerospace research & development (House of Commons on Exiting the European Union Committee, 2017a).

The UK's aerospace ecosystem has also been beneficiated from public funding coming from the EU (ADS Group, 2017; Business Energy and Industrial Strategy Committee, 2018b; Butcher, 2018). For instance, the programme Horizon 2020 was developed to spread R&D grants over EU's 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 on Exiting the European Union Committee, 2019). The UK's aerospace ecosystem receives annually nearly £100m from the Horizon 2020 programme (Business Energy and Industrial Strategy Committee, 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.

2.3.1.7 Privatisation of aerospace companies

Although the government´s funding has been a determinant for the evolution of the UK's aerospace sector, the privatisation of public companies has historically been also a key enabler (Garside, 1998; Broadberry and Leunig, 2013). 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.

2.3.1.8 Strategic alliances of manufacturing firms

Another key factor for the evolution and success of the UK's aerospace ecosystem is the association and collaboration of firms not only a 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 British Aerospace (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).

2.3.1.9 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's 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 (Figure 9), popular products are identified. Popular products are those products, apart from the aerospace products, in which the UK has continuously demonstrated an RCA>1 across the five periods under analysis (1992-2016). The full list of products is presented in Table 3. Here, codes are grouped in the following industrial ecosystems: *Automotive ecosystem* (code 78), *Chemicals 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 *Non-Agricultural products ecosystem* (codes 87 and 89).

Table 3. 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)
Chemicals 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
Non-agricultural products ecosystem	87	Instruments and apparatus
	89	Miscellaneous manufactured articles

The products classified by industrial ecosystems is then presented and discussed with experts on the UK's aerospace ecosystem. After a discussion about the influence of each industrial ecosystem on the growth of the UK's 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 "driving force behind the UK exports of industrial goods" (SMMT, 2019) and a "British success story" (House of Commons on Exiting the European Union Committee, 2019). As in 2018, the automotive industry accounted for 14.4% of all exported goods in the UK, positioning this sector as the UK's largest exporter of goods (SMMT, 2019).
- *Chemicals ecosystem* includes products such as dyeing, tanning and colouring materials, inorganic chemicals, perfume and cleaning preparations, and plastics in non-primary forms. The UK's chemicals 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 on Exiting the European Union Committee, 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.
- *Non-agricultural products ecosystem* refers mainly to the ecosystem required for the production of other goods not included within previous classifications (others apart from the automotive, chemicals, 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. The next step is the categorisation of the key enablers using the ISM and MICMAC methodologies, which is detailed in the following sections.

2.3.2 Key enablers for the emergence of aerospace ecosystems – Mexico case example

In this part of the research, the Mexican aerospace ecosystem is used as a case example of an emergent ecosystem. Here, key enablers are identified and categorised using a similar methodology and philosophical approach, as described in the previous section.

As elaborated for the UK's aerospace ecosystem, key enablers for the Mexican´s aerospace ecosystem are identified through a quantitative analysis (section 6.1) 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's 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.

2.3.2.1 The Mexican aerospace ecosystem landscape

The beginning of the Aerospace industry in Mexico backs to the early 1900s when, in 1915, an innovative propeller named 'Anahuac' was designed and manufactured in this country (Romero 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 the production, MRO and R&D (ProMexico, 2017; INEGI, 2018).

In Figure 5, 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 amount 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 amount 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) (Hernandez 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 (Hernandez Martinez *et al.*, 2015).
– *Sonora:* this cluster has more than 50 SMEs dedicated primarily to the production of turbine's 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 (Hernandez Martinez *et al.*, 2015).

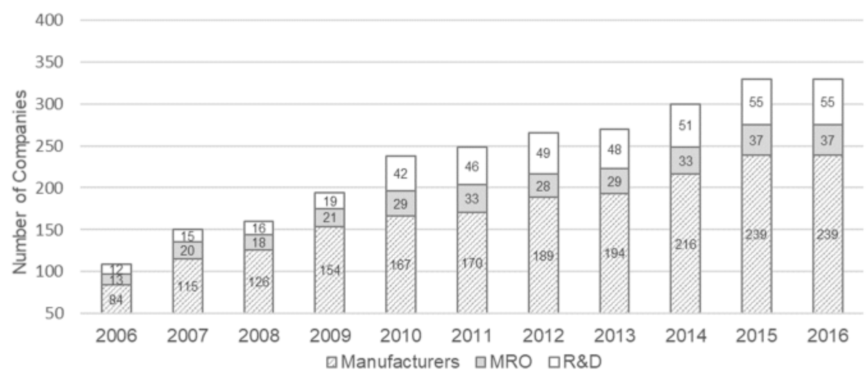


Figure 5. Evolution of aerospace companies in Mexico

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 growth has been achieved to some extent by the enablers identified in this research, which are listed in Table 4. Similarly to the UK's 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 in the following sections.

Table 4. 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 (section 6.1)	Automotive ecosystem
	Agricultural products ecosystem
	Non-agricultural products

2.3.2.2 Geopolitical factors

Mexico's geographical location as a USA's neighbour and trade agreements with this country are key enablers that have propelled its attractiveness to foreign manufacturing firms (Quesada *et al.*, 2015; Cabrera Padilla and Rodriguez Suarez, 2018; Morsi, Whealan-George and Clevenger, 2018; Meraz-Rodríguez, Ayvar-Campos and Papadopoulos, 2019). 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's exports (15%) and second in imports (14%), after China (22%) (Observatory of Economic Complexity, 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 (Cabrera Padilla and Rodriguez Suarez, 2018).

2.3.2.3 Labour: low cost and highly-qualified

Mexico's 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; Trimble, 2016; Morsi, Whealan-George and Clevenger, 2018). As in 2020, the minimum wage in Mexico per hour is $0.82 US dollars ($15.4 Mexican pesos) for most of the country, and $1.23 US dollars ($23.2 Mexican pesos) for regions bordering with the USA. Whereas in the USA, the federal minimum wage per hour is $7.25 US dollars. 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's labour force is considered as highly-qualified (Coffin, 2013; ProMexico, 2017; Cabrera Padilla and Rodriguez Suarez, 2018). It is particularly strong in manufacturing capabilities, such as metal-mechanic processes needed for the automotive and aerospace sector (Cabrera Padilla and Rodriguez Suarez, 2018).

2.3.2.4 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 (ProMexico, 2017; Cabrera Padilla and Rodriguez Suarez, 2018). 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 (Cabrera Padilla and Rodriguez 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´s requirements, the government opened a public university, Aeronautical University of Queretaro (UNAQ), located next to Bombardier´s facilities. Mexican´s government claims that this educational institution promoted the attraction of new foreign investments and enabled the evolution of the aerospace ecosystem (Luna-Ochoa, Robles-Belmont and Suaste-Gomez, 2016; Luna *et al.*, 2018; Meraz-Rodríguez, Ayvar-Campos and Papadopoulos, 2019; Muñoz-Sanchez *et al.*, 2019). Nowadays, more than twenty educational institutions are offering specialised courses in this sector (ProMexico, 2017).

2.3.2.5 Supporting organisations

Organisations part of the Mexican's *Triple Helix,* as first proposed in the framework developed by (Leydesdorff and Etzkowitz, 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; ProMexico, 2017; Morsi, Whealan-George and Clevenger, 2018).

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 non-profit 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 (Archundia 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's road maps (Cabrera Padilla and Rodriguez Suarez, 2018). Examples of reports containing such strategies are *the national plan flight Mexico's aerospace industry road map 2014* (Archundia Ortiz *et al.*, 2014), *2015* (Hernandez 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* (Cabrera Padilla and Rodriguez 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.

2.3.2.6 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) (Cabrera Padilla and Rodriguez 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, 2019a). From 2007 until 2016, the Mexican aerospace ecosystem received USD 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 twelfth-largest exporter of aerospace products in the world, holding nearly 2% of world exports (INEGI, 2018).

2.3.2.7 Other industrial ecosystems

This part of the research aims at the identification of other ecosystems that have endorsed the evolution of the Mexican aerospace ecosystem. Such industrial ecosystems, considered in this research as key enablers, are part of the quantitative analysis presented in section 6.1.

From the evolution of the networks of emergent aerospace ecosystems (Figure 24), popular products are identified. Popular products are those products, apart from the aerospace products, in which Mexico has continuously demonstrated an RCA>1 across the five periods under analysis (1992-2016). The full list of products is presented in Table 5. 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 *Non-agricultural products ecosystem* (codes 81 and 82).

Table 5. 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
Non-agricultural products ecosystem	81	Prefabricated buildings, sanitary, lighting and fixtures
	82	Furniture and parts thereof

As elaborated during the UK's aerospace ecosystem analysis, the products classified by industrial ecosystems (listed in Table 5) 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 *non-agricultural products ecosystem*.

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

– *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 (Cabrera Padilla and Rodriguez Suarez, 2018). Mexico's 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 (Hernandez 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.
- *Non-agricultural 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, which is detailed in the following sections.

2.4 Research gaps

The literature review shreds of evidence the following research gaps:

- **There is an absence of theory to understand at a country-level how the aerospace ecosystem has evolved**
- **There is an absence of theory to understand in particular which other industrial ecosystems have nurtured the growth of aerospace ecosystems**.
- There is an absence of theory to identify and categorise the key enablers that have helped the growth of aerospace ecosystems.

The majority of researches and practitioners have helped the aerospace ecosystem by individually addressing particular challenges that the aerospace ecosystem has faced. However, notwithstanding the vast amount of literature on the aerospace industry, there is an absence of theory to understand at a country-level how the aerospace ecosystem has changed and adapted to such challenges in the past years. Understanding patterns of how the aerospace ecosystem has evolved is essential to cope with the challenges that the aerospace industry is facing. Consequently, in this research, previous gaps are intended to be filled to some extent by developing an analytical approach for particular aerospace ecosystems. Network science, ISM and MICMAC methodologies are used for the understanding of the evolution and for the categorisation of key enablers for the progression of developed and emergent aerospace ecosystems.

2.5 Summary

In this chapter, the literature review of this research is presented. First, a description of the processes followed to search, evaluate, synthesis and analysis of the existing literature are introduced. Then, a literature review of *methods for analysing industrial ecosystems* and *categorisation of key enablers* is presented using a narrative approach. Finally, the key enablers for the growth of the UK and Mexican aerospace ecosystems are introduced.

After studying the available methods for analysing industrial ecosystems, network science is selected as the methodology to address the aim of this research. The selection is based on the fact that this science is among the most suitable for analysing the structure of systems containing static components. In addition, it has gained interest among scientists as it is a powerful approach for representing and analysing industrial ecosystems. ISM and MICMAC methodologies are selected for the categorisation of key enablers.

Results of the literature review evidence a lack of studies focused on analysing the evolution of aerospace ecosystems at a macro level. Evidence suggests that network science has recently gained interest among scientist to develop economic theories based on country-products networks. However, no study was found of studies with similar objectives as defined for this research. Similarly, ISM and MICMAC are widely applied methodologies for categorising key enablers. However, they haven't been used for key enablers that have nourished the growth of aerospace ecosystems. This gap in the literature is addressed in this research.

In the next chapter, the research methodology followed to address the research gap, aim and objectives of this research are presented.

Chapter 3 - Research methodology

This chapter introduces the philosophical position and the empirical research design selected for this research.

The key components of a research process could be classified in *ontology, epistemology, methodology, methods* and *sources* (Hay, 2002). *Ontology* answers what is out there to know, *epistemology* answers what and how can we know about it, *methodology* answers how can the knowledge be acquired, *methods* refers to the precise procedures to get the knowledge, and *sources* answer the type of data that can be collected to get the knowledge (Grix, 2002).

The next sections introduce the decisions undertaken amongst each of the key components of the process followed during the research presented in this thesis.

3.1 Philosophical position: *ontology* and *epistemology*

A research journey starts with the *ontology*. The word *ontology* originates from combining two Greek terms: *onto,* which means *being,* and *logos*, which means *reason*. *Ontology* is the branch of the philosophy that is concerned about the nature of social reality beyond which theory is constructed. It intends to answer what is out there to know. The ontology of research could be addressed by undertaking two contrasting perspectives: *objectivism* and *constructivism*. The former one refers to a philosophical position which assumes that the existence of social phenomena and its implications are not dependent on social actors. In contrast, the latter one assumes a dependence of social actors (Grix, 2002).

The following building block of the research is the *epistemology.* The word *epistemology* originates from combining two Greek terms: *episteme,* which means *knowledge,* and *logos*. *Epistemology* is the branch of the philosophy conferenced about the theory of knowledge, particularly to its methods, and the alternative means to get the knowledge. It intends to answer what and how can we know about the knowledge. The epistemology of a research study could be addressed by undertaking two opposing philosophical positions: *positivism* and *interpretivism.* The former one supports a philosophical position in which is assumed that the study of social reality may be addressed by undertaking methods of natural science. This philosophical position is typically addressed by taking quantitative approaches. On the other hand, the latter is a philosophical position which assumes the need for a strategy that respects the dissimilarity among humans and objects of natural science. Qualitative methods are usually part of the latter philosophy (Grix, 2002).

The philosophical positions undertaken in this research are *constructivism* (ontology) and a combination of *positivism* and *interpretivism* (epistemology). As described previously in section 1.4, this research intends to understand a real-world phenomenon. Mainly, this research aims at understanding the aerospace ecosystem by identifying evolution patterns and key enablers that have encouraged its growth. Hence, the philosophical positions are congruent with the scope of this research. *Constructivism* is selected at is assumed that the evolution of aerospace ecosystems is dependent on social actors, such as other industrial ecosystems. *Positivism* is chosen to address the first three research questions raised for this research. It is believed that patterns in the evolution of aerospace ecosystems can be identified by the imitation of natural science and its methods. Network science, and in particular, nestedness analysis, initially developed for biological ecosystems analysis, is part of the chosen *positivism*. *Interpretivism* is selected to address the last research question: *which key enablers have promoted the evolution of aerospace ecosystems*. ISM and MICMAC methods are part of the qualitative approach undertaken in this part of the research.

3.2 Methodological choice

This section introduces the methodology, methods and sources selected, and empirical design for this research. *Methodology* answers how can the knowledge be acquired, *methods* refers to the precise procedures to get the knowledge, and *sources* answer the type of data that can be collected to get the knowledge.

The types of research could be classified according to its *application, objectives and enquiry mode.* In regards to its *application,* it can be *applied* or *pure* research. *Pure* research is characterised for containing abstract and specialised concepts and for possibly not having a practical application (Bailey, 1978). *Applied* research is a research in which the procedures and methods followed are gathered in such a way that they can be applied to solve practical problems or used in other ways, such as for the formulation of policies or the understanding of a phenomenon (Kumar, 2011). According to the *objectives*, a research can be *descriptive*, *exploratory*, *explanatory* or *correlational*. *Descriptive* research tries to make information available or describe a problem scientifically. *Exploratory* research attempts to answers questions about a problem where little is acknowledged. *Explanatory* research tries to explain the relationship between the different characteristics of a situation. A *correlational* study attempts to examine or establish the existence of a connexion between two or more characteristics of a phenomenon. From the viewpoint of *enquiry mode*, research can be *quantitative* or *qualitative*. *Quantitative* research uses rationalism as its philosophy, quantifies the extent of variations, follows a structured and rigid methodology, and formulates theories based on reliability and objectivity. *Qualitative* research uses empiricism as its philosophy, explores perceptions and feelings, and emphasises on the description of variations based on fewer cases.

Based on the previous classifications, the methodological choices of this research intend to be *applied*, *exploratory* and a combination of *quantitative* and *qualitative* methodological approaches.

3.2.1 Empirical research design

The steps in a research process can also be grouped according to the following activities (Van de Ven, 2007): *problem formulation, theory building, research design and problem-solving. Problem formulation* is the activity in which the research problem and the purpose of the research are identified. Literature review and feedback from experienced people in the area are part of this activity. *Theory building* is when a hypothesis is elaborated by *abductive, deductive* and *inductive* reasoning. *Abductive* refers to the theory that is built based on finding the simplest explanation for a set of observations. *Deductive* theory-building relies on gathering a conclusion following a top-down logic; here, conclusions are reached following one or more statements. On the other hand, *inductive* theory building relies on gathering conclusions following a bottom-up logic; here, general conclusions are drawn based on some evidence of the reality. The main difference between *deductive* and *inductive* reasoning is that conclusions of the former one are absolute, while conclusions of the latter one may or not be guaranteed. *Research design* refers to the elaboration of a process model to scrutinise the different theories and to address the research questions. *Problem-solving* is the act of communicating, interpreting and applying the findings that respond to the problem formulation.

Although previous activities do not necessarily follow a sequence during a research study, it usually starts with *problem formulation*. The research presented in this thesis started with a literature review and feedback from experienced people to *formulate the problem*. The following step is the elaboration of the *research design,* which is described in Figure 6. Subsequently, the problem-solving and finally, the theory-building using a combination of deductive and inductive approaches.

The empirical research design for the identification of patterns and key enablers for aerospace ecosystems evolution is illustrated in Figure 6. As illustrated in this graph, the research process presented in this thesis is divided into four steps: *problem formulation, research design, problem-solving and theory building.*

The *problem formulation* started with a literature review on the main challenges that the aerospace ecosystem is facing. The outcome motivated the aim and objectives of the research programme.

The *research design* started with the elaboration of the research methodology. Here, it was defined that a combination of quantitative and qualitative methodologies are selected for addressing the aim and objectives. In regards to the philosophical positions, *constructivism* is selected for the elaboration of the research methodology, *positivism* is chosen for the quantitative analysis, and *interpretivism* for the qualitative analysis.

The next step is *problem-solving.* The first part of the quantitative analysis started with the data collection: exports data from 1992 to 2016. Then, the data is analysed with network science. To this aim, the RCA is calculated, and a correlation analysis is elaborated. The former one is used to identify the countries of study and their catalogue of products (with an RCA>1). The latter one is used to identify all the other products (with an RCA>1) that have been positively correlated with the growth of the aerospace ecosystem. The qualitative analysis started with the data collection of the key enablers. Here, two sources are used: a literature review of key enablers, and other ecosystems that have been related to the evolution of aerospace ecosystems (obtained from the quantitative analysis at a microscopic level).

Finally, *theory building* is approached by using *deductive* and *inductive* philosophies. The data is analysed at a macroscopic level (network level) for the identification of evolution patterns. The identification of other industrial ecosystems that have nourished the growth of developed aerospace ecosystems is obtained by analysing the networks at a microscopic level (nodes level). Finally, the key enablers are categorised and validated, using experts' opinion, via ISM and MICMAC methods.

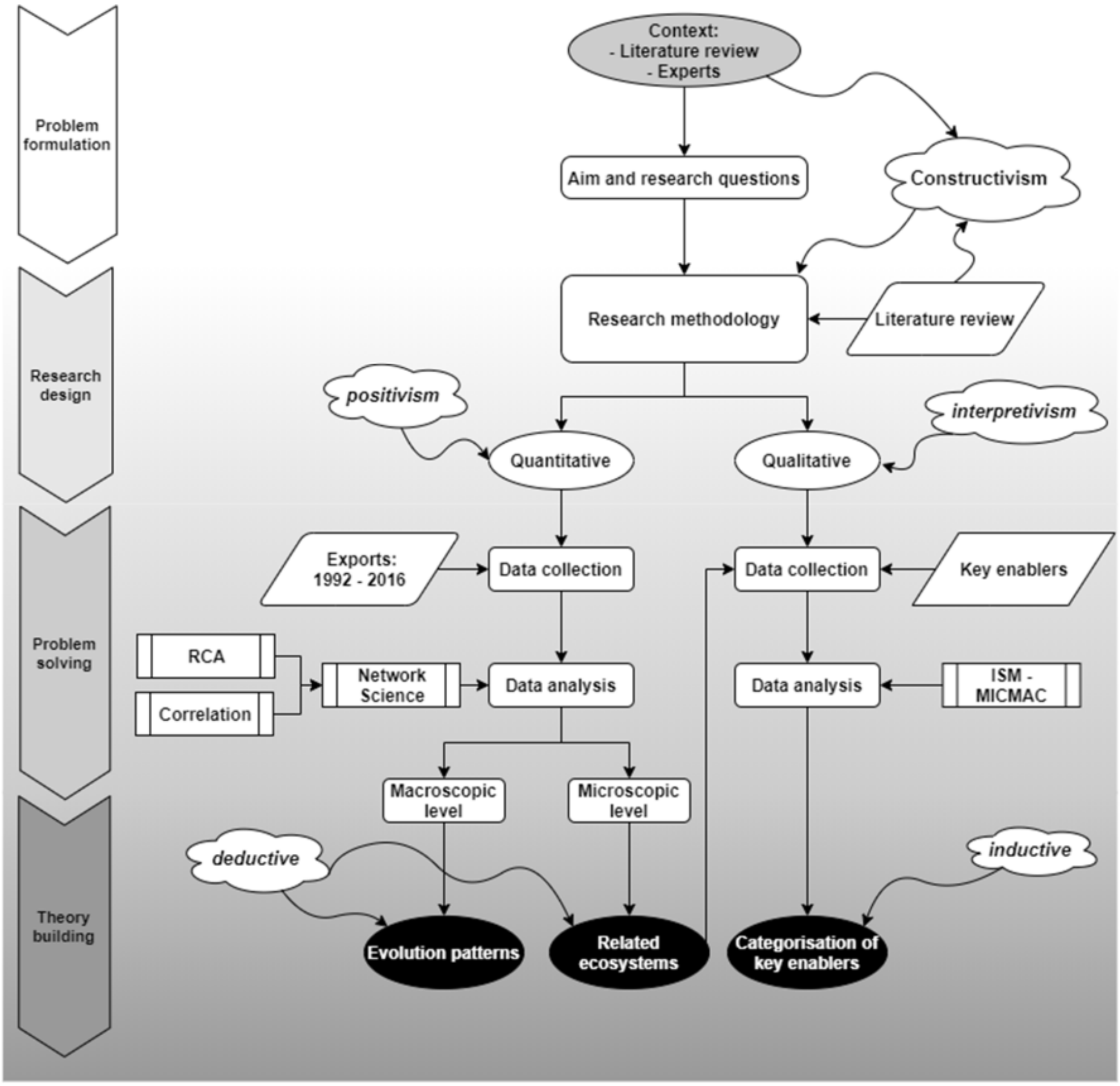


Figure 6. The empirical research design for the identification of patterns and key enablers for aerospace ecosystems evolution

3.3 Summary

In this chapter, an introduction of the philosophical position and the empirical research design selected for this research is presented.

The philosophical positions undertaken in this research are *constructivism* (ontology) and a combination of *positivism* and *interpretivism* (epistemology). *Constructivism* is selected at is assumed that the evolution of aerospace ecosystems is dependent on social factors, such as other industrial ecosystems. *Positivism* is chosen because the patterns in the evolution of aerospace ecosystems may be identified by the imitation of natural science and its methods. *Interpretivism* is selected to identify the key enablers that have fostered the evolution of aerospace ecosystems. ISM and MICMAC methods are part of the qualitative approach undertaken in this part of the research.

The methodological choices of this research intend to be *applied*, *exploratory* and a combination of *quantitative* and *qualitative* approaches. *Applied* because the procedures and methods selected for this research are gathered in such a way that they can be applied to solve real-world problems, such as for the formulation of policies to enhance the growth of emergent aerospace ecosystems. *Exploratory* because this research attempts to answers questions about a problem where little is acknowledged: patterns and key enablers part of the evolution of aerospace ecosystems that may be applied to foster the progression of emergent ones. Quantitative and qualitative methodological approaches by using network science, ISM and MICMAC methodologies.

The theory-building of this research uses a combination of *deductive* and *inductive* reasoning. A *deductive* reasoning refers to the process in which a conclusion is obtained by narrowing the available alternatives. In this research, a *deductive* approach is undertaken when identifying which other industrial ecosystems have nurtured the evolution of aerospace ecosystems. An *inductive* reasoning is when general conclusions are reached based on some evidence of reality. In this research, an *inductive* approach is taken by the identification of a limited number of key enablers and when pretending that enhancement policies for an emergent aerospace ecosystem can be formulated assuming that the path of developed ecosystems can be emulated.

In the next chapters, a detailed description of the methods and sources used in this research and results are presented.

Chapter 4 - Patterns in the evolution of developed aerospace ecosystems – a quantitative analysis

This chapter describes the process followed to answer the following objectives:

1) Identification of patterns that have characterised the evolution of aerospace ecosystems
2) Identification of other industries that have nourished the growth of aerospace ecosystems

The two objectives are addressed from the developed aerospace ecosystems perspective. First, historical international trade data from 1992 to 2016 is collected. Then, the RCA on aerospace products is computed. The most prominent ecosystems on exporting aerospace products over the last years are identified. The RCA for the rest of the product portfolio is calculated, and the correlation with the aerospace exports is also computed.

Then, bipartite country-products networks are developed, aiming at the identification of patterns and similarities in the evolution of developed aerospace manufacturing countries ecosystems. Among the main findings is that developed ecosystems tend to become more analogous, as countries lean towards having a revealed comparative advantage in the same group of products. Furthermore, this analysis also helps to identify which particular industries have nourished the growth of the aerospace ecosystems over a twenty-five years period. The next sections detail the followed procedures.

4.1 Procedure for the identification of evolution patterns using network science

The philosophy undertaken in this part of the research is *constructivism* (ontology) and *positivism* (epistemology), using *quantitative* methods and *deductive* reasoning for theory-building.

First, a brief introduction to the methodology, methods and sources is presented. Then, a more detailed description is presented in the following sections.

Data is collected from 1992 to 2016 obtained from the United Nations (UN) Comtrade database. Using the RCA analysis, two groups of countries are selected. One group of countries that have been consistently among the top aerospace exporters, and another group of countries that have shown significant improvement on aerospace exports (the study is complemented by identifying all the other products with an RCA>1 for each selected country). Aiming at the identification of patterns across different periods, the 25 years data is divided into periods with an equal amount of years. Thus, five periods of five years are identified to formulate the analysis. For each period and country, a correlation analysis is performed to identify the strength of the statistical relationship between the RCA value on aerospace products and the RCA values of other products countries exported.

A total of ten bipartite, unweighted and undirected networks are produced (five networks per group of countries). Each graph is defined as $G = (N, E)$ (Newman, 2010) comprising:

- $N = X \cup Y$ set of nodes, where X are countries and Y are products with $RCA \geq 1$.
- $E \in X \cap Y$ set of edges, where a connection is made only when a specific product Y has an RCA>1 at that country X.

Besides, the colour of E depicts the Pearson correlation coefficient (ρ). Red edges indicate $\rho \geq 0.5$ and black edges all the others.

Subsequently, the evolution of networks' topology among the different periods and groups are analysed and compared. Finally, evolution patterns are identified through node-level and network-level metrics, including a nestedness analysis.

The next sections include a more detailed procedure followed for the elaboration of the bipartite networks and the identification of evolution patterns.

4.1.1 Data collection

The data includes exports figures from 1992 to 2016 obtained from the UN, using Standard International Trade Classification (SITC) revision 3. The data acquisition was conducted during May – July 2018, from the UN Comtrade database available online at https://comtrade.un.org/. The source data used for the analysis was selected as it is claimed to be the most complete trade database available worldwide (UN Statistics Division, 2017) and because it has been commonly used among scientific studies. For instance, it has been used to develop economic theories (Hidalgo and Hausmann, 2009; Caldarelli *et al.*, 2012; Bahar, Hausmann and Hidalgo, 2014; Hartmann *et al.*, 2016, 2017) and economics-related studies (Ercsey-Ravasz *et al.*, 2012; Saracco *et al.*, 2016; Mariani *et al.*, 2019) using network science.

There are two commodities' classifications available: Harmonised System (HS) and SITC. The first one is mainly used by countries to collect their trade statistics. The latter one, which is the one selected for this analysis, is maintained by the United Nations (UN) and recommended for analytical purposes (The World Bank, 2010; Luttenberger and Zedlitz, 2017). Within the SITC nomenclature, there were four revisions available at the time when data was collected: revision 1 containing data from 1962, revision 2 containing data from 1976, revision 3 with data from 1986 and revision 4 with data from 2007. Revision 3 is chosen as it is the latest classification with more than twenty years of historical data. Older revisions were not considered as there is no available data for some countries such as China. After analysing SITC revision 3 data, although it has data from 1986, it was decided to use data only from 1992 to 2016. This decision is based on the fact that previous years do not have available data for some countries. For instance: in 1988, data is not available for many countries, such as the USA, China, Brazil and Mexico; from 1989 to 1991, data is not available for China; in 2017, data is not available for many countries, such as France, China, Netherlands and other countries.

SITC nomenclature is grouped in 5 different levels to classify products according to their origin, where each level is represented by one digit. The most detailed level is the five-digit classification. However, one of the limitations described by the UN statistic division is that countries do not necessarily report data for each level and each year (United Nations Statistics Division, 1991). Thus, it is concluded that the two-digit classification is the most appropriate given the lack of data for more detailed levels.

After analysing all commodity codes and levels under revision 3, it is noted that there is not a commodity code that comprises all aerospace manufacturing products. For instance, commodity code ‘792 - Aircraft, associated equipment’ seems to include all aerospace manufacturing products. However, it does not include products such as ‘7131 – Aircraft piston engines’ or ‘82111 – Seats of a kind used for aircraft’. Consequently, a new code is proposed to encapsulate all aerospace products: ‘Code A: aerospace and associated equipment’ (Table 6). Duplicates are avoided by subtracting modified codes from its upper levels.

Table 6. Code A: aerospace and associated equipment

Code	Description
6253	Tyres, pneumatic, new, of a kind used on aircraft
7131	Aircraft piston engines
714	Engines, motors non-electric
792	Aircraft, associated equipment
82111	Seats of a kind used for aircraft
88571	Instrument panel clocks and clocks of a similar type, for vehicles, aircrafts

To facilitate the analysis, groups of commodities are used as presented in Table 7 (manufactured products) and Table 8 (primary products), based on the statistical office of the Eurostat (from the European Union) classification (Eurostat, 2013). Data is classified into primary and manufactured products. Primary products are those traded as found in nature, whereas manufactured products are goods processed from primary products. Subsequently, groups are proposed based on their industrial origin.

Table 7. The proposed group of commodities: *manufactured products*

Group	Code	Product
Aerospace Products	A	Aerospace and associated equipment
Automotive Products	78	Road vehicles (automotive products)
Chemicals	51	Organic chemicals
	52	Inorganic chemicals
	53	Dyeing, tanning and colouring material
	55	Perfume, cleaning and preparations
	56	Fertilisers, manufactured
	57	Plastics in primary forms
	58	Plastics in non-primary forms
	59	Chemical materials and products
Machinery	71	Power generating machinery and equipment
	72	Machinery for specialised industries
	73	Metalworking machinery
	74	General industrial machinery
	75	Office machines and adapted machines
	76	Telecommunications and sound recording equipment
	77	Electric machinery and parts
Metals	67	Iron and steel
	68	Non-ferrous metals
	69	Manufactures of metals
Miscellaneous Products	62	Rubber manufactures
	63	Wood and cork manufactures
	64	Paper, paperboard and articles thereof
	66	Non-metallic mineral manufactures
	81	Prefabricated buildings, sanitary, lighting and fixtures
	82	Furniture and parts thereof
	83	Travel goods, handbags and similar containers
	87	Instruments and apparatus
	88	Photographic equipment, optical goods
	89	Miscellaneous manufactured articles
Pharmaceutical Products	54	Medicinal and pharmaceutical products
Textiles and Clothing	61	Leather, dressed fur
	65	Textile yarn, fabrics, made-up articles
	84	Articles of apparel and clothing accessories
	85	Footwear
Transport Equipment	79	Other transport equipment

Table 8. The proposed group of commodities: *primary products*

Group	Code	Product
Agricultural Products	00	Live animals
	01	Meat and meat preparations
	02	Dairy products and birds' eggs
	03	Fish and fish preparations
	04	Cereals and cereal preparations
	05	Vegetables and fruit
	06	Sugars, sugar preparations and honey
	07	Coffee, tea, cocoa, spices
	08	Feeding stuff for animals
	09	Miscellaneous edible products and preparations
	11	Beverages
	12	Tobacco and tobacco manufactures
	21	Hides, skins, fur skins, raw
	22	Oilseeds, oleaginous fruits
	23	Crude rubber (incl. synthetic)
	24	Cork and wood
	26	Textile fibres and their wastes
	29	Crude animal, vegetable materials
	41	Animal oils and fats
	42	Fixed vegetable fats and oils
	43	Processed animal or vegetable oils
Energy	32	Coal, coke and briquettes
	33	Petroleum and products
	34	Gas, natural and manufactured
	35	Electric current
Non-Agricultural Raw materials	25	Pulp and waste paper
	27	Crude fertilizers and crude minerals
	28	Metalliferous ores and metal scrap

4.1.2 Data assumptions and limitations

The UN Comtrade database has more than 3.3 billion records with detailed exports and imports of around 200 countries and more than 6000 different products (UN Statistics Division, 2017). According to the (United Nations Statistics Division, 1991), the following limitations should be considered when using SITC nomenclature for analytical purposes. First, all the data available is shared with the UN Statistics Division by the statistical authorities of each country, where countries do not necessarily provide data for every year and nomenclature level. Consequently, the UN does not estimate any missing data that is not reported by a country. To address this issue, where considered necessary, the missing values are obtained by following three possible paths. The first way is by consulting trade databases available for each country. If no information is obtained, a value is estimated by using the exports' share average of the six nearest years of data available. In the case when a few data are available (less than 20 years available), the commodity code is excluded. The commodity codes excluded are: '91 – Mail not classed by kind', '93 – Special transactions not classified', '96 – Coin non-gold and non-current' and '97 – Gold, non-monetary and excluding ores'. In regards to the products included within the exports figures, SITC revision 3 considers entrepot or bonded warehouse trade, re-exports, trade-in bunkers and stores with foreign ships and aircraft, but it does not include goods passing through the country for purposes of transport only. In regards to the defence sector, there is a unique commodity code used to classify products from this origin. To clarify this issue, the concern is raised to the UN statistics division. The answer obtained is the following: "Military goods can be part of UN Comtrade if they are reported as such by countries; however, for some countries, data for this type of commodity trade is confidential. In the latter case, the commodity may be identified at the chapter level but at the 5-digit level, or it may just be lumped under 93 – Special transactions not classified". Therefore, defence sector products are considered under this analysis only if countries report this data to the UN.

For China, the individual administrative regions (SAR - Special administrative region of China) are combined into one single value. Meaning that exports figures of China considered in this analysis constitute values from China, plus Hong Kong and Macao.

4.1.3 Revealed comparative advantage (RCA)

Understanding that raw exports figures do not necessarily provide conclusive evidence on the capability of a country to export a product, a metric suitable for this study is researched. The RCA is chosen as it has been widely used in academic and economic analyses (French, 2017). RCA is based on comparing the exports of a specific country with the exports of the rest of the world (equation (4-1)). An RCA>1 depicts that a country has revealed comparative advantage of exporting a specific product; the higher RCA value, the higher advantage.

$$RCA = \frac{\frac{Country' s\ Exports\ of\ Specific\ Product}{Country' s\ Total\ Exports}}{\frac{World\ Exports\ of\ Specific\ Product}{Total\ World\ Exports}} \quad \textbf{(4-1)}$$

During the research design it is concluded that two groups of countries are needed for the analysis: one group that has been consistently among the top on aerospace products, and another group of countries that have improved their exports capability on aerospace products by moving from RCA<1, calculated using code A. As both groups contain countries with developed aerospace ecosystems, this will help with the aim of this research by the identification of evolution patterns that could be emulated by developing ecosystems.

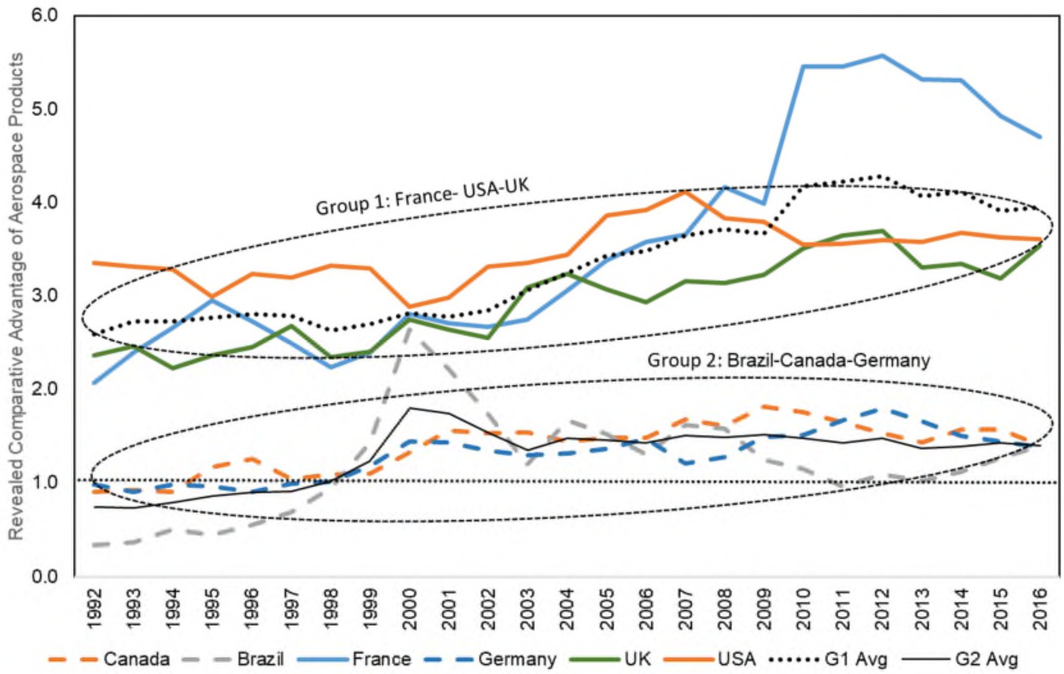
Results evidence that the countries with the most developed ecosystems (group one – G1) are France (FRA), the United Kingdom (UK) and the United States of America (USA). For group two (G2), Brazil (BRA), Canada (CAN) and Germany (DEU) are selected as they evolved from an emerging aerospace ecosystem to an ecosystem with a revealed comparative advantage. This conclusion is obtained based on the fact that these countries have demonstrated the highest RCA on aerospace products over all the period of study, as depicted in Figure 7

A. These countries improved from having an RCA<1 at the beginning of the study, to maintain an RCA>1 since 1999.

In addition, the results evidenced that the total exports on a specific product do not necessarily evidence their capability to export that product, when compared to other countries (as illustrated on Figure 7 A and B)).

The next step is the identification of other products that have consistently demonstrated an RCA>1 in both groups of countries.

A



B

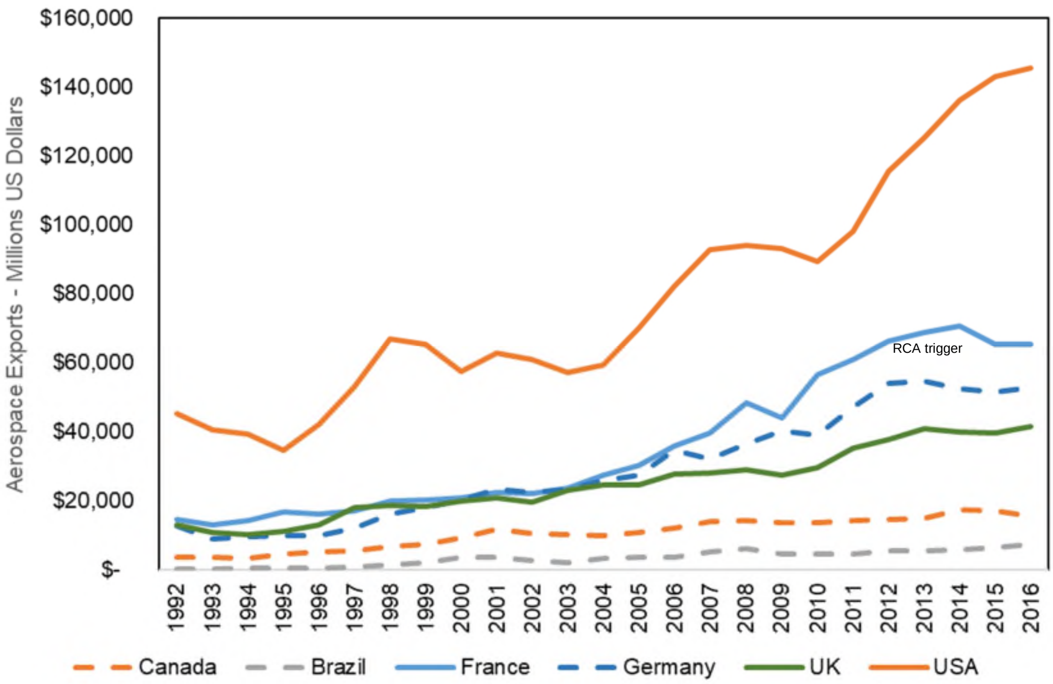


Figure 7. A - Evolution of RCA on aerospace products using code A for calculations (a value ≥1 depicts that the country has an RCA on exporting aerospace products). B - Million US Dollars of aerospace products exports

4.1.4 Correlation analysis

Pearson Correlation analysis is used to identify the strength of the statistical relationship between aerospace products and other goods, with an RCA>1, exported by each country. Only positive correlations are considered ($\rho \geq 0.5$), as the aim is to identify those relationships where aerospace exports rise by increasing the exports of any other product.

The correlation analysis is elaborated for all the country-products selected for this research. To exemplify the procedure, an example of one country-product is presented next. Thus, an example of the Pearson correlation calculations between RCA values of code '78 – Road Vehicles' and 'A - Aerospace and Associated equipment' for France are given in Table 9. Results evidence positive correlation values for the periods 1992 – 1996, 1997 – 2001 and 2012 – 2016, and negative values for the other two periods. Only positive values (≥ 0.5) are considered in the analysis and represented in the bipartite country-products networks. The main finding from this analysis is the identification of all the commodities that have been positively correlated with the evolution of the aerospace exports at each country. Thus, a list of products (with an RCA>1) that have been correlated to each country at every period of study is obtained. An example of the list of commodity codes, with an RCA>1, that have been positively correlated with the growth of France's aerospace ecosystem is presented in Table 10. The list of products is used for the elaboration of the networks, where these codes are connected to each country with red links. Results are presented and discussed in further sections.

Table 9. Correlation example between RCA of code A and 78 for France

1992 - 1996			**1997 - 2001**			**2002 – 2006**			**2007 – 2011**			**2012 – 2016**		
Year	**78**	**A**	**Year**	**78**	**A**	**Year**	**78**	**A**	**Year**	**78**	**A**	**Year**	**78**	**A**
1992	1.20	2.07	1997	1.26	2.49	2002	1.47	2.67	2007	1.36	3.65	2012	1.16	5.57
1993	1.17	2.39	1998	1.26	2.23	2003	1.49	2.74	2008	1.29	4.16	2013	1.10	5.31
1994	1.21	2.65	1999	1.30	2.39	2004	1.60	3.05	2009	1.34	3.98	2014	1.09	5.31
1995	1.23	2.95	2000	1.43	2.81	2005	1.53	3.38	2010	1.27	5.45	2015	1.07	4.92
1996	1.25	2.72	2001	1.44	2.70	2006	1.44	3.58	2011	1.28	5.46	2016	1.06	4.70
Correlation	0.68			0.89			- 0.10			- 0.86			0.93	

Table 10. List of commodity codes, with an RCA>1, that have been positively correlated with the growth of France's aerospace ecosystem

	1992-1996	1997-2001	2002-2006	2007-2011	2012-2016
Commodity Codes	01, 02, 09, 35, 51, 53, 54, 55, 64, 74, 78 and 83	02, 04, 21, 41, 54, 55, 57, 59, 64, 67, 78 and 83	00, 02, 04, 08, 09, 11, 41, 53, 54, 55, 57, 59, 62, 64, 69, 71, 74, 83 and 89	00, 02, 04, 09, 11, 21, 41, 54, 55, 59, 64, 81, 83 and 89	01, 04, 06, 09, 11, 41, 54, 55, 57, 62, 64, 71, 74 and 78
total	**12**	**12**	**19**	**14**	**14**

4.1.5 Networks development

The next step is the elaboration of the bipartite country-product networks for each period and group of countries. The networks are elaborated using the export data, from 1992 to 2016, grouped by countries, as detailed in previous sections. An example of the bipartite networks developed in this research programme is presented in Figure 8. The networks generated in this work are undirected, unweighted and bipartite. The graphs are produced using the software 'Cytoscape', version 3.7.2. This software is an open-source platform, written in Java, designed particularly for visualising and analysing complex networks. It is free to use and download at https://cytoscape.org/.

For developing each network, two classes of nodes are defined: countries and products. The countries are represented with grey, red and black nodes: France and Canada are represented with grey nodes; the United Kingdom and Germany with red nodes; and Brazil and the United States with black nodes. The products are represented with blue and green nodes: blue nodes are manufactured products, and green nodes are primary products. The colour and label of the nodes are related to the group of commodities (presented in Table 7 and Table 8). Only goods with an RCA>1 at any country subject of study are represented as nodes in each graph.

The countries and products are connected between each other by edges. Edges are used to connect the products with an RCA>1 to each country of study, which means that commodity's nodes are connected with any country's nodes only where there is an RCA>1. Edges are also used to represent a correlation between exporting aerospace products at each country and any other commodity. Red edges depict a positive correlation above 0.5 and grey edges depict a correlation below this value.

A graph for each period and group of countries are developed, producing a total of ten graphs. The bipartite country-products networks for G1 are presented in Figure 9, and for G2 in Figure 10. The analysis of the evolution of these graphs will be used for the identification of evolution patterns and ecosystems related to the growth.

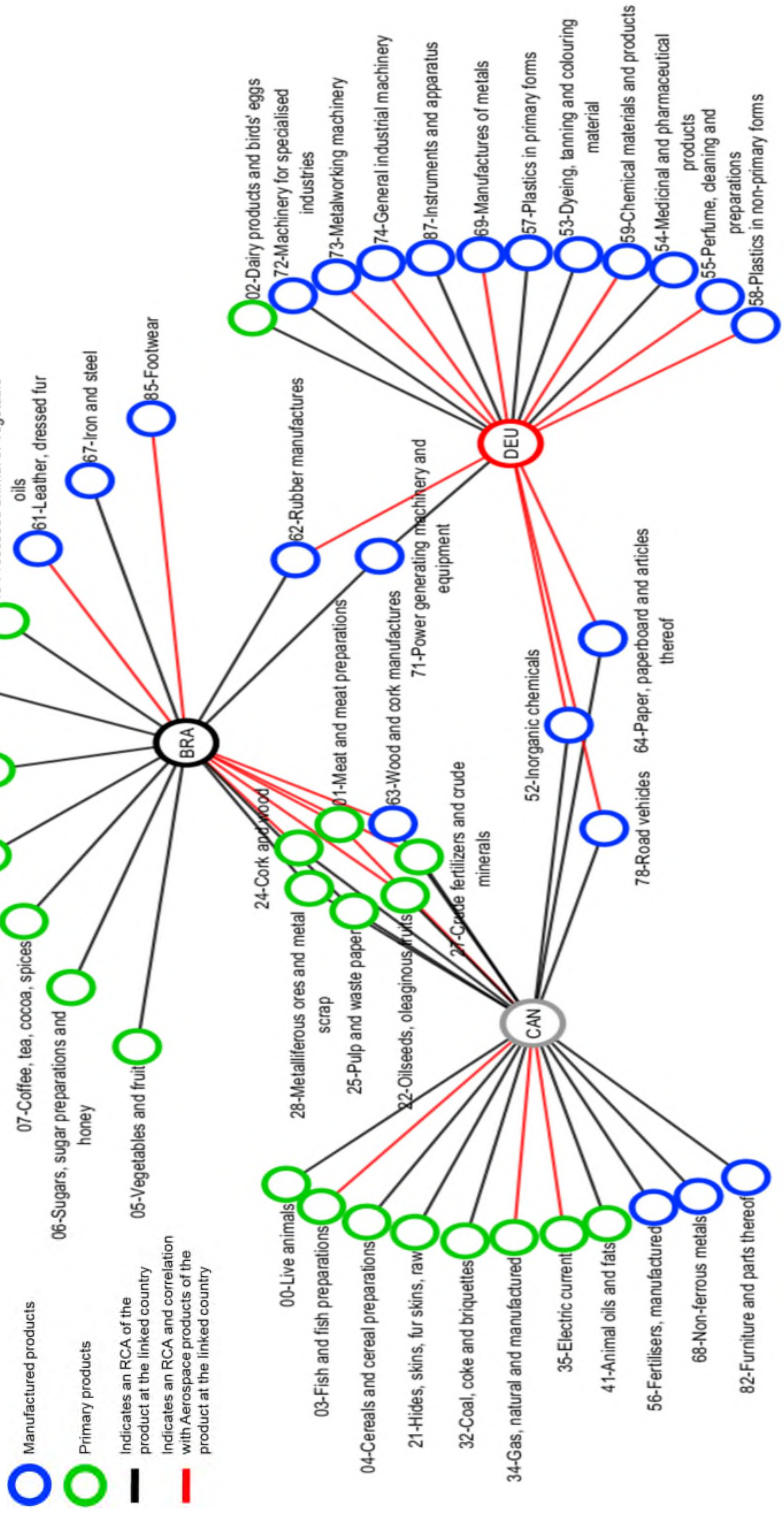
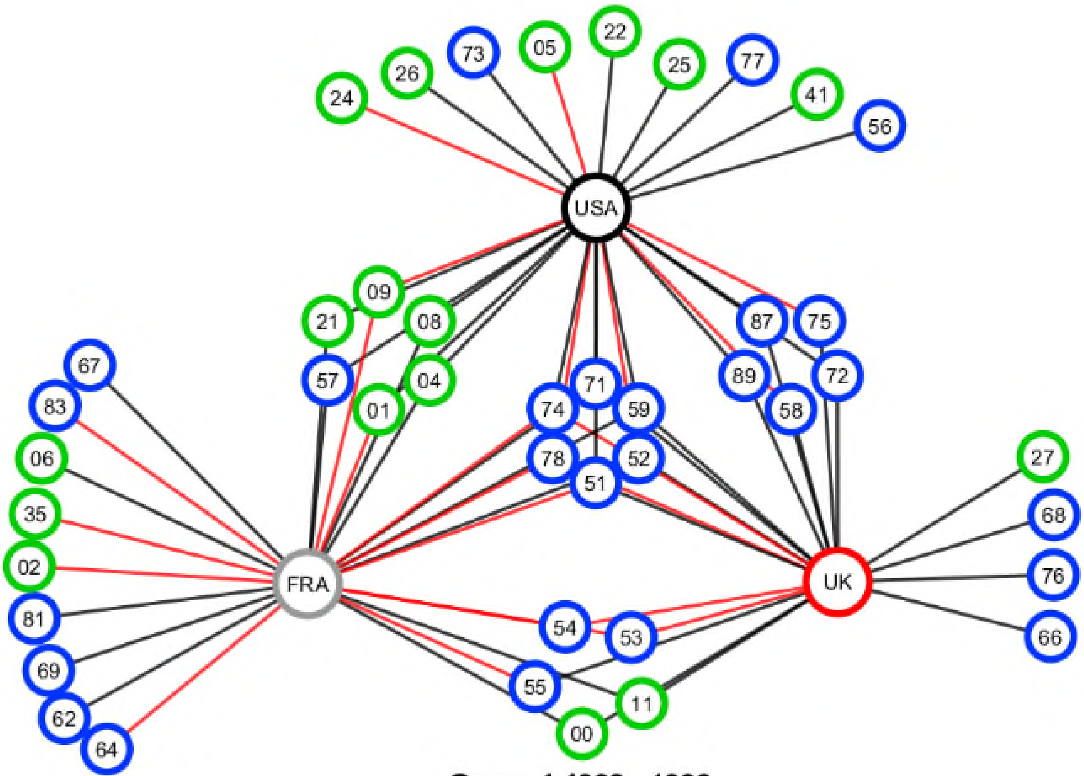
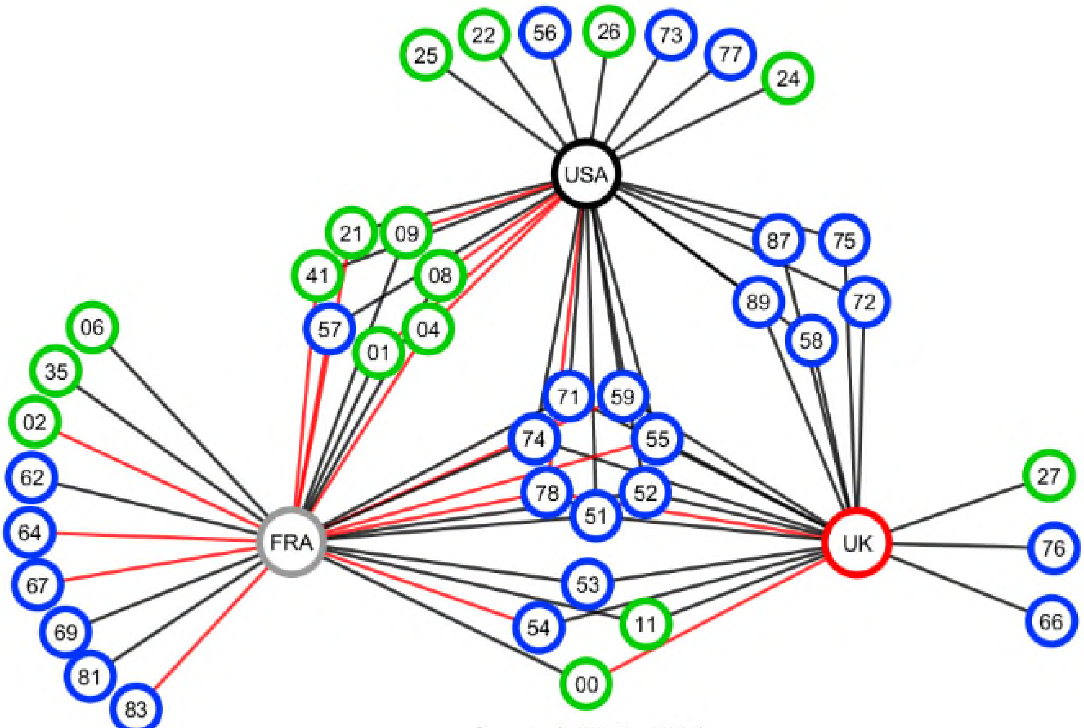


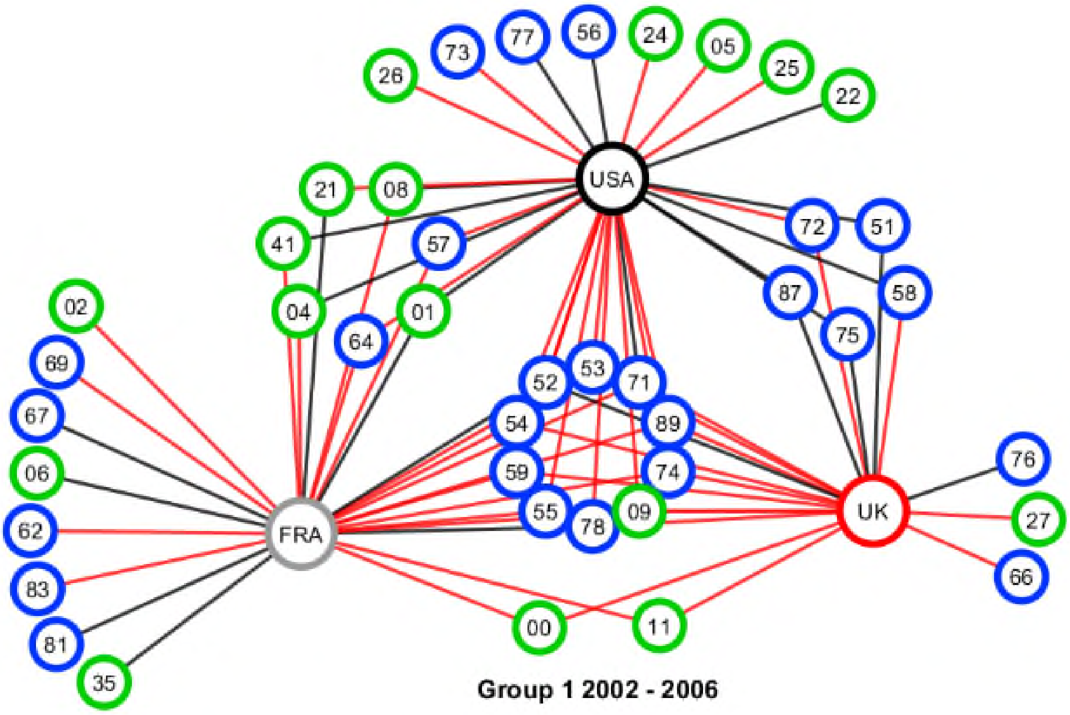
Figure 8. Bipartite country-products network structure



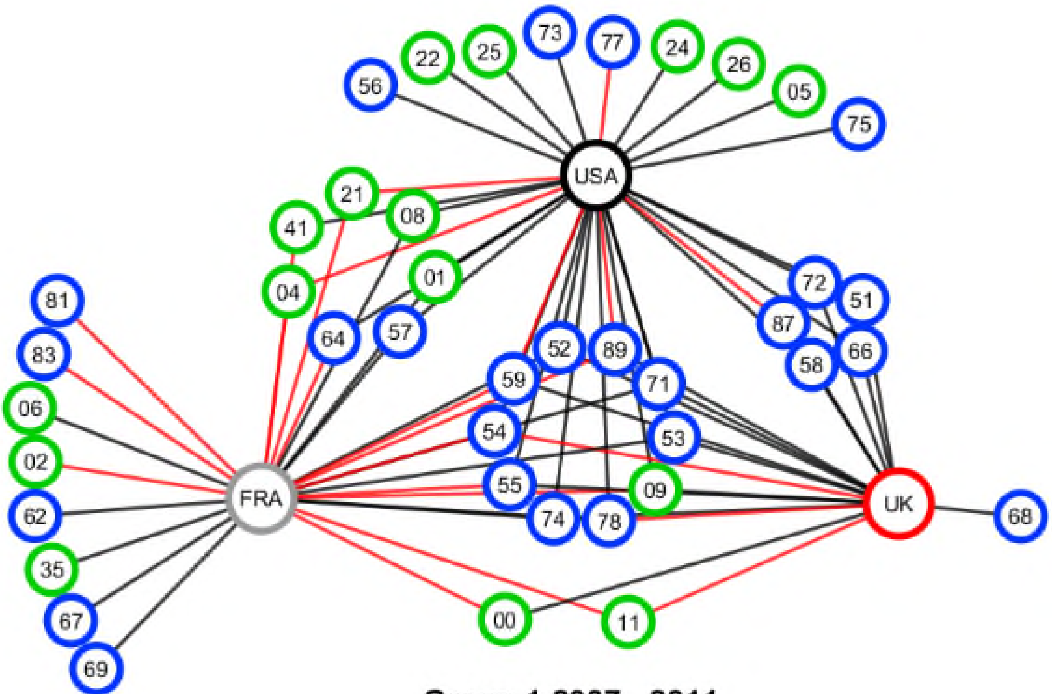
Group 1 1992 - 1996



Group 1 1997 - 2001



Group 1 2002 - 2006



Group 1 2007 - 2011

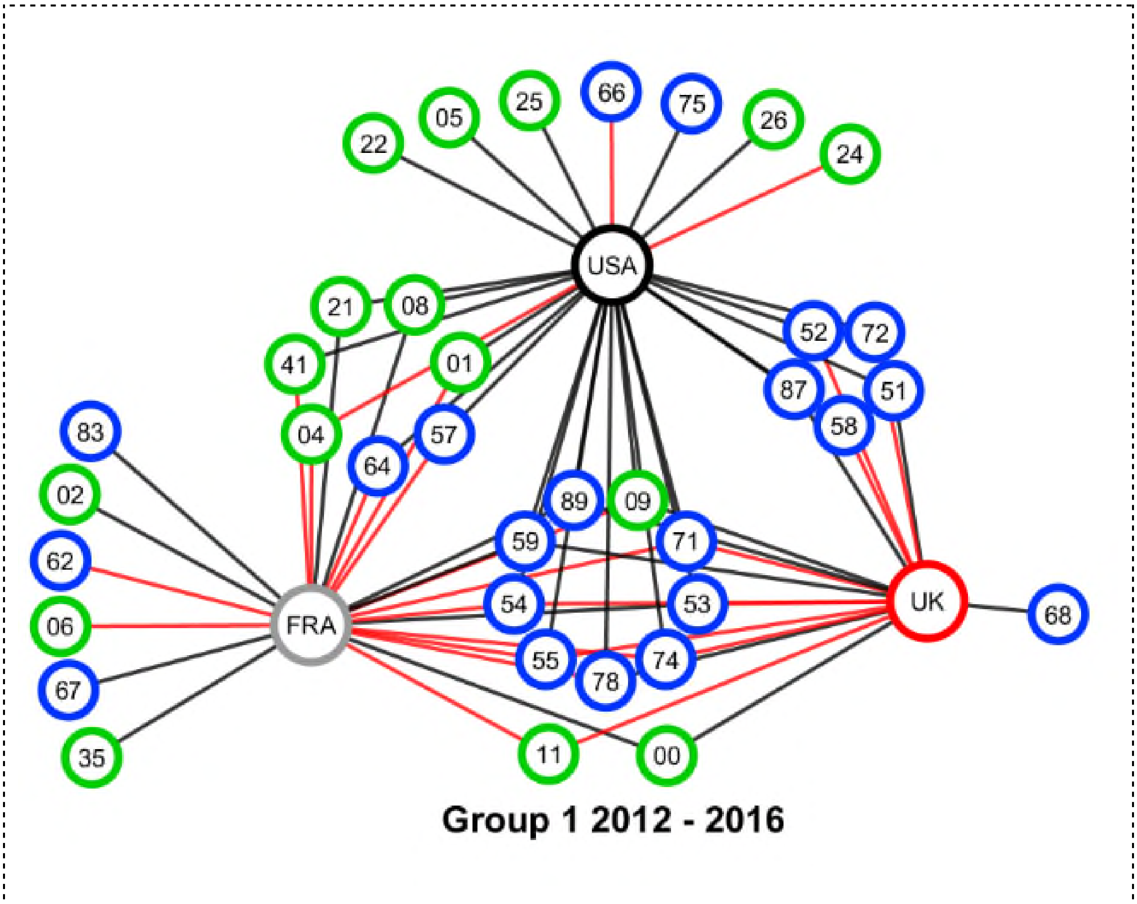
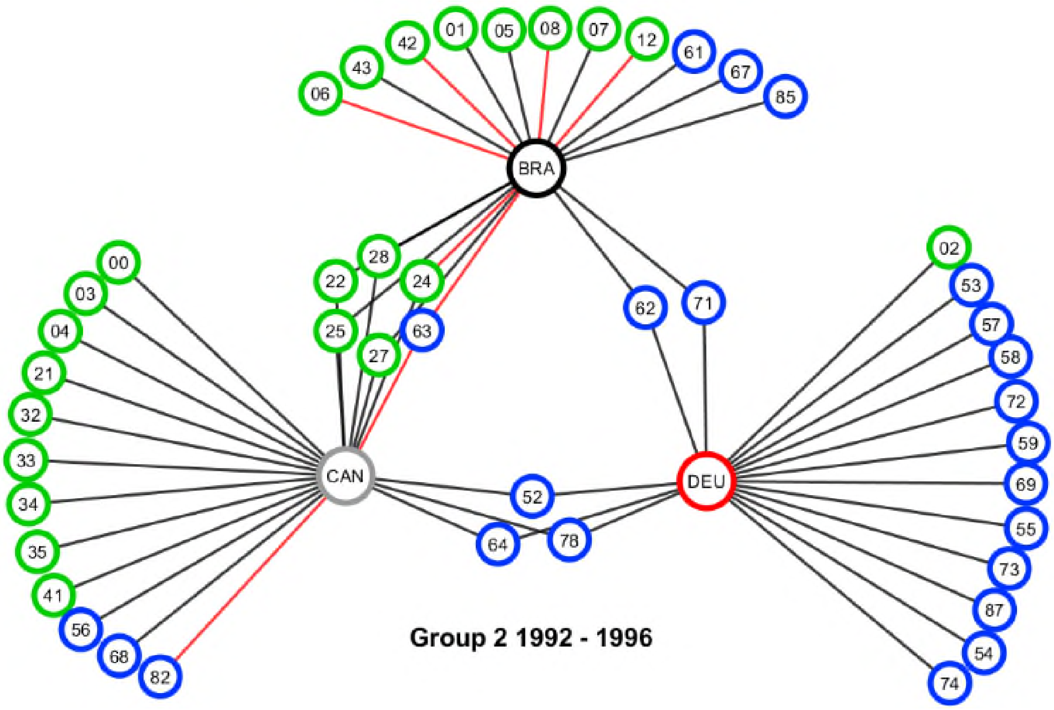
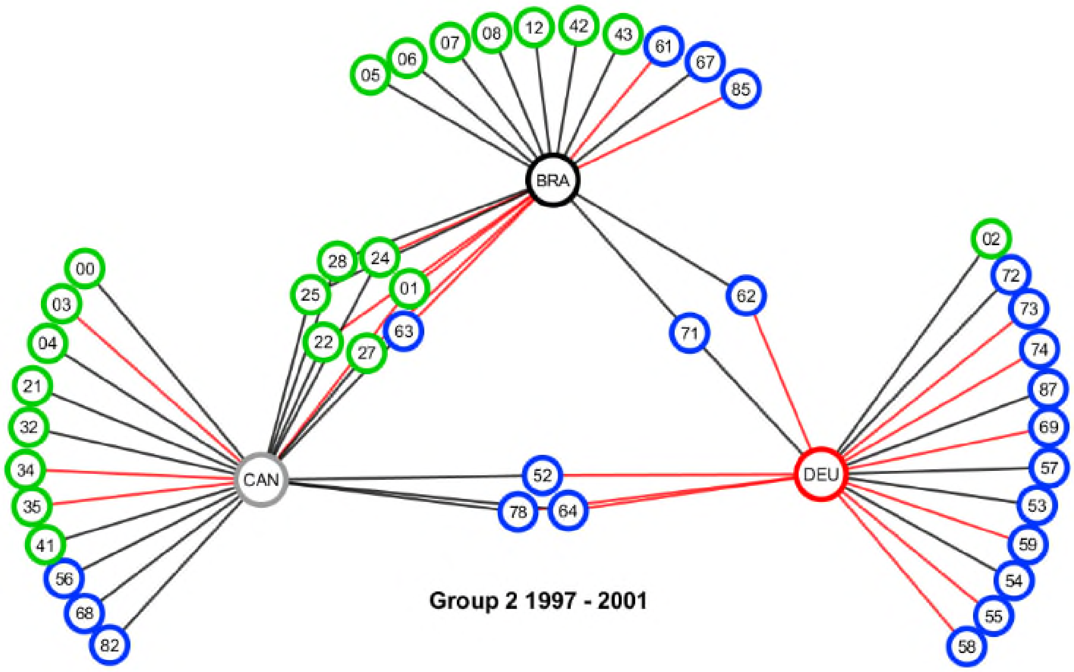


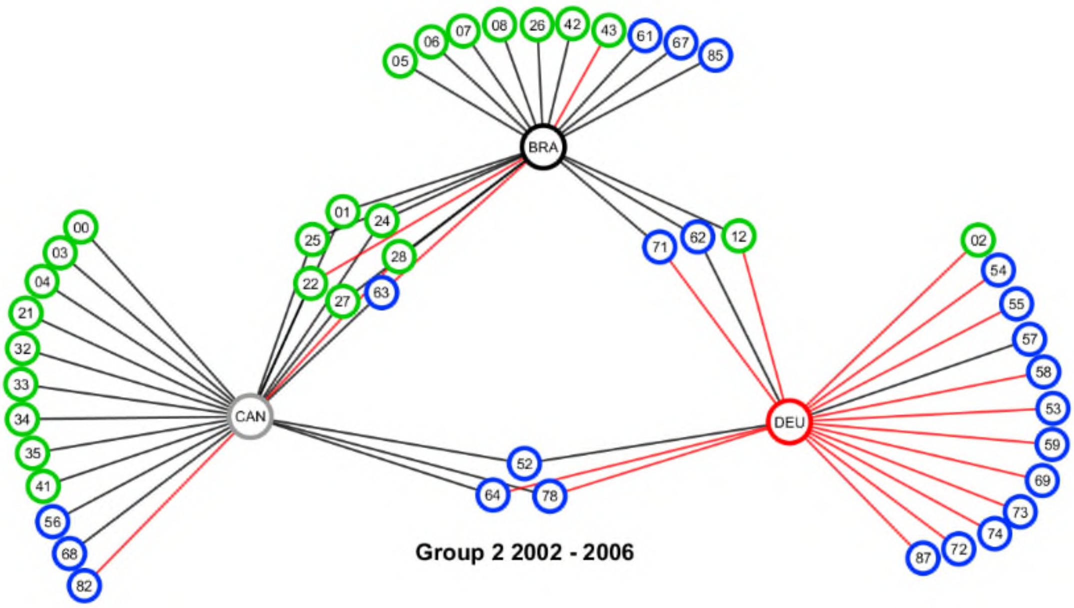
Figure 9. Bipartite country-products networks for G1



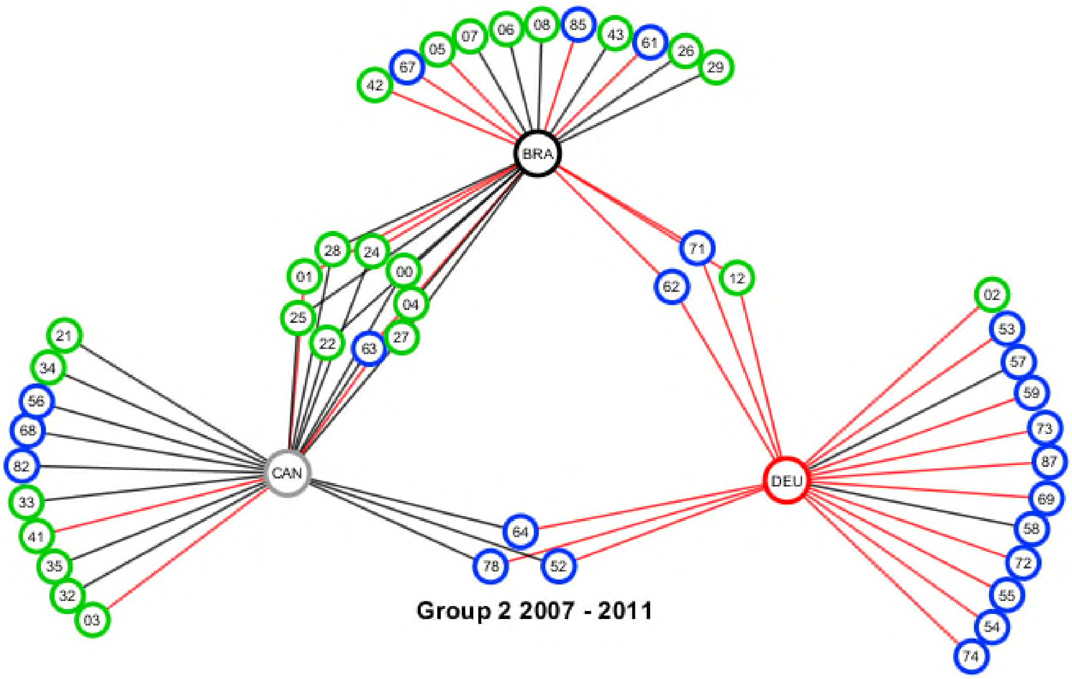
Group 2 1992 - 1996



Group 2 1997 - 2001



Group 2 2002 - 2006



Group 2 2007 - 2011

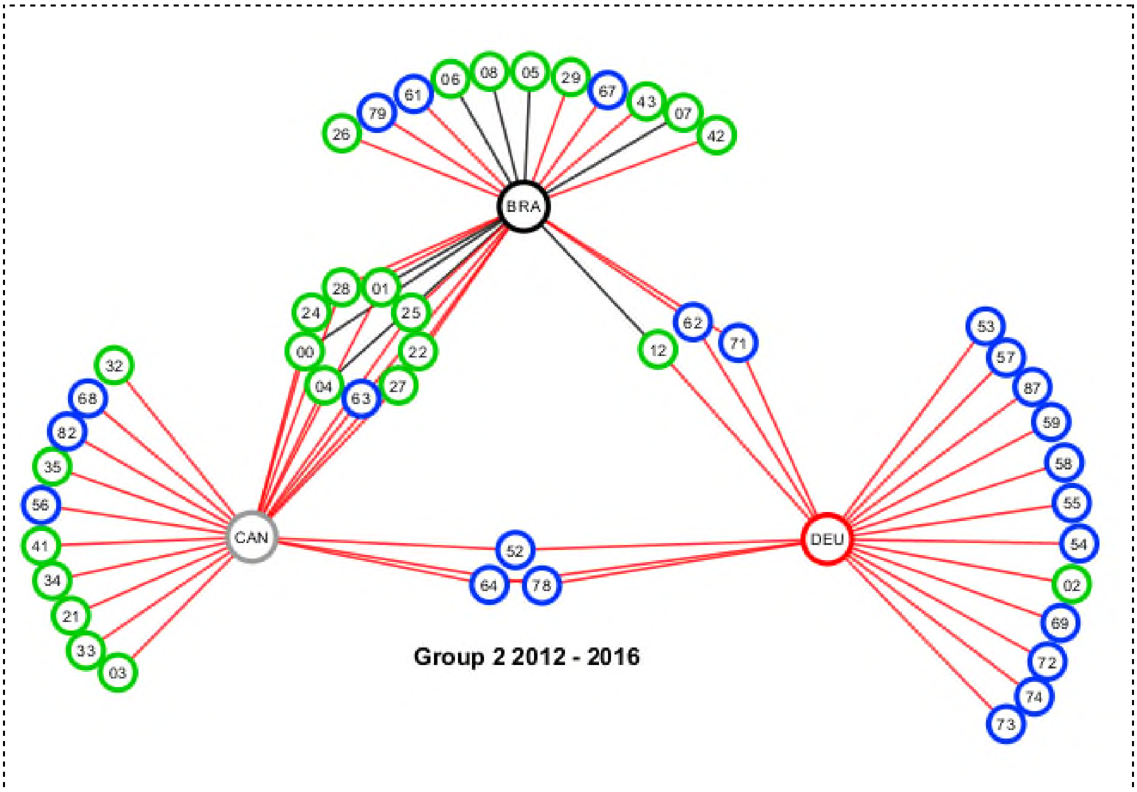


Figure 10. Bipartite country-products networks for G2

Figure 9 and Figure 10 show the evolution over the five periods of the bipartite country-products networks for group one and two, respectively.

The next step is the analysis of the networks. The pattern of connections of a network can be analysed from a macroscopic and microscopic level. The macroscopic level refers to the properties that can be observed at a network scale, while the microscopic level analyses properties that typify the particular position of an individual node in a network (Newman, 2010; Brandes *et al.*, 2013). The following metrics are selected at the macroscopic level: *centralisation*, *density, matrix temperature, Brualdi and Sanderson (BR) and nested overlap and decreasing fill (NODF),* where the two latter ones are part of a nestedness analysis; at the microscopic level: *degree centrality*.

At a network-level, the analysis is used for the identification of patterns that can be observed when considering the countries and products of each group as a whole system. From this perspective, the main expected findings are the characteristics found on the way in which products and countries are organised during the course of the different periods (for instance, the variations in the number of shared products as a group throughout all periods).

In practical terms, the analysis at a node-level is helpful for the identification of the products that have been related to the evolution of aerospace ecosystems. Two types of relations are analysed at a microscopic level: the popular products and the popular correlated products:

- Popular products are those products, apart from the aerospace products, in which the group of countries have continuously demonstrated an RCA>1 across the five periods under analysis. The product popularity is obtained by calculating the variations in the number of links per product throughout all the periods: the higher number of links, the higher popularity. These products can be identified by their position in the network, where the nodes located at the centre of the networks have the highest popularity. This is because such nodes have the highest number of connections. For instance, the most popular products for G1 from 1992 to 1996 are the six blue nodes located at the centre of the network (first graph of Figure 9): codes 51, 52, 59, 71, 74 and 78. In practical terms, this means that the three countries (France, the UK and the USA) have developed an RCA>1 on the six products. The networks' evolution evidence that the number of popular products increases overtime: it started with six product-nodes at the centre of the networks and finished with nine product-nodes in the last period.
- Popular correlated products are those products that have been the most positively correlated over the networks' evolution. Such products are obtained by calculating the variations in the number of red links per product throughout the five periods. For instance, during the first period of analysis of G2 (the first network of Figure 10), there are seven codes that have been positively correlated with the aerospace ecosystem: 06, 08, 12, 24, 42, 63 and 82. These nodes are the only products with at least one red link connected. From previous codes, the most popular correlated product is code 63. This is because it is the code with the highest number of red

links: two red links, one linked to Canada and the other one linked to Brazil. In practical terms, the previous finding means that code 63 has positively correlated on the aerospace ecosystem's growth of Canada and Brazil.

In the next sections, a description of the analysis and results of the macroscopic and microscopic levels are presented.

4.1.6 Network analysis at a macroscopic level

In this section, a description of the macroscopic analysis is described. In the first part, results of network centralisation and network density measures are presented. Then, the results of the nestedness analysis are also introduced. Here, the process for the elaboration of the adjacency matrices and the nestedness' measurement is discussed.

Centralisation measures the distribution of connectedness around particular nodes in a network. Density measures the relationship between actual and potential connections within a network. While a high value of network centralisation reveals that connections are centralised in fewer nodes, a low value reflects that the power is more equally distributed. In regards to the density of a network, the highest value is when all nodes are connected with all others (Hausmann and Hidalgo, 2010; Newman, 2010). In practical terms, results of previous measures are used for the identification of the characteristics that depict the organisation of products-countries relations per group throughout the five periods. In more detail, the main finding expected is the identification of patterns in the variation on the number of shared products by groups during the five periods.

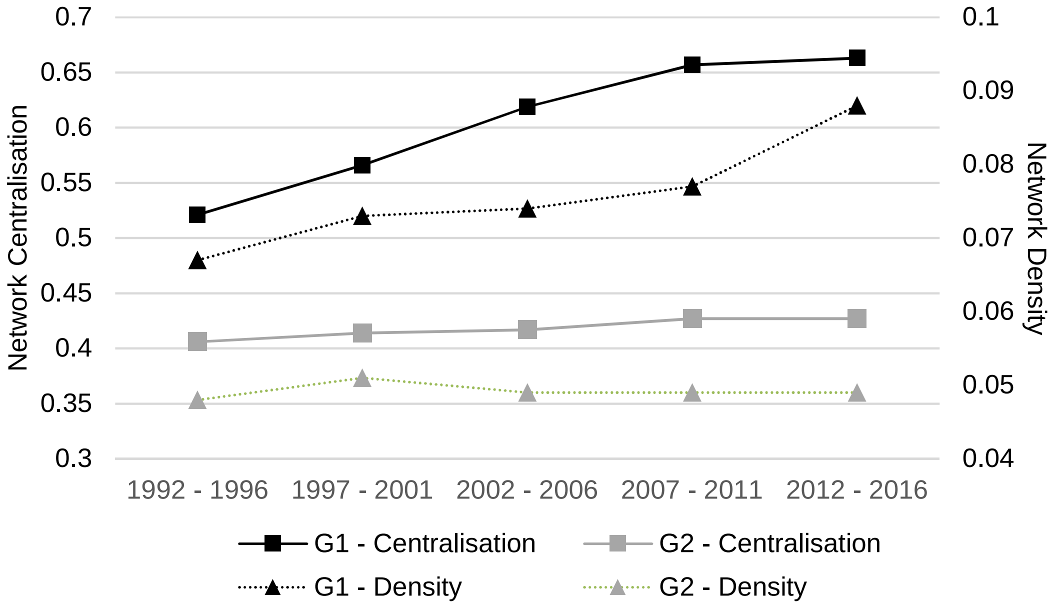


Figure 11. Network centralisation and network density for G1 and G2

Figure 11 pieces of evidence that as the aerospace ecosystem evolves, country-products networks tend to increase their cohesiveness and to distribute the power across fewer nodes. This is aligned with the RCA evolution, where both groups improved their aerospace ecosystem capability. As illustrated, across all periods of study, the group with a less developed aerospace ecosystem has lower values of centralisation and density than the developed ones. G2 developed a minor increase across the analysis, with an overall increase lower than 10% in both metrics. G1 experienced an increase higher than 20% in both measures. The difference in both metrics between the two groups relies mainly upon the variations in the number of shared products per group: the group of countries with more developed aerospace ecosystems tend to have a superior amount of shared products. Previous results evidence that networks' centrality and density of the country-products networks increase as their ecosystem improves. For instance, G1's network centrality increased from 0.52 to 0.66, and the network density increased from 0.067 to 0.88. Simultaneously, G1's RCA average increased from 2.6 to 3.9. A more detailed discussion of results, interpretation of results in practical terms and conclusions are presented in the following sections.

4.1.6.1 Nestedness analysis

Nestedness was introduced in ecology to describe patterns of two types of bipartite networks: species-species and species-habitat networks. The first one raises as a result of an interaction between two different species, in which both of them benefit from the interaction. The interaction between insects and plants, pollinators/feeders-plants, are examples of mutualistic networks (Bascompte *et al.*, 2003; Jordano, Bascompte and Olesen, 2006). The second type is used to describe the distribution patterns of species across isolated habitats. The study of the geographical distribution of species within islands are examples of these networks (Hultén, 1937; Darlington, 1957; Daubenmire, 1975). Inspired by previous studies, scientists have emulated the nestedness approach from ecology to other types of networks, such as social networks, inter-organisational networks, supply chain networks and country-products trade networks.

Aligned with previous studies, this research analyses nestedness patterns across the evolution of country-products trade networks of aerospace ecosystems. Mainly, this study emulates the mutualistic networks approach from ecology to identify patterns on the distribution of products with an RCA>1 among the evolution of aerospace ecosystems. Here, 'species' are emulated as 'products' and 'habitats' as 'countries'.

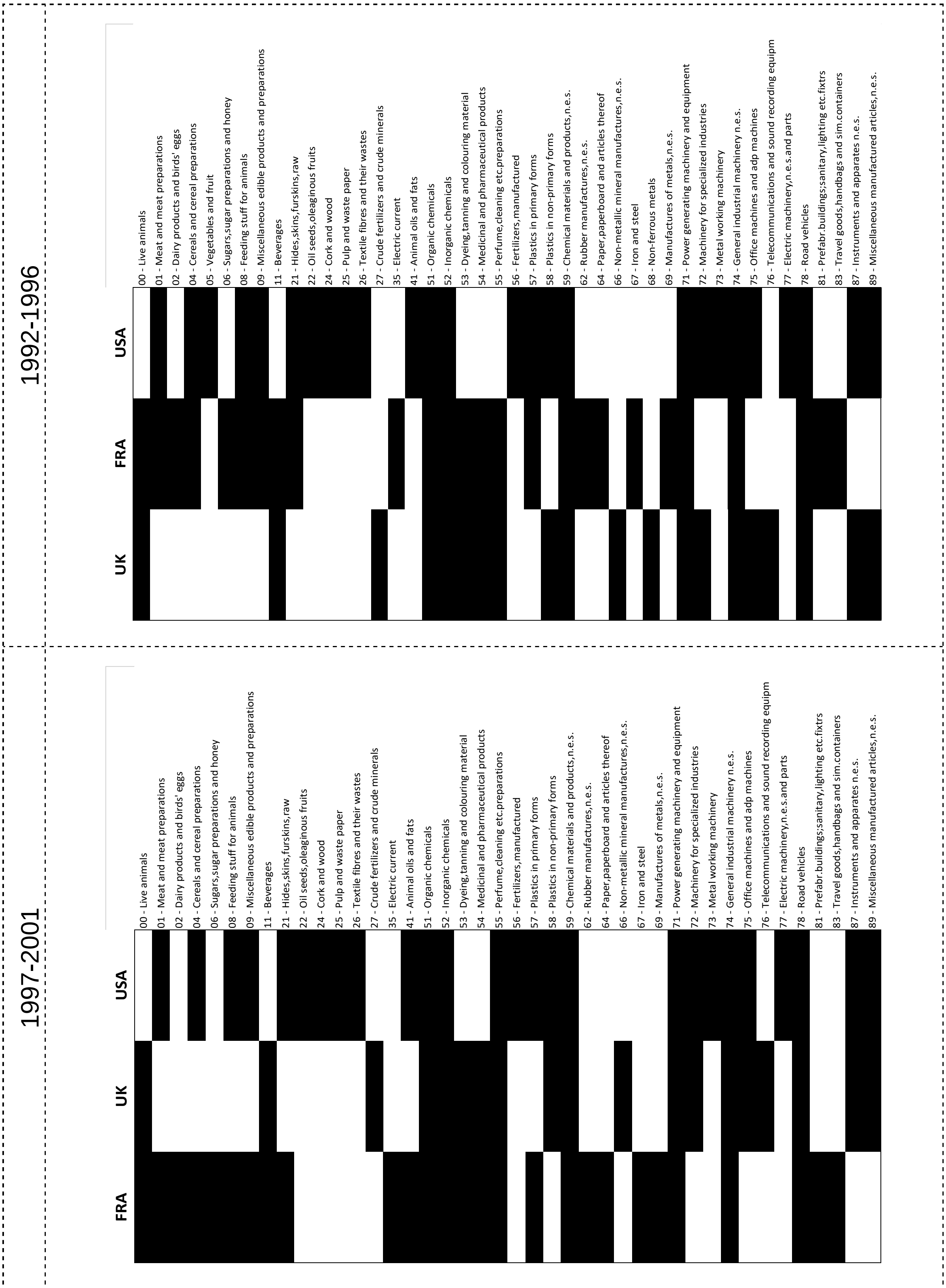
Nested patterns are analysed by using 'unpacked' and 'packed' adjacency matrices. The term 'unpacked' refers to those adjacency matrices where the sorting of rows and columns does not follow a predefined order. The term 'packed' refers to those adjacency matrices where columns and rows are sorted in decreasing order according to the marginal sums, starting in the upper rows and left-hand columns (Ulrich, Almeida-Neto and Gotelli, 2009).

A total of five 'unpacked' and five 'packed' adjacency matrices are generated for each group of countries: one 'unpacked' and one 'packed' adjacency for each bipartite country-products network (developed in section 4.1.5). Each adjacency matrix contains all the products (as columns) in which the countries (as rows) of the group have developed an RCA>1 during that period.

The ‘unpacked’ matrices for G1 and G2 are presented in Figure 12 and Figure 14, respectively. The sorting of rows and columns in these graphs does not follow a predefined order.

The ‘packed’ matrices of G1 and G2 are illustrated in Figure 13 and Figure 15, respectively. These matrices are elaborated by sorting the columns and the rows of the ‘unpacked’ matrices in decreasing order according to the marginal sums, starting in the upper rows and left-hand columns. In the ‘packed’ matrices, overlapping country-products nodes with the highest degree are grouped in the top left corner, according to the marginal sums.

The development and analysis of the evolution of the adjacency matrices are used for the identification of patterns. In particular, the study on the evolution of ‘packed’ matrices is used to identify if there are any patterns on the way in which countries have distributed their products with an RCA>1. Increased country-products’ overlapping in the top-left corner of ‘packed’ matrices shreds of evidence a nestedness’ increment. In practical terms, this means that the evolution of packed matrices depicts a pattern in which most popular products are produced by the countries with the largest number of products with an RCA>1. Moreover, this generalist-generalist interaction increases over time and accordingly to their RCA development. Thus, the results evidence that the relations between the exported products with an RCA>1 and countries are not randomly distributed. The previous conclusion is obtained after comparing the evolution of ‘unpacked’ versus ‘packed’ matrices for each group.


1992-1996
UK
FRA
USA
00 - Live animals
01 - Meat and meat preparations
02 - Dairy products and birds' eggs
04 - Cereals and cereal preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
08 - Feeding stuff for animals
09 - Miscellaneous edible products and preparations
11 - Beverages
21 - Hides,skins,furskins,raw
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
26 - Textile fibres and their wastes
27 - Crude fertilizers and crude minerals
35 - Electric current
41 - Animal oils and fats
51 - Organic chemicals
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
56 - Fertilizers,manufactured
57 - Plastics in primary forms
58 - Plastics in non-primary forms
59 - Chemical materials and products,n.e.s.
62 - Rubber manufactures,n.e.s.
64 - Paper,paperboard and articles thereof
66 - Non-metallic mineral manufactures,n.e.s.
67 - Iron and steel
68 - Non-ferrous metals
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
72 - Machinery for specialized industries
73 - Metal working machinery
74 - General industrial machinery n.e.s.
75 - Office machines and adp machines
76 - Telecommunications and sound recording equipm
77 - Electric machinery,n.e.s.and parts
78 - Road vehicles
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
83 - Travel goods,handbags and sim.containers
87 - Instruments and apparates n.e.s.
89 - Miscellaneous manufactured articles,n.e.s.
1997-2001
FRA
UK
USA
00 - Live animals
01 - Meat and meat preparations
02 - Dairy products and birds' eggs
04 - Cereals and cereal preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
08 - Feeding stuff for animals
09 - Miscellaneous edible products and preparations
11 - Beverages
21 - Hides,skins,furskins,raw
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
26 - Textile fibres and their wastes
27 - Crude fertilizers and crude minerals
35 - Electric current
41 - Animal oils and fats
51 - Organic chemicals
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
56 - Fertilizers,manufactured
57 - Plastics in primary forms
58 - Plastics in non-primary forms
59 - Chemical materials and products,n.e.s.
62 - Rubber manufactures,n.e.s.
64 - Paper,paperboard and articles thereof
66 - Non-metallic mineral manufactures,n.e.s.
67 - Iron and steel
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
72 - Machinery for specialized industries
73 - Metal working machinery
74 - General industrial machinery n.e.s.
75 - Office machines and adp machines
76 - Telecommunications and sound recording equipm
77 - Electric machinery,n.e.s.and parts
78 - Road vehicles
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
83 - Travel goods,handbags and sim.containers
87 - Instruments and apparates n.e.s.
89 - Miscellaneous manufactured articles,n.e.s.

2007-2011

2002-2006

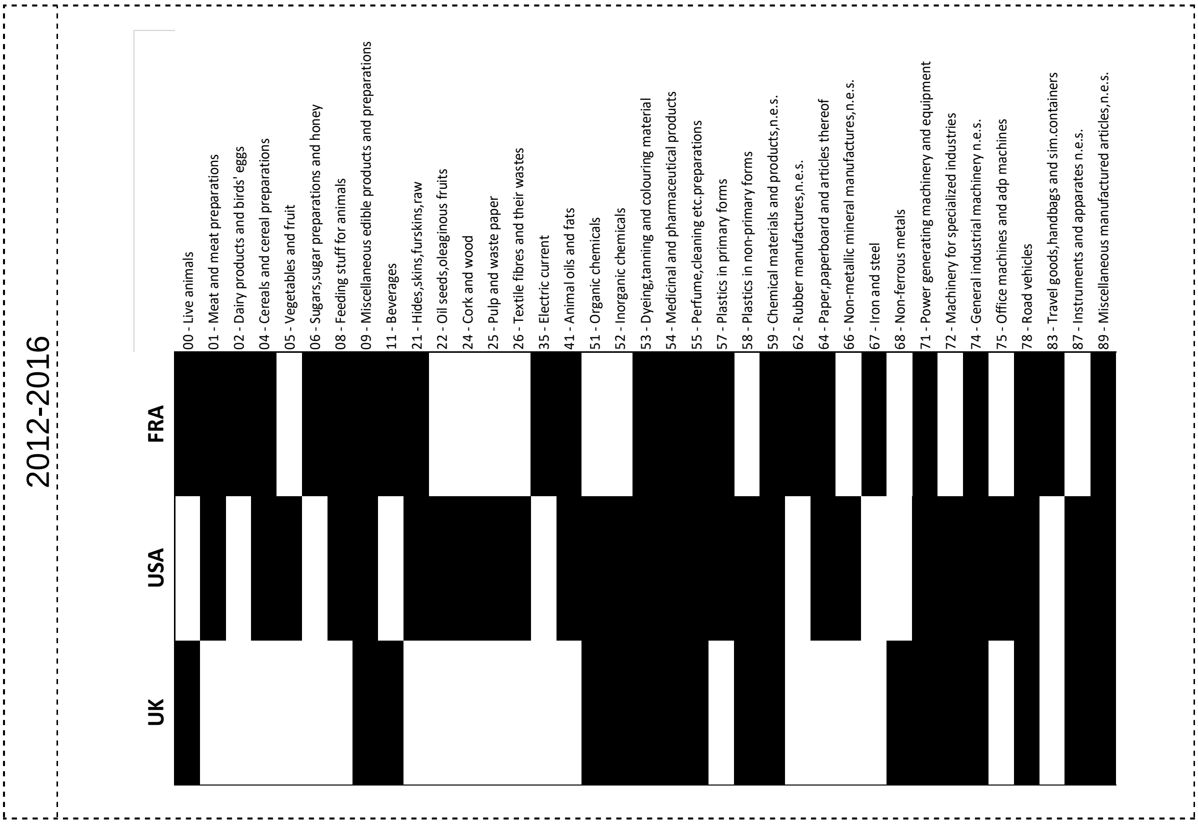
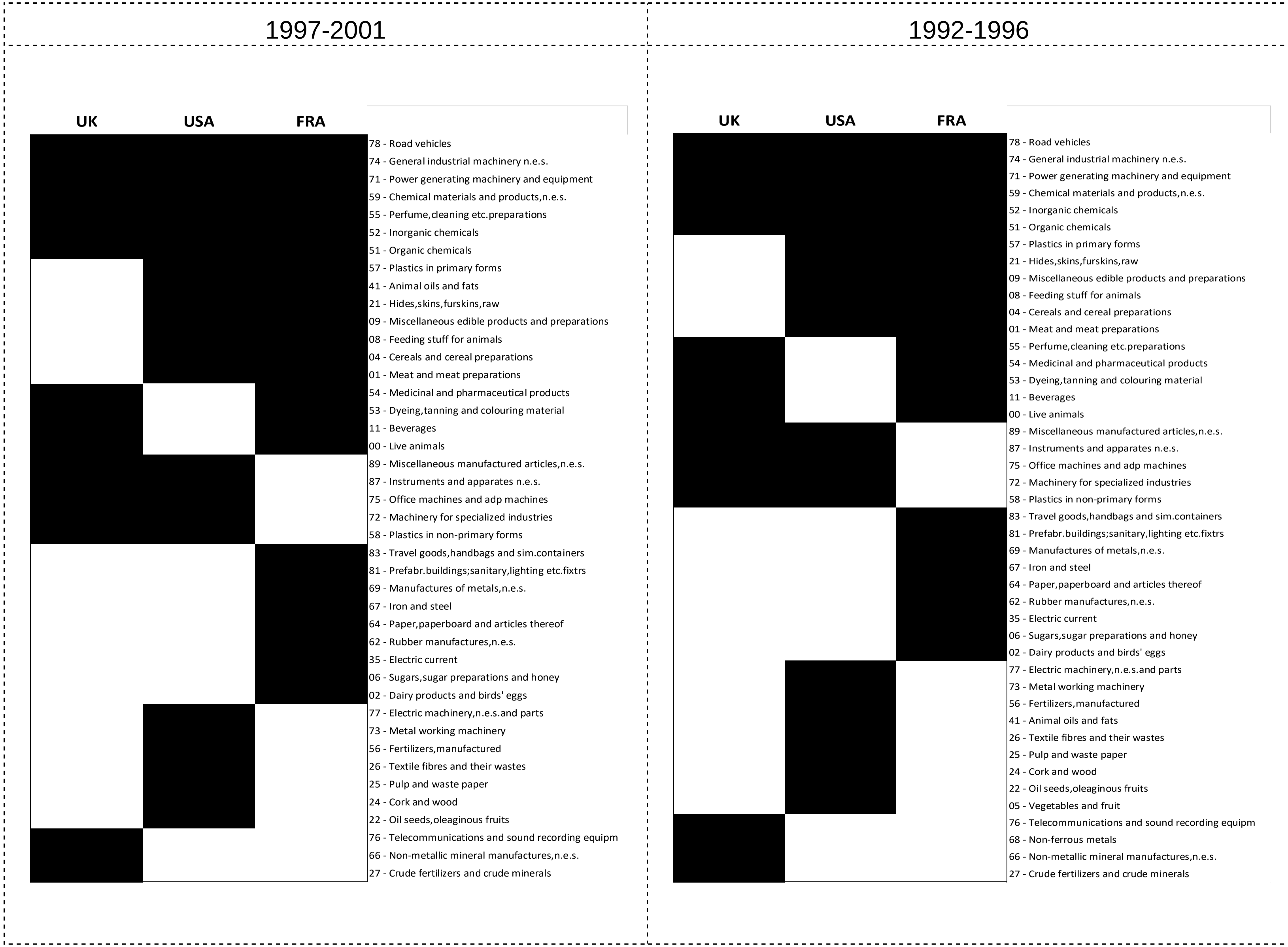
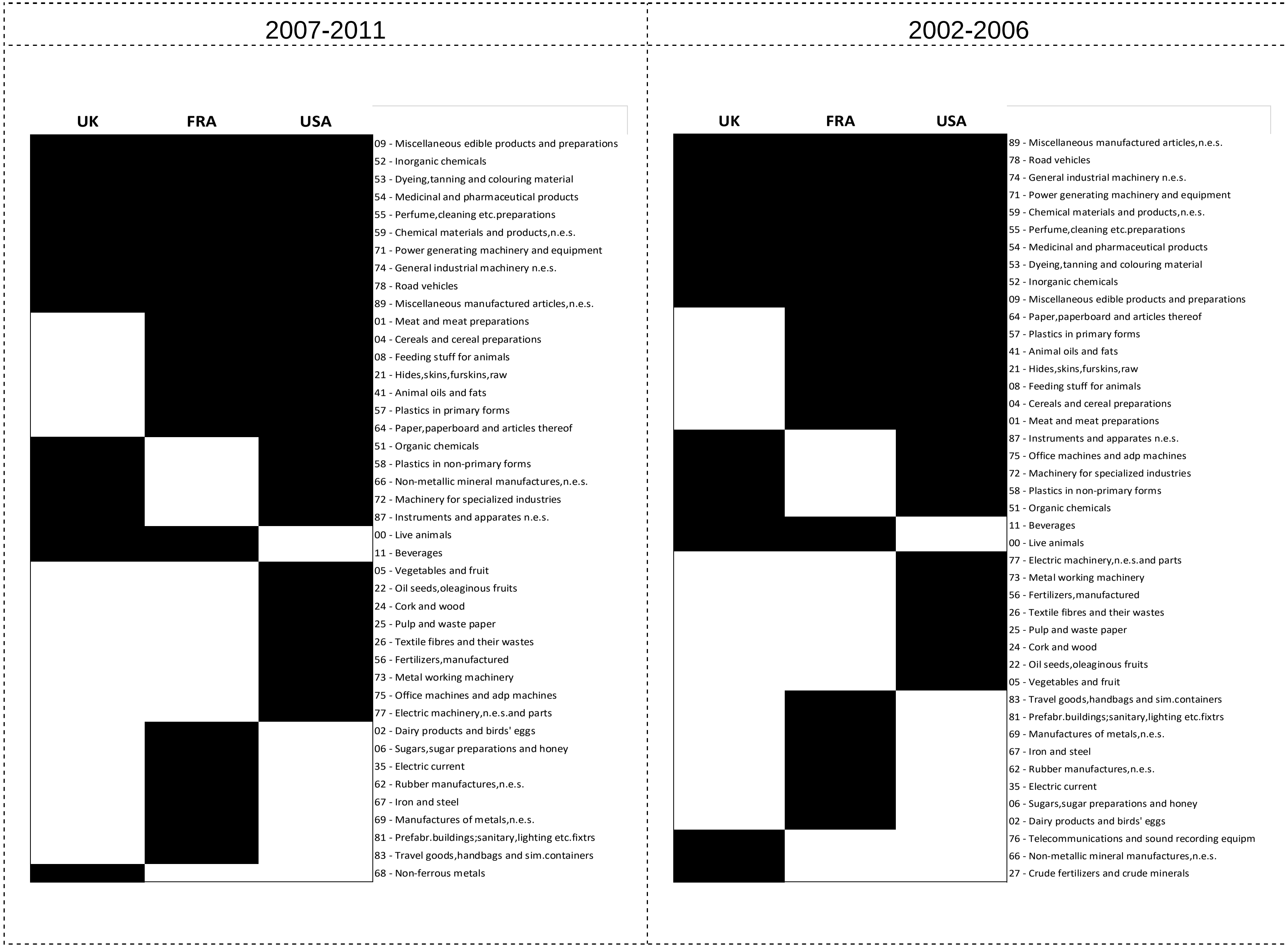


Figure 12. Evolution of unpacked matrices for G1: France, the United Kingdom and the USA


1997-2001
UK
USA
FRA
78 - Road vehicles
74 - General industrial machinery n.e.s.
71 - Power generating machinery and equipment
59 - Chemical materials and products,n.e.s.
55 - Perfume,cleaning etc.preparations
52 - Inorganic chemicals
51 - Organic chemicals
57 - Plastics in primary forms
41 - Animal oils and fats
21 - Hides,skins,furskins,raw
09 - Miscellaneous edible products and preparations
08 - Feeding stuff for animals
04 - Cereals and cereal preparations
01 - Meat and meat preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
11 - Beverages
00 - Live animals
89 - Miscellaneous manufactured articles,n.e.s.
87 - Instruments and apparates n.e.s.
75 - Office machines and adp machines
72 - Machinery for specialized industries
58 - Plastics in non-primary forms
83 - Travel goods,handbags and sim.containers
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
69 - Manufactures of metals,n.e.s.
67 - Iron and steel
64 - Paper,paperboard and articles thereof
62 - Rubber manufactures,n.e.s.
35 - Electric current
06 - Sugars,sugar preparations and honey
02 - Dairy products and birds' eggs
77 - Electric machinery,n.e.s.and parts
73 - Metal working machinery
56 - Fertilizers,manufactured
26 - Textile fibres and their wastes
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
76 - Telecommunications and sound recording equipm
66 - Non-metallic mineral manufactures,n.e.s.
27 - Crude fertilizers and crude minerals
1992-1996
UK
USA
FRA
78 - Road vehicles
74 - General industrial machinery n.e.s.
71 - Power generating machinery and equipment
59 - Chemical materials and products,n.e.s.
52 - Inorganic chemicals
51 - Organic chemicals
57 - Plastics in primary forms
21 - Hides,skins,furskins,raw
09 - Miscellaneous edible products and preparations
08 - Feeding stuff for animals
04 - Cereals and cereal preparations
01 - Meat and meat preparations
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
11 - Beverages
00 - Live animals
89 - Miscellaneous manufactured articles,n.e.s.
87 - Instruments and apparates n.e.s.
75 - Office machines and adp machines
72 - Machinery for specialized industries
58 - Plastics in non-primary forms
83 - Travel goods,handbags and sim.containers
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
69 - Manufactures of metals,n.e.s.
67 - Iron and steel
64 - Paper,paperboard and articles thereof
62 - Rubber manufactures,n.e.s.
35 - Electric current
06 - Sugars,sugar preparations and honey
02 - Dairy products and birds' eggs
77 - Electric machinery,n.e.s.and parts
73 - Metal working machinery
56 - Fertilizers,manufactured
41 - Animal oils and fats
26 - Textile fibres and their wastes
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
05 - Vegetables and fruit
76 - Telecommunications and sound recording equipm
68 - Non-ferrous metals
66 - Non-metallic mineral manufactures,n.e.s.
27 - Crude fertilizers and crude minerals


2007-2011
2002-2006
UK
FRA
USA
09 - Miscellaneous edible products and preparations
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
59 - Chemical materials and products,n.e.s.
71 - Power generating machinery and equipment
74 - General industrial machinery n.e.s.
78 - Road vehicles
89 - Miscellaneous manufactured articles,n.e.s.
01 - Meat and meat preparations
04 - Cereals and cereal preparations
08 - Feeding stuff for animals
21 - Hides,skins,furskins,raw
41 - Animal oils and fats
57 - Plastics in primary forms
64 - Paper,paperboard and articles thereof
51 - Organic chemicals
58 - Plastics in non-primary forms
66 - Non-metallic mineral manufactures,n.e.s.
72 - Machinery for specialized industries
87 - Instruments and apparates n.e.s.
00 - Live animals
11 - Beverages
05 - Vegetables and fruit
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
26 - Textile fibres and their wastes
56 - Fertilizers,manufactured
73 - Metal working machinery
75 - Office machines and adp machines
77 - Electric machinery,n.e.s.and parts
02 - Dairy products and birds' eggs
06 - Sugars,sugar preparations and honey
35 - Electric current
62 - Rubber manufactures,n.e.s.
67 - Iron and steel
69 - Manufactures of metals,n.e.s.
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
83 - Travel goods,handbags and sim.containers
68 - Non-ferrous metals
UK
FRA
USA
89 - Miscellaneous manufactured articles,n.e.s.
78 - Road vehicles
74 - General industrial machinery n.e.s.
71 - Power generating machinery and equipment
59 - Chemical materials and products,n.e.s.
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
52 - Inorganic chemicals
09 - Miscellaneous edible products and preparations
64 - Paper,paperboard and articles thereof
57 - Plastics in primary forms
41 - Animal oils and fats
21 - Hides,skins,furskins,raw
08 - Feeding stuff for animals
04 - Cereals and cereal preparations
01 - Meat and meat preparations
87 - Instruments and apparates n.e.s.
75 - Office machines and adp machines
72 - Machinery for specialized industries
58 - Plastics in non-primary forms
51 - Organic chemicals
11 - Beverages
00 - Live animals
77 - Electric machinery,n.e.s.and parts
73 - Metal working machinery
56 - Fertilizers,manufactured
26 - Textile fibres and their wastes
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
05 - Vegetables and fruit
83 - Travel goods,handbags and sim.containers
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
69 - Manufactures of metals,n.e.s.
67 - Iron and steel
62 - Rubber manufactures,n.e.s.
35 - Electric current
06 - Sugars,sugar preparations and honey
02 - Dairy products and birds' eggs
76 - Telecommunications and sound recording equipm
66 - Non-metallic mineral manufactures,n.e.s.
27 - Crude fertilizers and crude minerals

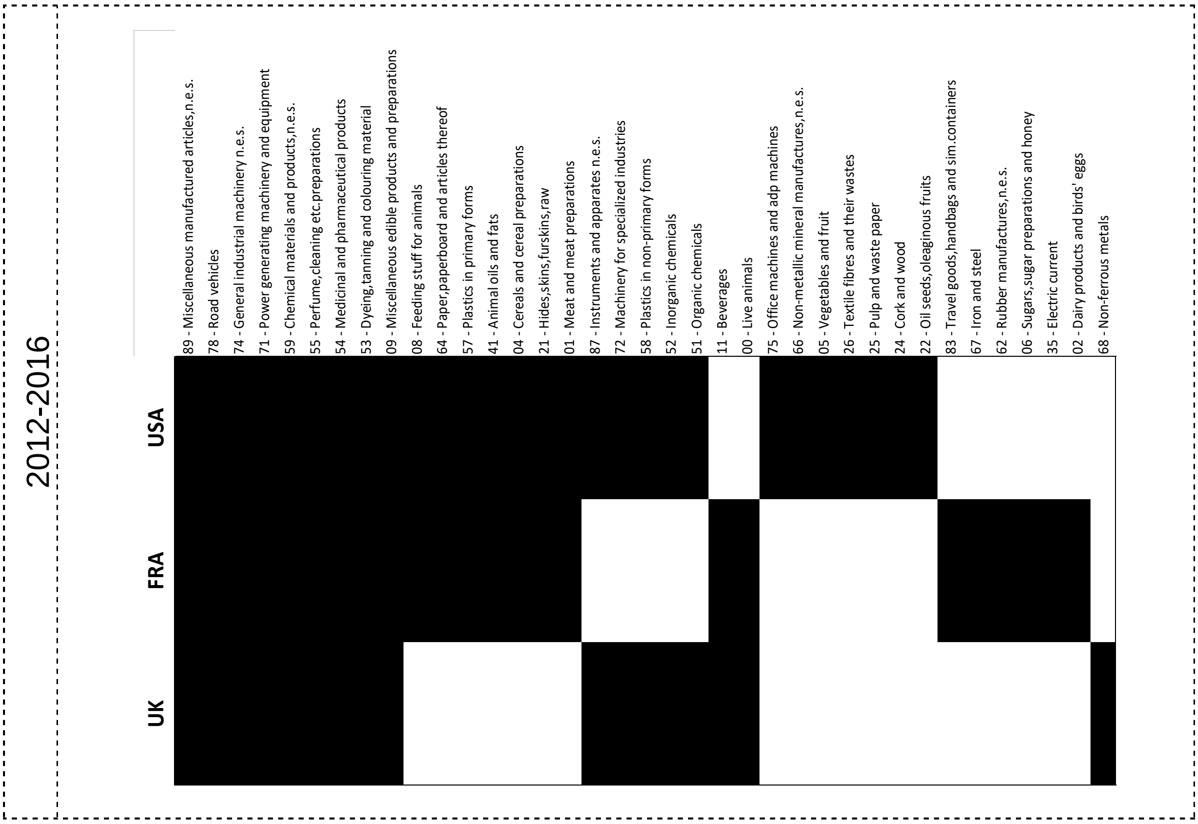
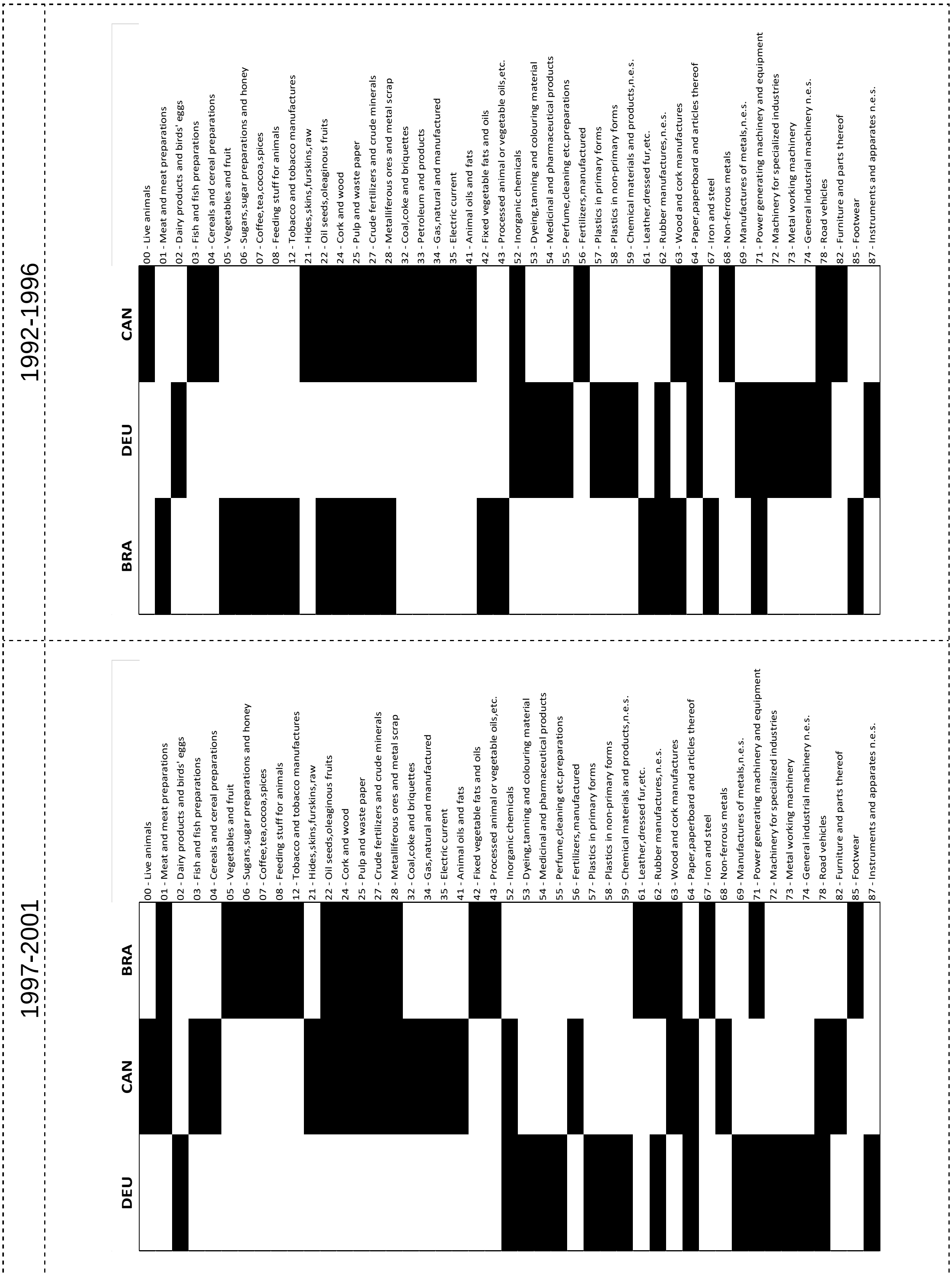
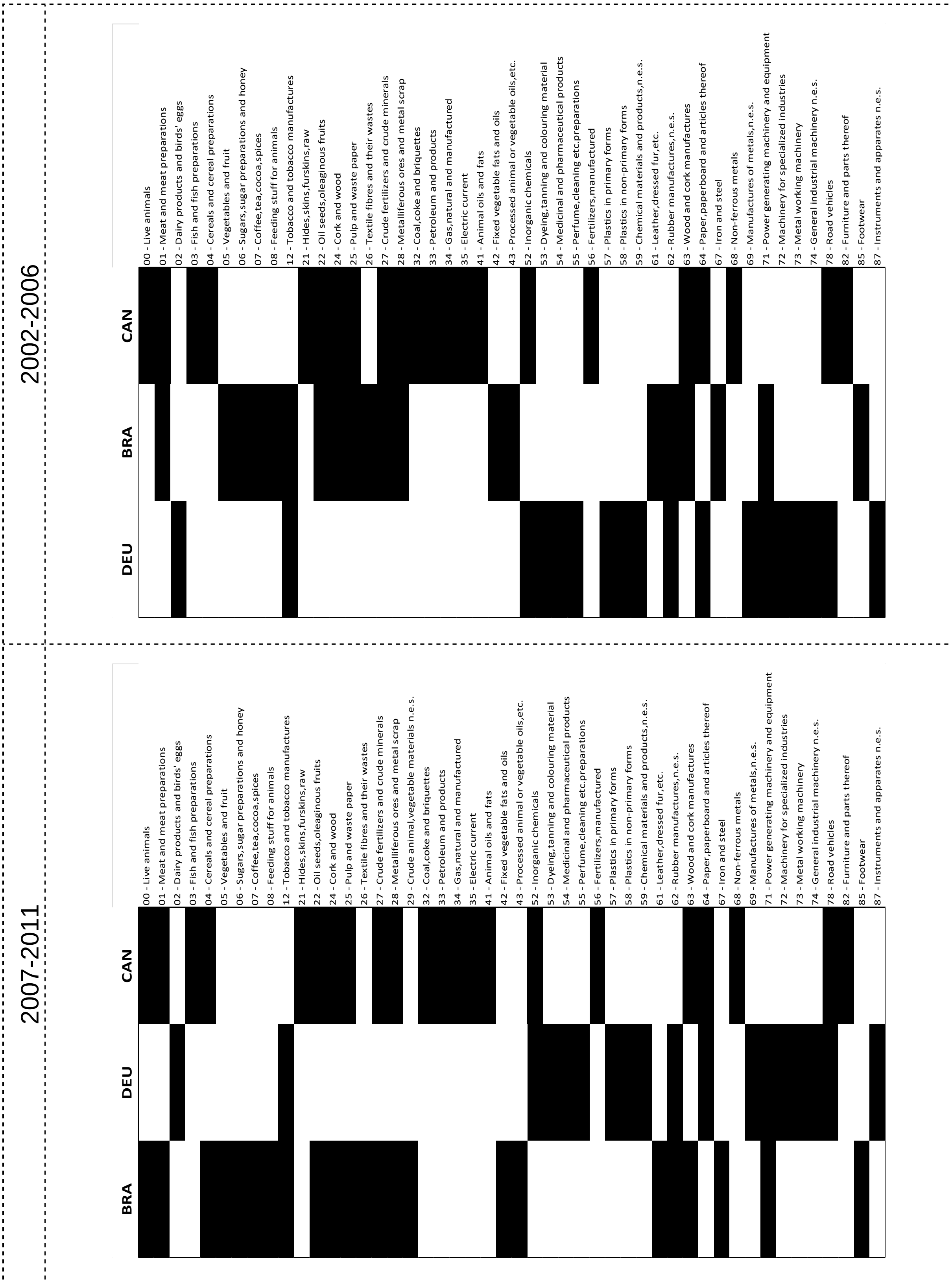


Figure 13. Evolution of packed matrices for G1: France, the United Kingdom and the USA


1992-1996
1997-2001
BRA
DEU
CAN
00 - Live animals
01 - Meat and meat preparations
02 - Dairy products and birds' eggs
03 - Fish and fish preparations
04 - Cereals and cereal preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
07 - Coffee,tea,cocoa,spices
08 - Feeding stuff for animals
12 - Tobacco and tobacco manufactures
21 - Hides,skins,furskins,raw
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
27 - Crude fertilizers and crude minerals
28 - Metalliferous ores and metal scrap
32 - Coal,coke and briquettes
33 - Petroleum and products
34 - Gas,natural and manufactured
35 - Electric current
41 - Animal oils and fats
42 - Fixed vegetable fats and oils
43 - Processed animal or vegetable oils,etc.
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
56 - Fertilizers,manufactured
57 - Plastics in primary forms
58 - Plastics in non-primary forms
59 - Chemical materials and products,n.e.s.
61 - Leather,dressed fur,etc.
62 - Rubber manufactures,n.e.s.
63 - Wood and cork manufactures
64 - Paper,paperboard and articles thereof
67 - Iron and steel
68 - Non-ferrous metals
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
72 - Machinery for specialized industries
73 - Metal working machinery
74 - General industrial machinery n.e.s.
78 - Road vehicles
82 - Furniture and parts thereof
85 - Footwear
87 - Instruments and apparates n.e.s.


2002-2006
DEU
BRA
CAN
00 - Live animals
01 - Meat and meat preparations
02 - Dairy products and birds' eggs
03 - Fish and fish preparations
04 - Cereals and cereal preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
07 - Coffee,tea,cocoa,spices
08 - Feeding stuff for animals
12 - Tobacco and tobacco manufactures
21 - Hides,skins,furskins,raw
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
26 - Textile fibres and their wastes
27 - Crude fertilizers and crude minerals
28 - Metalliferous ores and metal scrap
32 - Coal,coke and briquettes
33 - Petroleum and products
34 - Gas,natural and manufactured
35 - Electric current
41 - Animal oils and fats
42 - Fixed vegetable fats and oils
43 - Processed animal or vegetable oils,etc.
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
56 - Fertilizers,manufactured
57 - Plastics in primary forms
58 - Plastics in non-primary forms
59 - Chemical materials and products,n.e.s.
61 - Leather,dressed fur,etc.
62 - Rubber manufactures,n.e.s.
63 - Wood and cork manufactures
64 - Paper,paperboard and articles thereof
67 - Iron and steel
68 - Non-ferrous metals
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
72 - Machinery for specialized industries
73 - Metal working machinery
74 - General industrial machinery n.e.s.
78 - Road vehicles
82 - Furniture and parts thereof
85 - Footwear
87 - Instruments and apparates n.e.s.
2007-2011
BRA
DEU
CAN
00 - Live animals
01 - Meat and meat preparations
02 - Dairy products and birds' eggs
03 - Fish and fish preparations
04 - Cereals and cereal preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
07 - Coffee,tea,cocoa,spices
08 - Feeding stuff for animals
12 - Tobacco and tobacco manufactures
21 - Hides,skins,furskins,raw
22 - Oil seeds,oleaginous fruits
24 - Cork and wood
25 - Pulp and waste paper
26 - Textile fibres and their wastes
27 - Crude fertilizers and crude minerals
28 - Metalliferous ores and metal scrap
29 - Crude animal,vegetable materials n.e.s.
32 - Coal,coke and briquettes
33 - Petroleum and products
34 - Gas,natural and manufactured
35 - Electric current
41 - Animal oils and fats
42 - Fixed vegetable fats and oils
43 - Processed animal or vegetable oils,etc.
52 - Inorganic chemicals
53 - Dyeing,tanning and colouring material
54 - Medicinal and pharmaceutical products
55 - Perfume,cleaning etc.preparations
56 - Fertilizers,manufactured
57 - Plastics in primary forms
58 - Plastics in non-primary forms
59 - Chemical materials and products,n.e.s.
61 - Leather,dressed fur,etc.
62 - Rubber manufactures,n.e.s.
63 - Wood and cork manufactures
64 - Paper,paperboard and articles thereof
67 - Iron and steel
68 - Non-ferrous metals
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
72 - Machinery for specialized industries
73 - Metal working machinery
74 - General industrial machinery n.e.s.
78 - Road vehicles
82 - Furniture and parts thereof
85 - Footwear
87 - Instruments and apparates n.e.s.

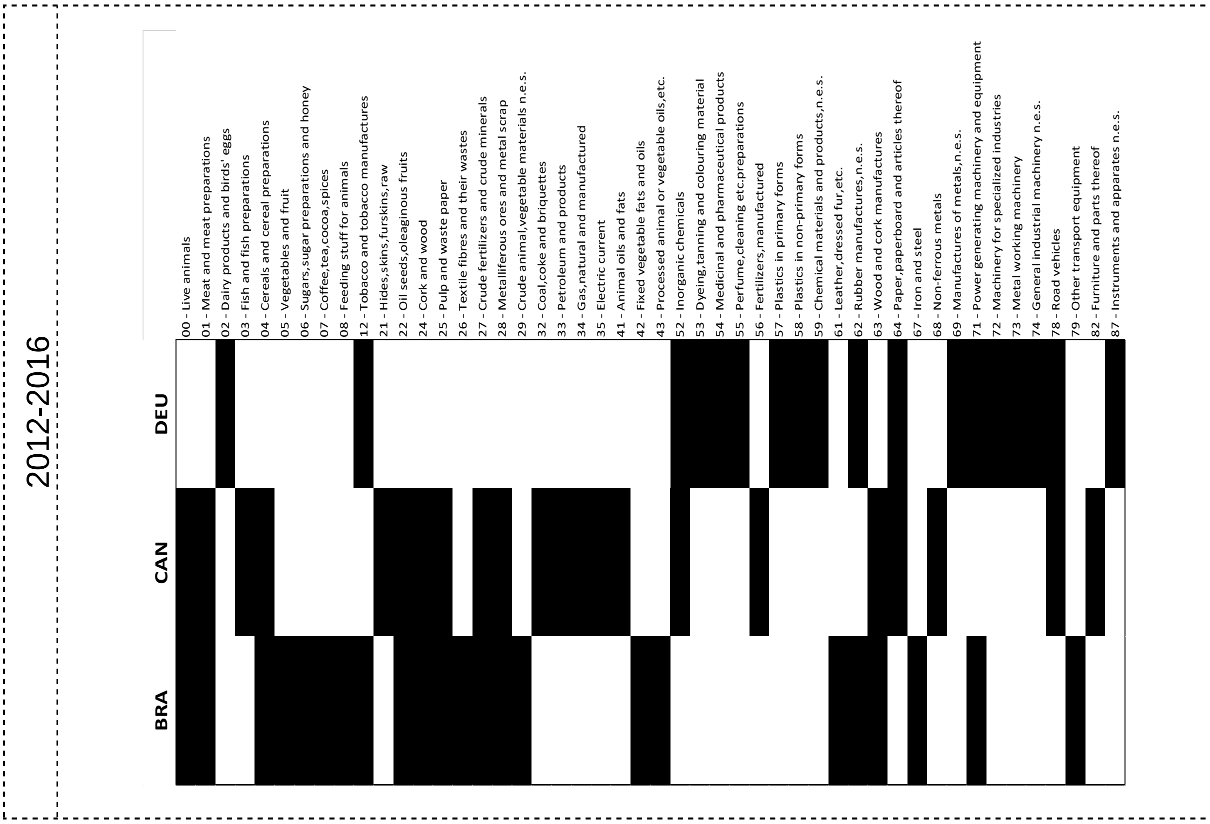
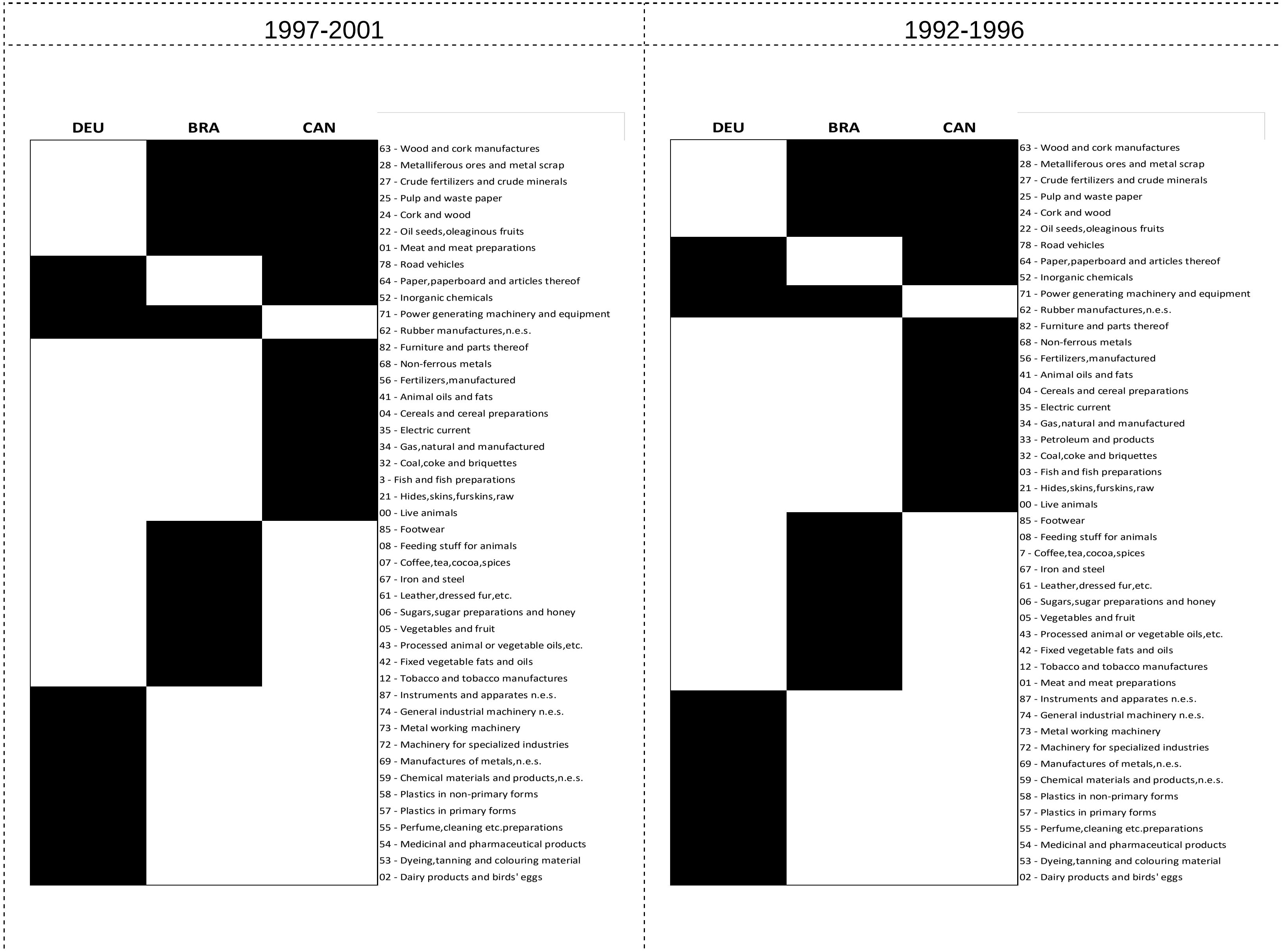
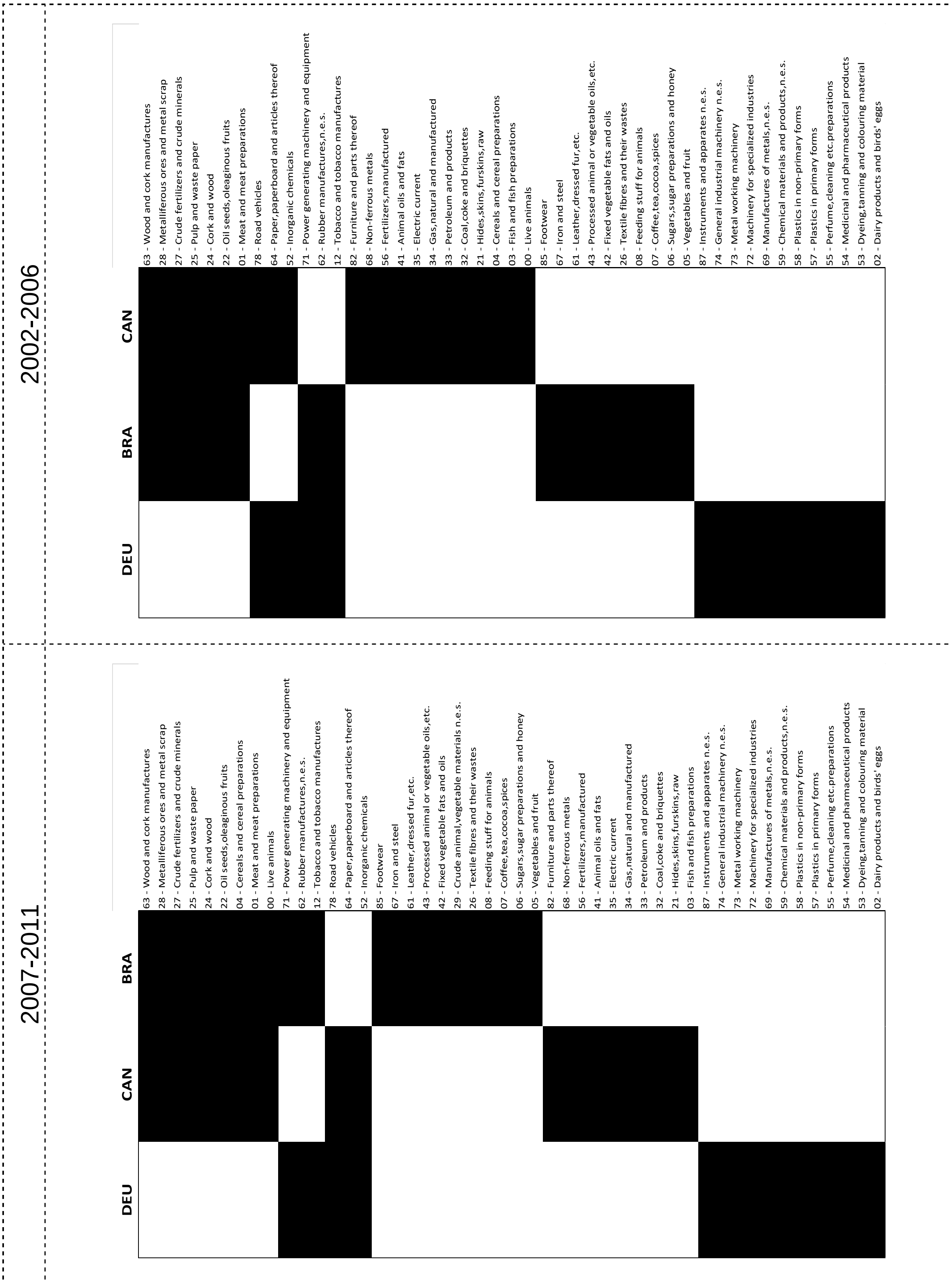


Figure 14. Evolution of unpacked matrices for G2: Brazil, Canada and Germany


1997-2001
DEU
BRA
CAN
63 - Wood and cork manufactures
28 - Metalliferous ores and metal scrap
27 - Crude fertilizers and crude minerals
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
01 - Meat and meat preparations
78 - Road vehicles
64 - Paper,paperboard and articles thereof
52 - Inorganic chemicals
71 - Power generating machinery and equipment
62 - Rubber manufactures,n.e.s.
82 - Furniture and parts thereof
68 - Non-ferrous metals
56 - Fertilizers,manufactured
41 - Animal oils and fats
04 - Cereals and cereal preparations
35 - Electric current
34 - Gas,natural and manufactured
32 - Coal,coke and briquettes
3 - Fish and fish preparations
21 - Hides,skins,furskins,raw
00 - Live animals
85 - Footwear
08 - Feeding stuff for animals
07 - Coffee,tea,cocoa,spices
67 - Iron and steel
61 - Leather,dressed fur,etc.
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
43 - Processed animal or vegetable oils,etc.
42 - Fixed vegetable fats and oils
12 - Tobacco and tobacco manufactures
87 - Instruments and apparates n.e.s.
74 - General industrial machinery n.e.s.
73 - Metal working machinery
72 - Machinery for specialized industries
69 - Manufactures of metals,n.e.s.
59 - Chemical materials and products,n.e.s.
58 - Plastics in non-primary forms
57 - Plastics in primary forms
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
02 - Dairy products and birds' eggs
1992-1996
DEU
BRA
CAN
63 - Wood and cork manufactures
28 - Metalliferous ores and metal scrap
27 - Crude fertilizers and crude minerals
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
78 - Road vehicles
64 - Paper,paperboard and articles thereof
52 - Inorganic chemicals
71 - Power generating machinery and equipment
62 - Rubber manufactures,n.e.s.
82 - Furniture and parts thereof
68 - Non-ferrous metals
56 - Fertilizers,manufactured
41 - Animal oils and fats
04 - Cereals and cereal preparations
35 - Electric current
34 - Gas,natural and manufactured
33 - Petroleum and products
32 - Coal,coke and briquettes
03 - Fish and fish preparations
21 - Hides,skins,furskins,raw
00 - Live animals
85 - Footwear
08 - Feeding stuff for animals
7 - Coffee,tea,cocoa,spices
67 - Iron and steel
61 - Leather,dressed fur,etc.
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
43 - Processed animal or vegetable oils,etc.
42 - Fixed vegetable fats and oils
12 - Tobacco and tobacco manufactures
01 - Meat and meat preparations
87 - Instruments and apparates n.e.s.
74 - General industrial machinery n.e.s.
73 - Metal working machinery
72 - Machinery for specialized industries
69 - Manufactures of metals,n.e.s.
59 - Chemical materials and products,n.e.s.
58 - Plastics in non-primary forms
57 - Plastics in primary forms
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
02 - Dairy products and birds' eggs


2007-2011
DEU
CAN
BRA
63 - Wood and cork manufactures
28 - Metalliferous ores and metal scrap
27 - Crude fertilizers and crude minerals
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
04 - Cereals and cereal preparations
01 - Meat and meat preparations
00 - Live animals
71 - Power generating machinery and equipment
62 - Rubber manufactures,n.e.s.
12 - Tobacco and tobacco manufactures
78 - Road vehicles
64 - Paper,paperboard and articles thereof
52 - Inorganic chemicals
85 - Footwear
67 - Iron and steel
61 - Leather,dressed fur,etc.
43 - Processed animal or vegetable oils,etc.
42 - Fixed vegetable fats and oils
29 - Crude animal,vegetable materials n.e.s.
26 - Textile fibres and their wastes
08 - Feeding stuff for animals
07 - Coffee,tea,cocoa,spices
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
82 - Furniture and parts thereof
68 - Non-ferrous metals
56 - Fertilizers,manufactured
41 - Animal oils and fats
35 - Electric current
34 - Gas,natural and manufactured
33 - Petroleum and products
32 - Coal,coke and briquettes
21 - Hides,skins,furskins,raw
03 - Fish and fish preparations
87 - Instruments and apparates n.e.s.
74 - General industrial machinery n.e.s.
73 - Metal working machinery
72 - Machinery for specialized industries
69 - Manufactures of metals,n.e.s.
59 - Chemical materials and products,n.e.s.
58 - Plastics in non-primary forms
57 - Plastics in primary forms
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
02 - Dairy products and birds' eggs
2002-2006
DEU
BRA
CAN
63 - Wood and cork manufactures
28 - Metalliferous ores and metal scrap
27 - Crude fertilizers and crude minerals
25 - Pulp and waste paper
24 - Cork and wood
22 - Oil seeds,oleaginous fruits
01 - Meat and meat preparations
78 - Road vehicles
64 - Paper,paperboard and articles thereof
52 - Inorganic chemicals
71 - Power generating machinery and equipment
62 - Rubber manufactures,n.e.s.
12 - Tobacco and tobacco manufactures
82 - Furniture and parts thereof
68 - Non-ferrous metals
56 - Fertilizers,manufactured
41 - Animal oils and fats
35 - Electric current
34 - Gas,natural and manufactured
33 - Petroleum and products
32 - Coal,coke and briquettes
21 - Hides,skins,furskins,raw
04 - Cereals and cereal preparations
03 - Fish and fish preparations
00 - Live animals
85 - Footwear
67 - Iron and steel
61 - Leather,dressed fur,etc.
43 - Processed animal or vegetable oils,etc.
42 - Fixed vegetable fats and oils
26 - Textile fibres and their wastes
08 - Feeding stuff for animals
07 - Coffee,tea,cocoa,spices
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
87 - Instruments and apparates n.e.s.
74 - General industrial machinery n.e.s.
73 - Metal working machinery
72 - Machinery for specialized industries
69 - Manufactures of metals,n.e.s.
59 - Chemical materials and products,n.e.s.
58 - Plastics in non-primary forms
57 - Plastics in primary forms
55 - Perfume,cleaning etc.preparations
54 - Medicinal and pharmaceutical products
53 - Dyeing,tanning and colouring material
02 - Dairy products and birds' eggs

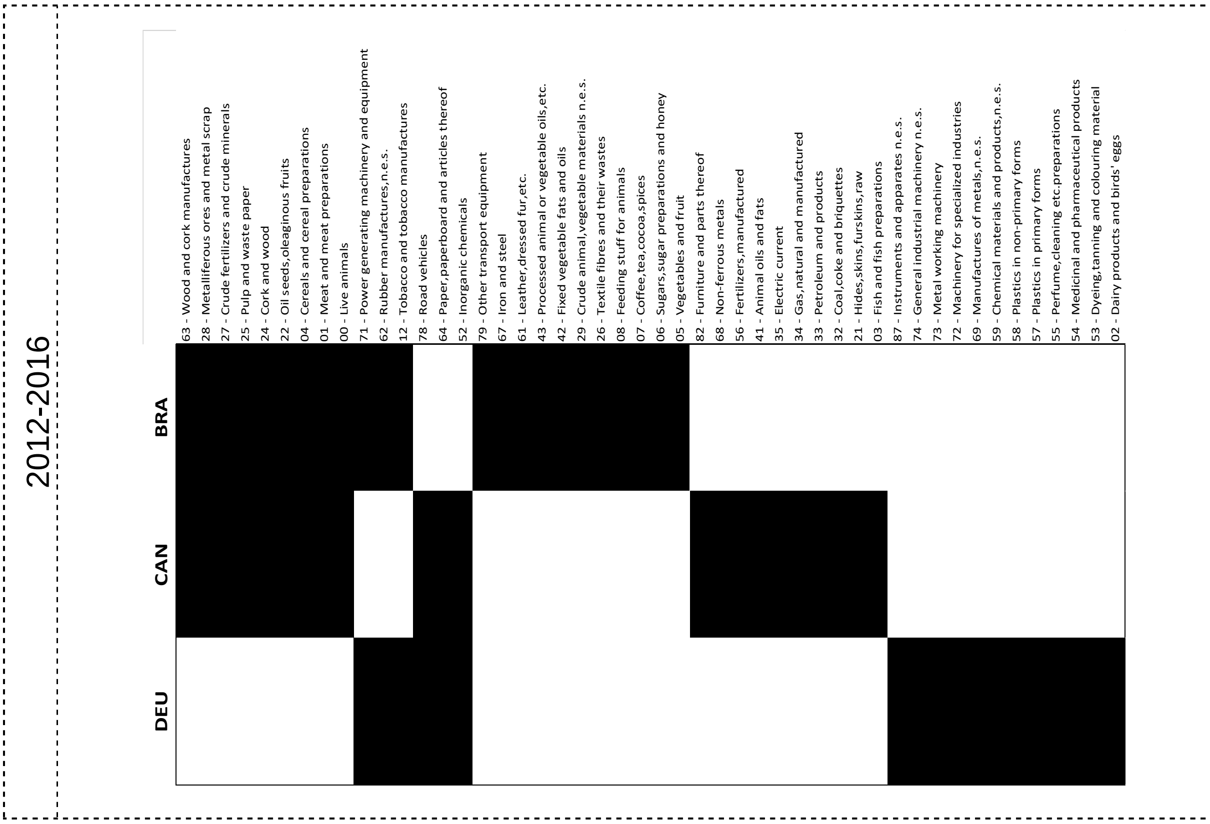
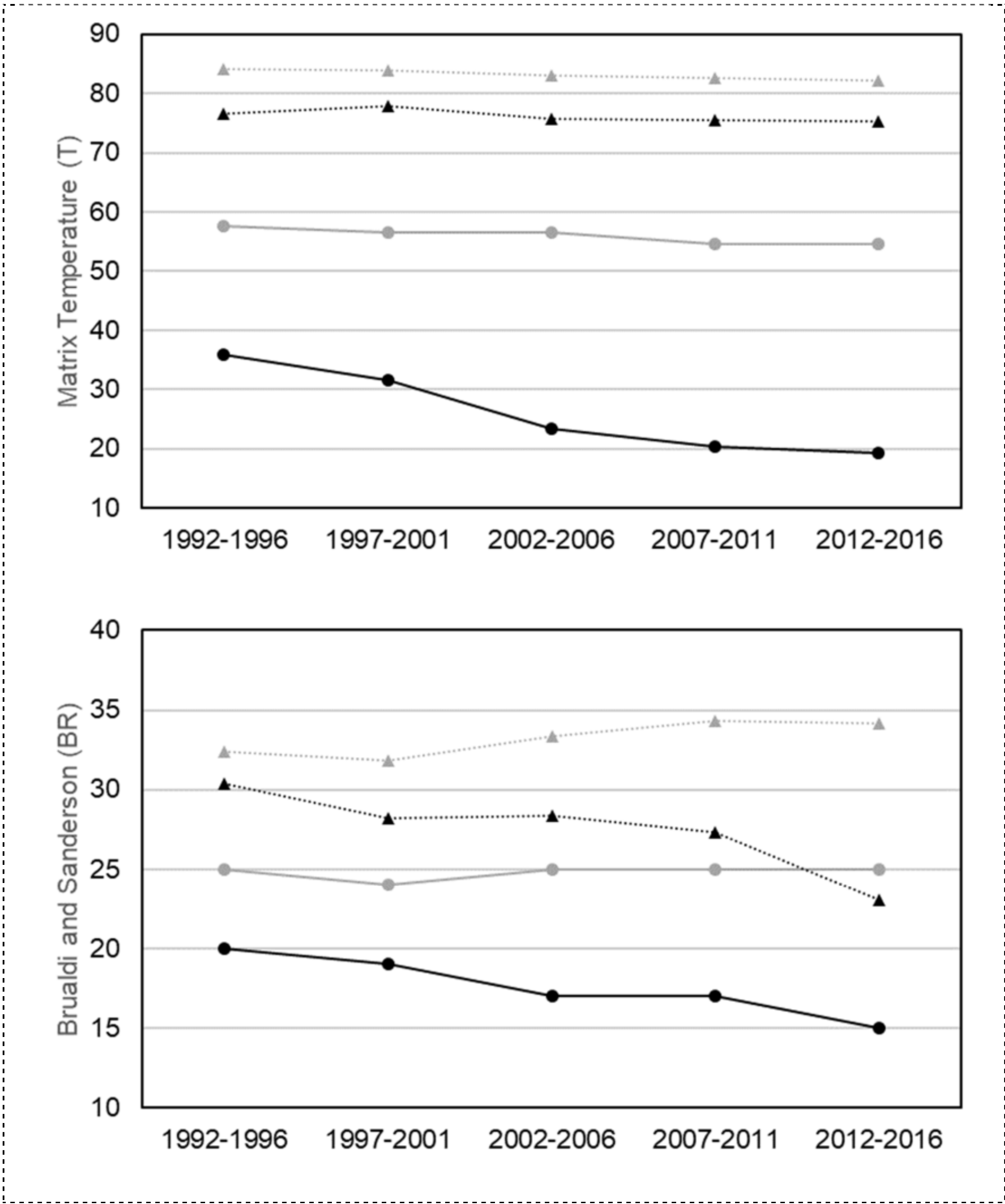


Figure 15. Evolution of packed matrices for G2: Brazil, Canada and Germany

The next step is to measure the nestedness level (and its evolution) of the packed matrices. To this aim, two steps are followed. The first one is a measurement with suitable nestedness metrics. The second step is to validate the results. The validation process is elaborated by comparing the nestedness metrics of each ‘packed’ graph with randomly generated graphs (null models); results are used to indicate if similar nestedness values can also be randomly obtained.

In regards to the nestedness’ measurement, most of the nestedness metrics are based on measuring either the gaps or the columns versus rows overlapping of the adjacency matrix. For instance, *matrix temperature (T)*, and *Brualdi and Sanderson (BR)* also named discrepancy (amount of absences) measures are gap based metrics, while *NODF* is an overlap counting metric. *T* is intrinsic to the spreading of gaps inside the matrix. A lower *T* depicts more order inside the matrix, meaning that presences are concentrated in the upper left corner; it represents the average residual from the *isocline of perfect nestedness* (Atmar and Patterson, 1993). The range is from 0 to 100, where 0 represents a perfectly nested matrix. In terms of countries-exports ecosystems, a lower temperature means the most popular products have a majority distribution in most popular countries. *BR* metric counts the number of absences or presences that must be modified to generate perfect nestedness (Brualdi and Sanderson, 1999). The less number of discrepancies, the more nestedness. *NODF* metric computes whether the occurrences of unpopular products within most popular countries, and whether depauperate country-products groupings represent subsets of the mighty ones (Ulrich, Almeida-Neto and Gotelli, 2009). The range is from 0 to 100, where 100 indicates perfect nestedness.

Then, each matrix is validated and compared with null models. Each packed matrix is compared to row-column proportional (PP) null models, as this is the most stringent and widely used among scientist to assess nestedness significance (Mariani *et al.*, 2019). Results are presented in Figure 16. Results evidence that the country-products networks are nested and that their nestedness’ level is higher when compared to randomly generated graphs. Both groups depict higher nestedness across all metrics when compared with the PP null model. Likewise, developed ecosystems, G1, have greater nestedness than the less developed ones, G2. Thus, it has been demonstrated that nestedness increases accordingly to the aerospace ecosystems evolution. A more in-depth analysis is undertaken in the following sections.



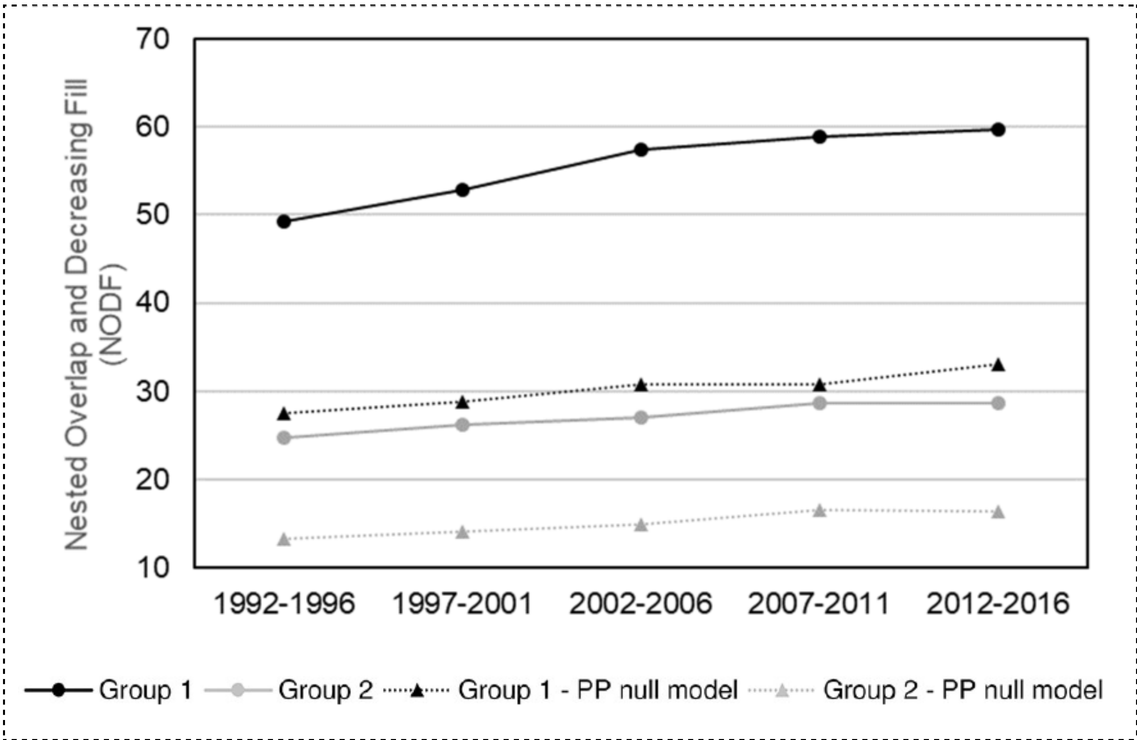


Figure 16. Nestedness measurement and validation with PP null models for G1 and G2

4.1.7 Network analysis at a microscopic level

Degree centrality is a metric used to compute the number of direct connections to a node. In this research, this measure is used to identify the most popular RCA>1 products within the ecosystems; where a higher degree reflects that more countries have an RCA>1 on a specific product (Borgatti and Halgin, 2014).

The degree centrality for each node of the bipartite networks is computed. Results are illustrated in Figure 17 (group 1) and Figure 18 (group 2). In these graphs, the commodity codes are grouped in manufactured and primary products, and the degree centrality is represented by colours: the darker the colour, the higher the degree centrality. The value of degree centrality is directly related to the number of countries that have developed an RCA>1 on that product. For instance, a degree centrality of 3 (the darkest blue) means that three countries have an RCA>1 on that product; a degree centrality of 0 (lightest blue) evidences that no country has developed an RCA>1 on that product. Results evidence that G1 has products with higher degree centrality than G2. This is evidenced by the fact that G2 does not have any product with a degree centrality of three. Results indicate that G1 has products with a higher popularity than G2. In practical terms, this means that countries of G1 develop an advantage in similar products.

The previous analysis aims at the identification of other products that have been related to the growth of aerospace ecosystems. Results are expected to serve as a foundation when an emergent ecosystem develops strategies for its aerospace ecosystem's enhancement. Further suggestions are presented in the last chapter.

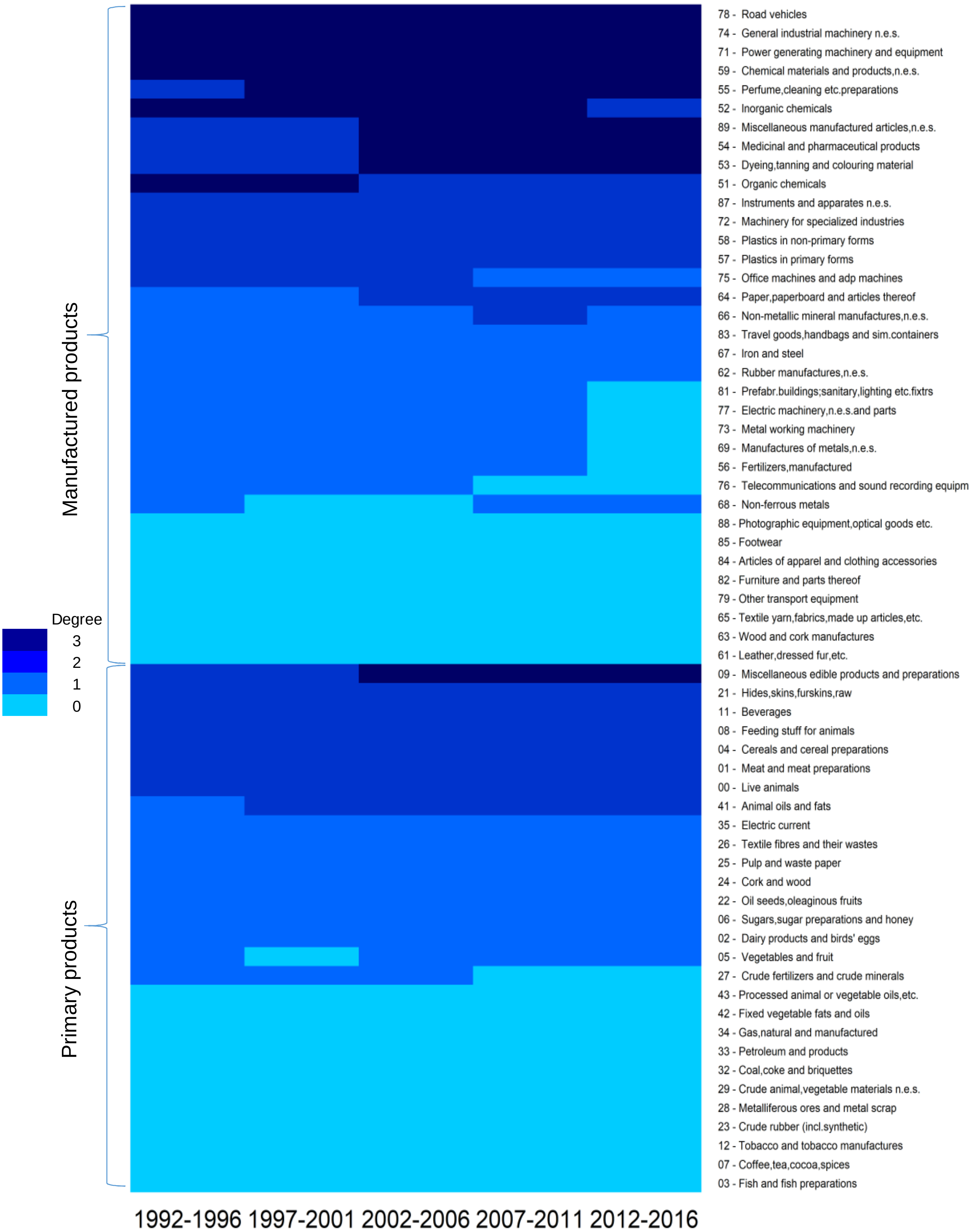


Figure 17. Degree centrality for G1

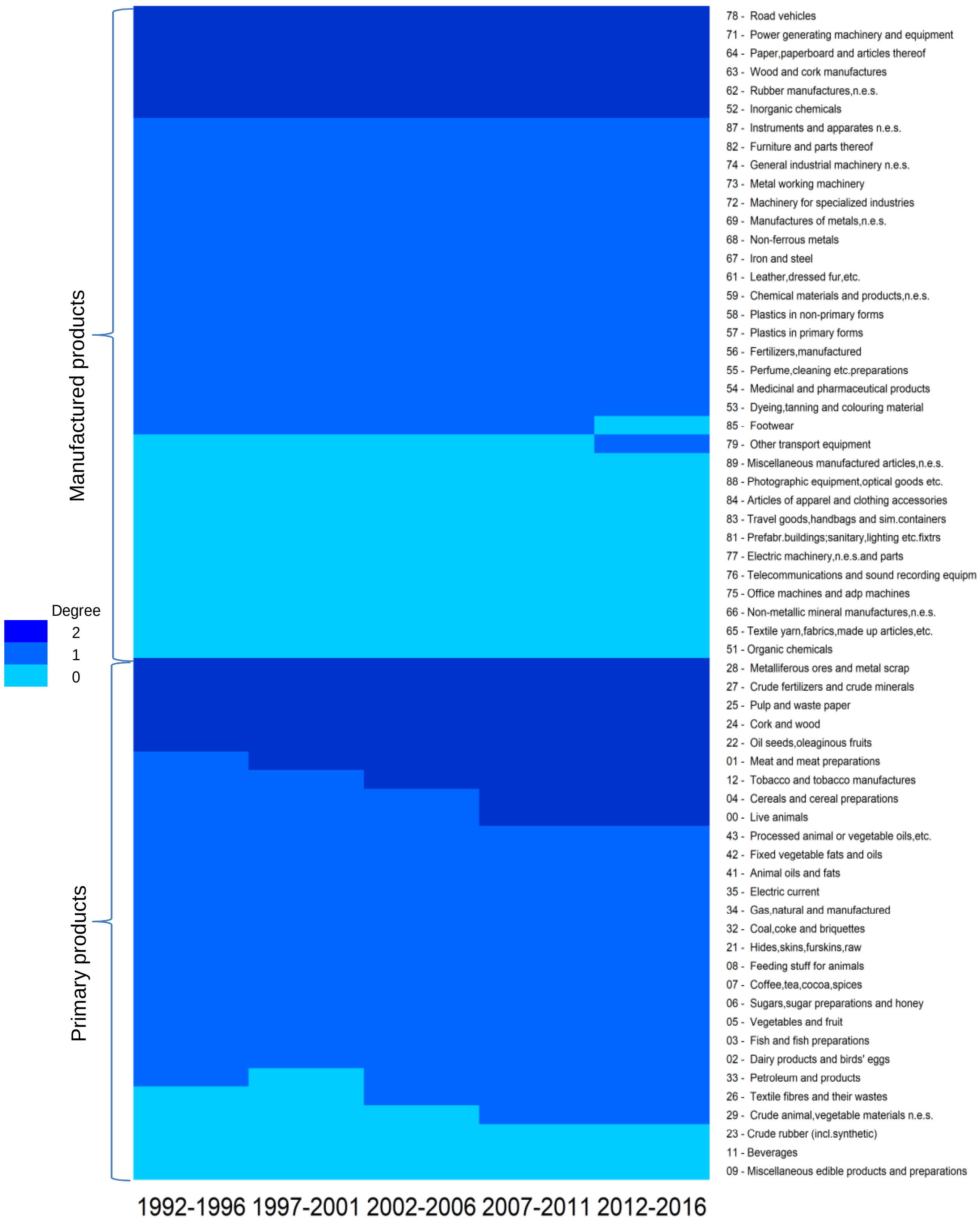


Figure 18. Degree centrality for G2

4.2 Identification of evolution patterns through the interpretation of results

Results evidence that the countries with the most developed aerospace ecosystems from 1992 to 2016 are France, the United Kingdom and the United States of America. RCA calculations are used for the identification of such ecosystems.

Results of RCA calculations are presented in Figure 7. These graphs shred of evidence that, from 1992 to 2016, several events influenced the economy worldwide and consequently, the aerospace ecosystem. Some examples include the early 1990s recession in the European Union and the USA, 'black Wednesday' in the United Kingdom in 1992, Asian financial crisis in 1997, Russian financial crisis in 1998, early 2000s recession, 9/11 terrorist attacks in the USA in 2001, the global financial crisis of 2007-2008, debts crisis in Greece, Ireland, Italy, Portugal and Spain starting in 2009, and other particular country-level events (Bhowmik, 2018; Roy and Kemme, 2019). Some of these events may have caused RCA fluctuations observed in Figure 7.

Overall, the USA exports the most Aerospace products in the world, followed by France, Germany, the United Kingdom and Canada. However, countries with the highest value of Aerospace exports do not necessarily have a superior RCA. For instance, since 2008, France depicted the highest RCA on aerospace products while the USA the highest amount of aerospace exports.

G1 depicted a consistent RCA>1 during the period of study. The RCA average on aerospace products for this group grew steadily during the first three periods of study, with a value of 2.8 in 1992 up to 4.3 in 2012. Since 2013, this value slightly decreased down to 3.9 in 2016. G2 has demonstrated a lower RCA than G1; starting to increase from 1998. Also, this group of countries achieved their peak at the end of 2000, mainly driven by the development of Brazil's aerospace ecosystem.

At the country level, RCA on aerospace products presents two central oscillations. The first one is experienced by Brazil starting in 1999. Brazil officially started its aerospace industry in 1941, when they created the governmental agency named Ministry of Aeronautics (MAER). A few years later, in 1945, they formed the Technical Centre of Aeronautics (CTA), aiming to promote the development of this sector. In 1950, they opened their first engineering school focused on aeronautics, named the Institute for Aerospace Technology (ITA). In 1969, Brazil's government founded EMBRAER, the Brazilian aerospace manufacturer, and in 1994, this company is denationalised (Yamashita, 2009). After privatisation, in 1999, Brazil started to develop an RCA>1 on aerospace products. During the same year, Brazil experienced a currency devaluation against the US Dollar, just a year after the Russian financial crisis. Both EMBRAER´s privatisation and devaluation of the Brazilian real could have been the enablers behind achieving the aerospace industry´s peak in 2000, followed by an abrupt decrease.

The other principal fluctuation is observed in 2010 when the French aerospace ecosystem grew. France is mainly an importer of components and equipment, and a final assembler and exporter of aeroplanes and helicopters, representing almost 65% of their aerospace exports. In recent years, the aerospace industry in this country has been one of the most important (Dortet-Bernadet *et al.*, 2016). The importance of this sector in its national economy is higher than it is for other key players. For instance, in 2015, 3.5% of its GDP is due to exports of aerospace products, whereas in countries such as the USA, the UK and Canada it represented only around 0.7% (Dortet-Bernadet *et al.*, 2016). Since the early 2000s, the French aerospace ecosystem gradually rose thanks to the sharp growth of air traffic, particularly from the Asia-Pacific region. Its RCA peaked in 2010-2012, just after the global financial crisis of 2007-2008, and after the USA slowed down after steady growth since 2000. This could have been driven predominantly by the increase in passenger demand, from the Asia-Pacific region. Singularly, 2010 is considered to be a year when the air traffic demand experienced a breakthrough (Dortet-Bernadet *et al.*, 2016). During this year, the numbers of passengers carried increased by nearly 17% from the previous year (from 2.25 in 2009 to 2.628 billion passengers in 2010) (The World Bank, 2019). After the RCA remained steady from 2010 to 2014, it experienced a sharp decrease in the following two years. Literature suggests that the drop is mainly because manufacturers experienced a lack of sufficient production capacity and a sharp fall in demand lead from oil-producing countries (Dortet-Bernadet *et al.*, 2016).

4.2.1 Evolution patterns identified at a network level

The analysis of the country-products networks developed in this study helped to identify patterns in the evolution of developed aerospace ecosystems. The patterns that have characterised the ecosystems' development at a macroscopic level are presented next.

Network density helps to evidence that networks of developed aerospace ecosystems increase their cohesiveness as their aerospace ecosystem develops. The cohesiveness' increase is driven by an increase in the number of actual versus potential connections. This means that countries tend to have fewer isolated nodes and more shared products with other countries. For instance, products that are connected only to one country for G1 decreased from 22 in the first period, to 14 in the last period. Concerning the group of less developed countries, the number of nodes unique to a single country is considerably higher than more developed countries. This group started with 35 nodes and decreased down to 33 during the last period.

In regards to network centralisation, it evidences that networks of developed ecosystems tend to centralise power in fewer nodes, by creating larger clusters with shared products in the networks. For instance, for G1, the number of products shared between the three countries rose from 6 in the first period up to 9 in the last period.

4.2.1.1 Patterns found through the nestedness analysis

Inspired by studies in other fields such as biological ecosystems, this research searches for nested patterns in the bipartite country-products networks. Measuring their nestedness using three widely applied metrics and comparing them with randomly generated networks, it is shown that the networks developed in this work are nested. More importantly, it has been demonstrated that more developed ecosystems present a higher level of nestedness and that it increases in tandem with an RCA in the aerospace ecosystems.

The packed matrices in Figure 13 and Figure 15 show a typical behaviour of how nestedness patterns are exposed after reordering the original matrices: increasing presences of country-products in the top left corner of each graph. Patterns reveal that countries with developed aerospace ecosystems tend to increase their diversification by developing an RCA>1 on more products rather than specialising only on one. Moreover, it is revealed that although countries develop an advantage on unique products, they increase competition with each other as they incline to develop an RCA>1 on a specific group of products. Nodes tend to form more massive clusters in the centre of the networks, meaning that as the countries' aerospace ecosystem develops, the number of shared products with other countries tends to increase. Thus, countries lean towards having an RCA>1 within the same group of products, evidencing that their ecosystems also tend to become more similar.

Nestedness analysis in this research has also contributed to confirm that mutualistic interaction patterns originally found in species-species networks are also found across networks of different nature. Nestedness patterns found in the country-products networks developed in this research are particularly aligned with the hypothesis that most common relations occur between generalists-generalists and that specialists are mainly related with generalists (Bascompte *et al.*, 2003; Jordano, Bascompte and Olesen, 2006). The latter hypothesis, specialist products produced mainly by generalist countries, is observed through the evolution of nestedness across different periods as it increases over time, and in particular more notorious on the packed matrices of G1 (Figure 13). For instance, the UK's aerospace ecosystem as a specialist country, positioned at the bottom of Figure 13 matrices, tends to reduce over time the number of specialist products and increase the generalist products. A similar scenario is depicted for the country situated in between the three countries (the USA during the first two periods and France during the last three periods), where the amount of generalist products tends to increase and the specialist products to reduce over time. A bit less evident but still identifiable, this hypothesis is also observed in G2 through the evolution of Figure 15 matrices. This is expected as nestedness of G2 is lower and presents a smaller increase over time than G1, as evidenced on results shown in Figure 16. Previous findings are also aligned with studies developed on networks from other industrial sectors, such as inter-organisational networks and networks from the automotive sector. For instance, patterns found in manufacturer-contractor interaction networks by (Saavedra, Reed-Tsochas and Uzzi, 2009) in which they found similar patterns than the mutualistic interaction patterns between species-species networks. Patterns found in automotive supply chain networks by (Brintrup *et al.*, 2012) in which they showed that generalist companies are the only ones producing specialist products and that specialists companies compete practically utterly in the generalist products market. It is also aligned with the study presented in (Brintrup, Barros and Tiwari, 2018), where they analysed the supplier-product distribution and supplier-manufacturer relations in the global automotive industry. They claim that specialist suppliers produce proper subsets of what generalist suppliers produce, and specialist products are only produced by generalist suppliers.

4.2.2 Products related to the evolution of developed aerospace ecosystems

The microscopic analysis is used to identify the specific products that have been linked to the growth of the aerospace ecosystems over the last 25 years.

Figure 17 and Figure 18 show the evolution of the product competition within groups. In these graphs, the degree centrality is directly linked with the number of countries that have developed an RCA>1 on that product. For G1, the amount of products with a degree centrality higher than 0 is higher in manufactured products than primary products. Here, manufactured products represent 61% of the products. That is not the case for G2, as these countries have a more balanced product portfolio with 51% represented by primary products. Such difference between primary and manufactured products diversification in the countries of each group could be because primary products are more dependent on the geographical location, climate and biodiversity of each country rather than choice or strategy.

As can be seen in Figure 7 A, the RCA on aerospace products for G1 depicts an upward trend until the third period, and experience a slight decrease during the last period. A similar pattern is found in the products with the highest degree centrality, as shown in Figure 17. The number of shared products by the three countries started with six during the first period, increased to seven during the second period, to ten during the third period, remained steady during the fourth period and finally decreased to nine during the fourth period. Apart from product *'09 - Miscellaneous edible products and preparations'* which increased its degree centrality from two during the second period to three during the third period, all the other products that increased the degree centrality are manufactured products. Only the products listed in Table 11 remained with a degree centrality equal to three among all the period of study.

Table 11. Most popular products for G1

'78 - road vehicles'
'74 - general industrial machinery'
'71 - power generating machinery and equipment'
'59 - chemical materials and products'

In contrast, G2 does not have common products within the three countries, and most of the products are unique to a single country. Countries of this group maintained unchanging the degree centrality distribution on manufactured goods: the same six products with the highest degree centrality during all the period of study. In regards to primary products, the number of products with the highest degree centrality increased from 11 to 12, then to 13, and finally to 15 during the last two periods. The products with the highest degree centrality among all the period of study for this group are listed in Table 12.

Table 12. Most popular products for G2

‘78 - road vehicles’
‘71 - power generating machinery and equipment’
‘64 - Paper, paperboard and articles thereof’
‘63 - Wood and cork manufactures’
‘62 - Rubber manufactures’
‘52 - Inorganic chemicals’
‘28 - Metalliferous ores and metal scrap’
‘27 - Crude fertilizers and crude minerals’
‘25 - Pulp and waste paper’
‘24 - Cork and wood’
‘22 - Oil seeds, oleaginous fruits’

It is relevant to highlight that ***‘78 - road vehicles’*** and **‘71** ***- power generating machinery and equipment’*** are the most popular products for both groups.

Similar to the finding from the nestedness analysis, the microscopic analysis helps to reinforce the hypothesis that countries with developed aerospace ecosystems tend to increase their diversification in tandem with their aerospace evolution, by developing an RCA>1 on more products rather than specialising only on one. This means that the number of products with an RCA>1 per country increases simultaneously with an increase in the RCA on aerospace products. For instance, G1 increased from having a total of 72 links country-products on the 1992 – 1996 period, up to 76 on the 2007 – 2011 period. At the same time, the RCA on Aerospace products for this group increased from an average of 2.6 in 1992, up to 4.2 in 2011. In contrast, the number of country-products links and RCA average on aerospace products decreased simultaneously throughout the last period. During the 2012 – 2016 period, the number of country-products links decreased down to 69, accompanied by a decrease in 2016 equivalent to 0.3 points on the RCA on Aerospace products, compared to 2011. For G2, the number of country-products links increased from 57 in the first period, up to 63 in the 2007 – 2011 period, while the RCA average on aerospace products increased from an average of 0.7 in 1992, up to an average of 1.4 in 2011. For this group, both figures remained constant during the last period of study. Previous findings are aligned with (Bustos *et al.*, 2012; Tacchella *et al.*, 2012), in which they claim that developed countries are highly diversified. The principal added value of this analysis is the identification of which particular industries have contributed the most with aerospace ecosystems development.

Regarding the products that have been correlated with the aerospace sector, manufactured products (91 for G1 and 77 for G2) depicted a higher amount of 'correlation links' than primary products (52 for G1 and 50 for G2).

For G1, the products that have been the most correlated with the aerospace evolution are presented in Table 13.

Table 13. Most popular correlated products with the aerospace evolution for G1

'78 - road vehicles'
'54 - medicinal and pharmaceutical products'

For G2, excluding the first period, as the group did not have an RCA>1 in aerospace products, the most popular correlated products are:

Table 14. Most popular correlated products with the aerospace evolution for G2

'78 - road vehicles'
'71 - power generating machinery and equipment'
'63 - wood and cork manufactures'
'62 - rubber manufactures'
'64 - paper, paperboard and articles thereof'
'01 - meat and meat preparations'

As it can be identified in Table 13 and Table 14, '*78 - road vehicles'* is the only product common for both groups.

4.3 Summary

In this chapter, the methods, sources and results of the study of evolution patterns are presented from a developed aerospace ecosystems perspective. Here, historical trade data over a 25 year period is collected and analysed through network science.

First, a detailed introduction to the methods and sources is presented. Then, the thorough procedure for the elaboration of bipartite country-products networks is introduced.

Subsequently, a description of the network analysis is elaborated from two perspectives: at a macroscopic level and a microscopic level.

Finally, a section with the interpretation of results is introduced. The interpretation of the results in this chapter leads to answer the following research objectives:

1) Identification of patterns that have characterised the evolution of aerospace ecosystems

Answer: this part of the research answers the patterns that have characterised the evolution of developed aerospace ecosystems. The key patterns of such ecosystems are the following:

- Developed aerospace ecosystems tend to increase their exported products' diversification by developing an RCA>1 on more products rather than specialising only on one.
- Developed aerospace ecosystems tend to have similar exported products' portfolio. Meaning that such countries tend to develop an RCA>1 in the same group of exported commodities.
- Networks of more developed aerospace ecosystems present a higher level of nestedness, and its nestedness develops in tandem with the evolution of the RCA>1 on aerospace products.
- Networks developed in this research are aligned with the claim, suggested by other scientists, that most popular interactions occur between generalist-generalist, and that specialist products are mainly produced by generalist countries.

2) Identification of other industries that have nourished the growth of aerospace ecosystems

Answer: this part of the research contributes to the identification on which other products have developed aerospace ecosystems specialised. This is evidenced by the identification of the specific exported commodities that countries have also developed an RCA>1 in tandem with the RCA>1 on aerospace products.

For the group of more developed ecosystems (the USA, the UK and France), the commodities that have been the most popular are: '78 - road vehicles', '74 - general industrial machinery', '71 - power generating machinery and equipment' and '59 - chemical materials and products'. For G2 (Canada, Germany and Brazil), the most popular products are '78 - road vehicles', '71 - power generating machinery and equipment', '64 - Paper, paperboard and articles thereof', '63 - Wood and cork manufactures', '62 - Rubber manufactures', '52 - Inorganic chemicals', '28 - Metalliferous ores and metal scrap', '27 - Crude fertilizers and crude minerals', '25 - Pulp and waste paper', '24 - Cork and wood' and '22 - Oilseeds, oleaginous fruits'.

A more extended discussion and main findings from the analysis elaborated in this chapter are discussed in chapter 7.

The following section continues with the identification of key enablers for the growth of a developed aerospace ecosystem: the United Kingdom.

Chapter 5 - The categorisation of key enablers for the evolution of developed aerospace ecosystems – the UK as a case example

This chapter describes the process followed to address objective 3 of the research programme: identification and categorisation of key enablers that have promoted the evolution of aerospace ecosystems, particularly for the UK aerospace ecosystem.

The identification and summary of the key enablers are presented in section 2.3.1. In this chapter, a description of the process for their categorisation is detailed.

5.1 The methodological approach for the qualitative analysis

The philosophy undertaken in this part of the research is *constructivism* (ontology) and *interpretivism* (epistemology), using *qualitative* methods and *inductive* reasoning for theory-building.

The process for the categorisation of the key enablers using ISM and MICMAC is described in Figure 19. 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 in the following sections.

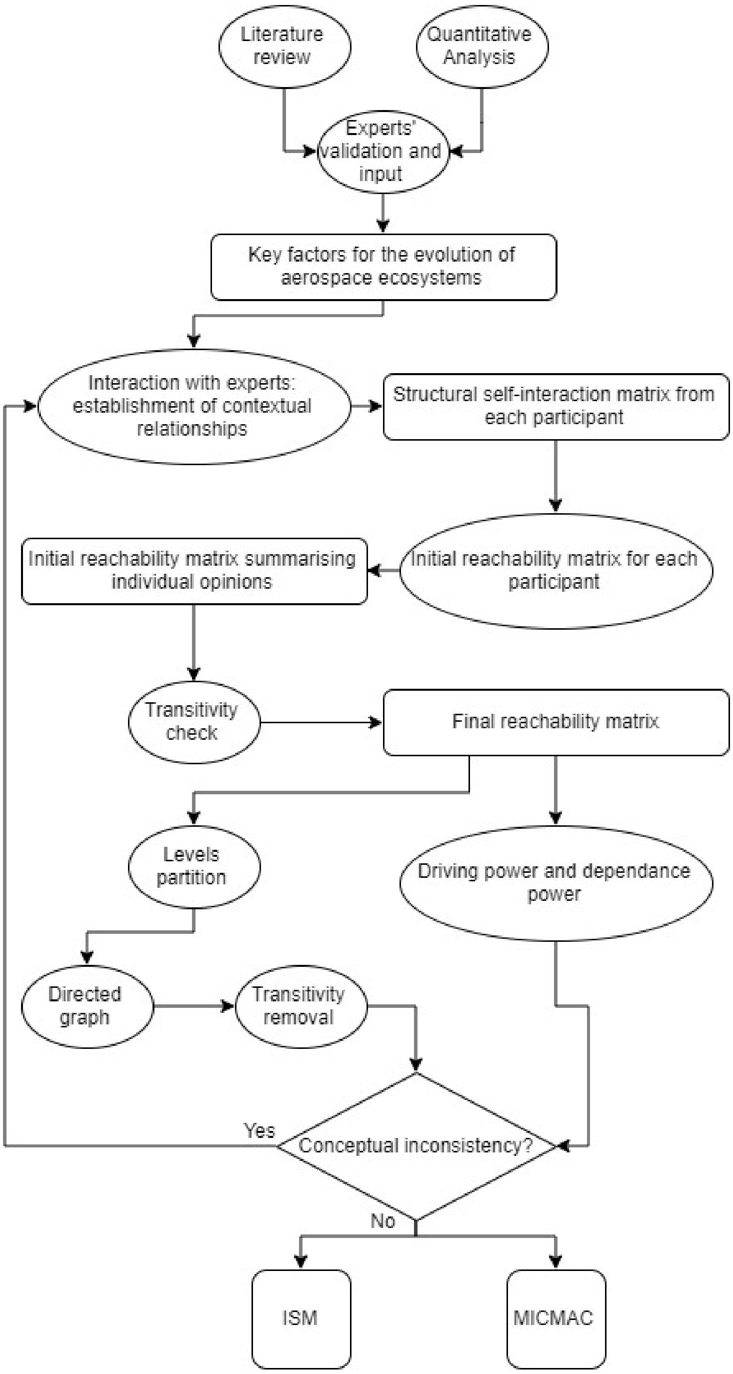


Figure 19. Methodology for the identification and categorisation of key enablers for the evolution of aerospace ecosystems - an ISM and MICMAC methodologies approach

5.2 The categorisation of key enablers using ISM – MICMAC methodologies

The categorisation of the key enablers is elaborated through the ISM and MICMAC methodologies.

The group of experts is selected based on their adherence to the UK's aerospace ecosystem and their professional background. The selection criteria aimed to select experts from both private and public sectors, with vast experience working in the UK's aerospace ecosystem. Therefore, the chosen group of participants consisted of four experts with more than ten years of working experience in the UK's aerospace industry; three of them working in the private sector and one expert working for a public R&D institute (Table 15). Experts' opinions are gathered in a workshop developed during the UK's 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 15. 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

5.2.1 Structural self-interaction matrix (SSIM)

The experts' opinion for the establishment of the cause-effect relationships via the SSIM can be gathered mainly by consensus or individual-opinions 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 the 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 its arguments.

In this research, the individual opinion's 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 individually fill in Table 17, using the symbols described in Table 16. For instance, considering that factor 2, *Supporting organisations,* influences factor 10, *Machinery ecosystem*, the symbol used is ▲. By using this symbol, it is assumed that factor 2 does not get affected by factor

10. A total of four SSIMs are generated (included in Appendix A – Individual SSIMs for the UK's aerospace ecosystem).

Table 16. 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 17. SSIM for the UK's aerospace ecosystem

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

5.2.2 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 (included in Appendix B – Individual IRMs for the UK's aerospace ecosystem). Each IRM is produced by converting each SSIM into a binary matrix, according to the rules from Table 18. 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 19. 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 18. 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 19. IRM for the UK's 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
Chemicals 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
Non-agricultural products ecosystem	**13**	0	0	0	0	0	0	0	0	1	0	1	0	1

5.2.3 Final reachability matrix (FRM)

The FRM adds more cause-effect relations by adding transitivity to the final IRM (Table 19). 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's aerospace ecosystem, presented in Table 20, 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 1's of each row. The latter is the number of factors that might affect this metric; it is obtained by adding all the 1's 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 (9 other factors plus the factor itself).

Table 20. FRM including transitivity for the UK’s 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
Chemicals 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
Non-agricultural 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	

5.2.4 Levels partition

The next step is the partition of the FRM into different levels. A summary of the level partitions is presented in Table 21. 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’s 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 21. 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

5.2.5 ISM model for the UK's aerospace ecosystem

The next step is the development of the directed graphs by using the levels partitions from the previous step. Figure 20 is the directed graph for the UK's aerospace ecosystem. The outcome of the level's partition from the previous step resulted in a 6 level model. Each level contains all the factors indicated in Table 21. 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 and1*'s from the FRM. Finally, the ISM model, Figure 21, is generated after removing the transitivity links and replacing numbers by statements.

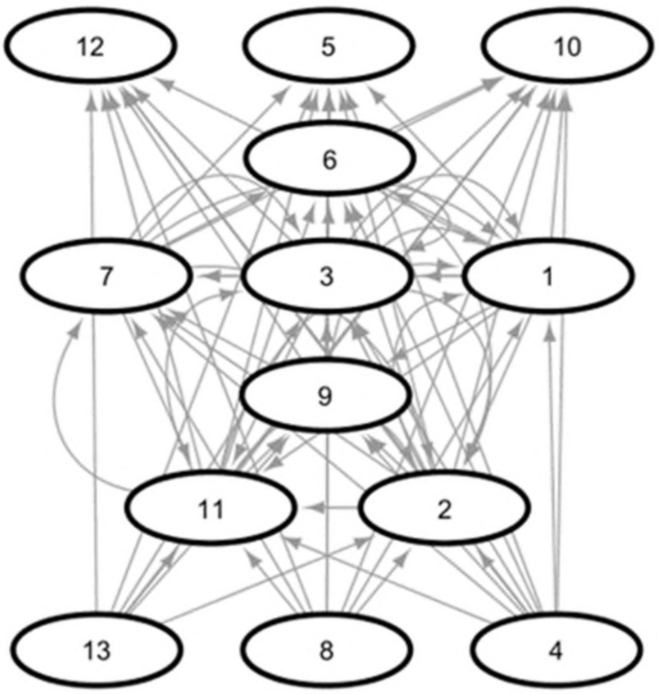


Figure 20. Directed graph for the UK's aerospace ecosystem

Figure 21. ISM model for the UK's aerospace ecosystem

5.2.6 MICMAC for the UK's 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, Shankar and Suhaib, 2008). Results are presented in Figure 22.

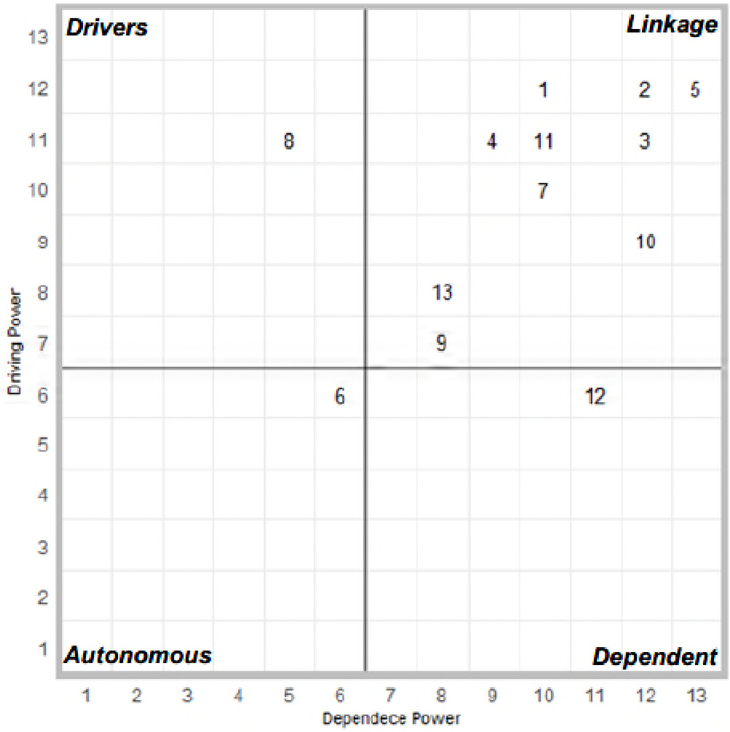


Figure 22. MICMAC for the UK's aerospace ecosystem

5.3 Interpretation of results

The key enablers are identified through a literature review and a quantitative analysis, and then validated and enriched with experts' opinion. Thirteen key enablers are identified. The next step of the research is the categorisation of the key enablers using ISM and MICMAC methodologies.

As part of the ISM methodology, the judgment of experts on the UK's aerospace ecosystem is used for the establishment of key enablers' cause-effect relationships. The group of experts consisted of professionals working in the private and public aerospace sector. Experts are carefully selected based on their adherence to the UK's aerospace ecosystem.

The analysis resulted in a six levels' ISM model, where each level represents the hierarchy of the key enablers. The bottom level, level 6, according to Table 21, 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 *non-agricultural products ecosystem* are considered as the key triggers for the evolution of the UK's aerospace ecosystem. Evidence suggests that the UK's aerospace ecosystem is tied-up to the *geopolitical factors* (House of Commons on Exiting the European Union Committee, 2017a), driven by free trade agreements with other nations, 95% of the UK's aerospace production is exported (ADS Group, 2019). The UK's automotive ecosystem is considered within the most important in the UK's good portfolio, as this sector's trades is the one that exports the most (SMMT, 2019). The *non-agricultural products ecosystem* embraces the infrastructure and supplier base developed for other manufactured products (others apart from the automotive, chemicals, 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 *chemicals ecosystem.* The UK's 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 on Exiting the European Union Committee, 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's 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 chemicals, machinery, pharmaceutical and medicinal, and non-agricultural 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's automotive ecosystem is considered within the most important in the UK's 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 (Figure 21). 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 *non-agricultural products ecosystem* is considered among the most influencers. *R&D 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 the categorisation of most of the key enablers as *linkage* factors, this results is expected as it evidences a balanced ecosystem with interconnected components, which is a characteristic of a country with a developed economy.

5.4 Summary

In this chapter, the methods, sources and results of the study for the categorisation of key enablers for the growth of aerospace ecosystems are presented from a developed aerospace ecosystems perspective: the United Kingdom.

ISM and MICMAC methodologies are selected for this part of the research. Overall, results are expected to some extent. The categorisation of the enablers using ISM indicates that the *automotive ecosystem, geopolitical factors* and *non-agricultural products ecosystem* are considered as the base for enabling all the others. On the other hand, *machinery ecosystem, R&D public funding* and *agricultural products ecosystem* are considered as the factors with the least influence power. The categorisation of the enablers using MICMAC indicates that most of the factors fall into the *linkage* category, which depicts a balanced ecosystem. In addition, *the automotive ecosystem* is considered as the only driver, reflecting that it is considered the one with the strongest influence of power. The conclusions from the analysis elaborated in this chapter, and a comparison with a developing aerospace ecosystem are discussed in chapter 7.

This chapter addressed objective 3 from a developed ecosystem perspective. In the next chapter, this question will be answered but now from a developing aerospace ecosystem perspective.

Chapter 6 - Case example: emergent aerospace ecosystems

This chapter aims at answering the following objectives, from the emergent aerospace ecosystems perspective:

1) Identification of patterns that have characterised the evolution of aerospace ecosystems.
2) Identification of other industries that have nourished the growth of aerospace ecosystems.
3) Identification and categorisation of key enablers that have promoted the evolution of aerospace ecosystems.

To this aim, similar procedures to the ones presented in previous chapters are followed. First, bipartite country-products networks based on 25-year historical trade data are developed, aiming at the identification of evolution patterns. Here, the two following countries are selected: China and Mexico. The selection of both countries is because both are characterised for having an RCA<1 in aerospace products and emerging aerospace ecosystems. Then, an ISM-MICMAC analysis of the Mexican aerospace ecosystem is elaborated aiming at the categorisation of key enablers for the evolution.

6.1 Patterns in the evolution of emergent aerospace ecosystems – China and Mexico case example

The methodological and philosophical approaches for the identification of evolutionary patterns in this chapter are the same as followed for the developed aerospace ecosystems, as described in previous chapters. In this case, China and Mexico are selected and defined as group three (G3). These countries are selected as evidence suggests that both countries have emergent aerospace ecosystems, although they have not developed a revealed comparative advantage of aerospace exports during the last decades.

The data used for the analysis is the same UN Comtrade data from 1992 to 2016 used for the developed ecosystems (section 4.1.1). The group of commodities proposed in Table 7 is also used for the RCA calculations.

Figure 23 illustrates the evolution of the RCA on aerospace products for China and Mexico. In this graph, the RCA average of group 1 (France, the USA and the UK) and the average of group 2 (Brazil, Canada and Germany) is also depicted so it can be compared with China and Mexico. Results indicate a significant difference among the countries. Clearly, China and Mexico's RCA is lower than G1 and G2, evidencing a lower evolution of their aerospace ecosystem. As evidenced, both countries have slightly developed their aerospace ecosystem but have not demonstrated an RCA>1 over the last decades. China improved the RCA from 0.1 in 1992 to 0.2 in 2016, while Mexico improved from 0.2 to 0.3 over the same period.

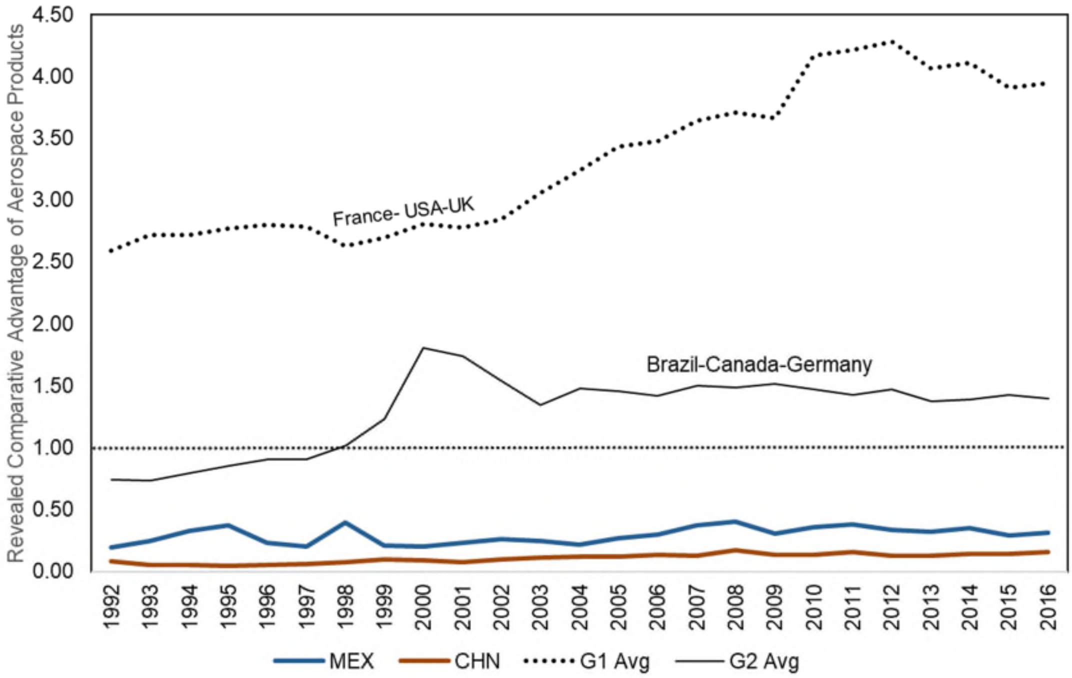
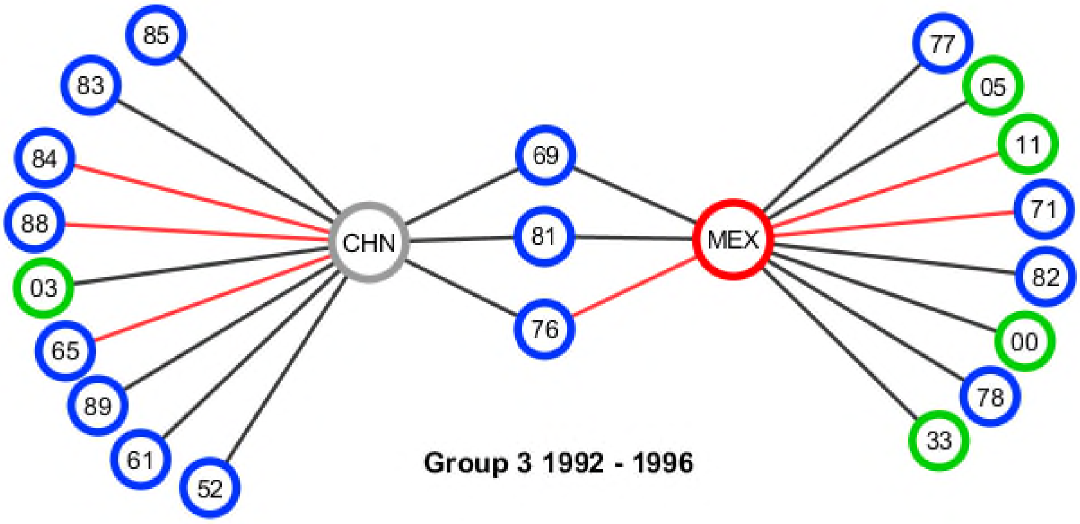
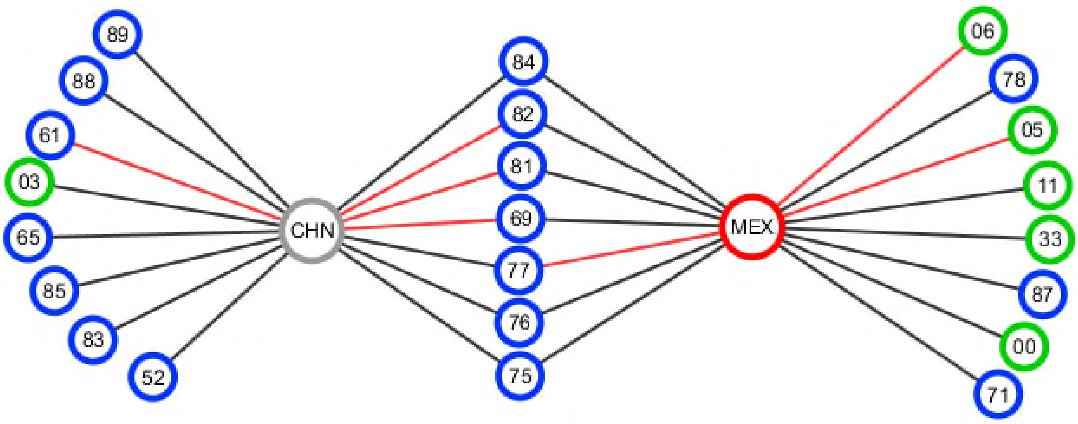


Figure 23. RCA of aerospace products for China and Mexico

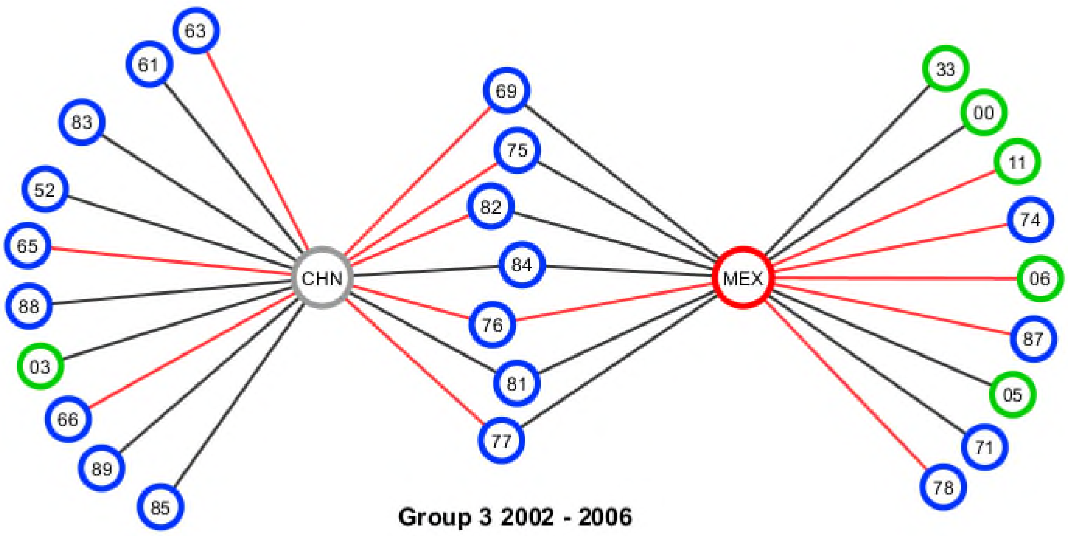
After calculating the RCA for all the other products of each country and elaborating a correlation analysis with the aerospace products, as exemplified in Table 5, the next step is the development of the bipartite country-products networks. Five bipartite networks are elaborated and depicted in Figure 24.



Group 3 1992 - 1996



Group 3 1997 - 2001



Group 3 2002 - 2006

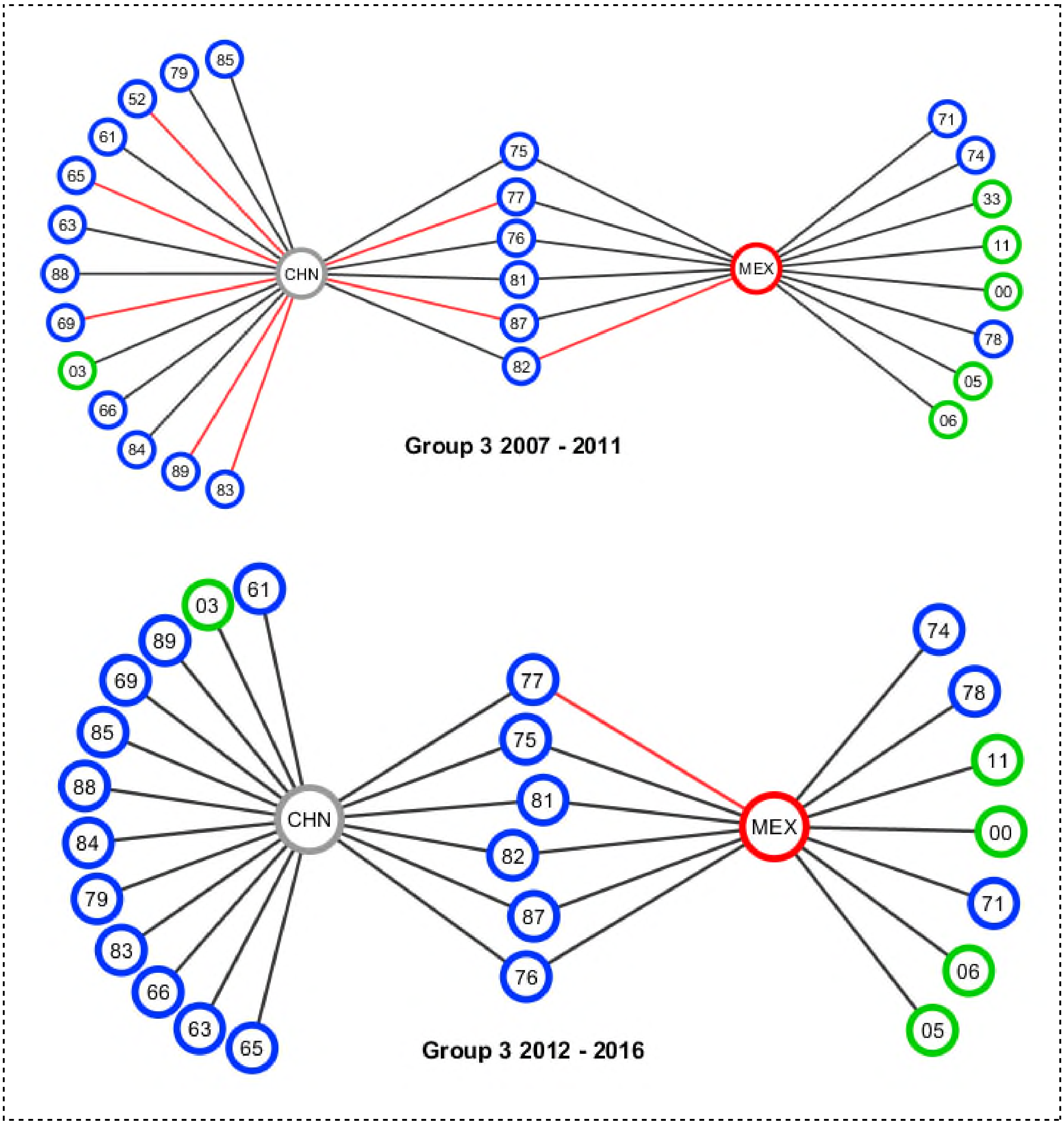


Figure 24. Bipartite country-products networks for G3

6.1.1 Networks analysis: macroscopic level

After the development of the bipartite country-products networks, the next step is their analysis with similar metrics as elaborated for G1 and G1. Similarly, the analysis is first elaborated at the macroscopic level (network level) and then at a microscopic level (node level). At the macroscopic level: network *centralisation*, network *density, matrix temperature, Brualdi and Sanderson (BR) and NODF*; and at the microscopic level: *degree centrality*.

Results of network centralisation and network density are presented in Figure 25. Considering both metrics, networks of G1 and G2 increased both, while G3 increased only the network centralisation. In regards to network centralisation, similar to G1 and G2, China and Mexico´s networks also increased this metric as larger clusters are formed in the centre of the networks. Contrary to G1 and G2, network density for G3 decreased among all the period of study. This means that China-Mexico networks decrease their cohesiveness while each country develops more nodes that are isolated. Thus, each country develops an RCA>1 in products that the other country does not have an RCA>1. Results are further discussed in the following sections.

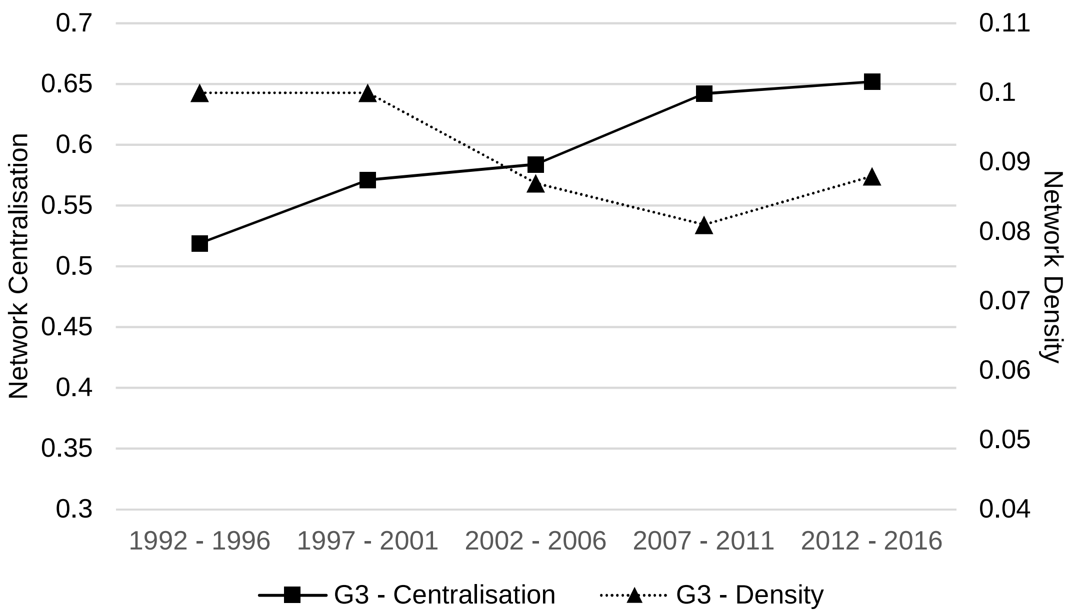
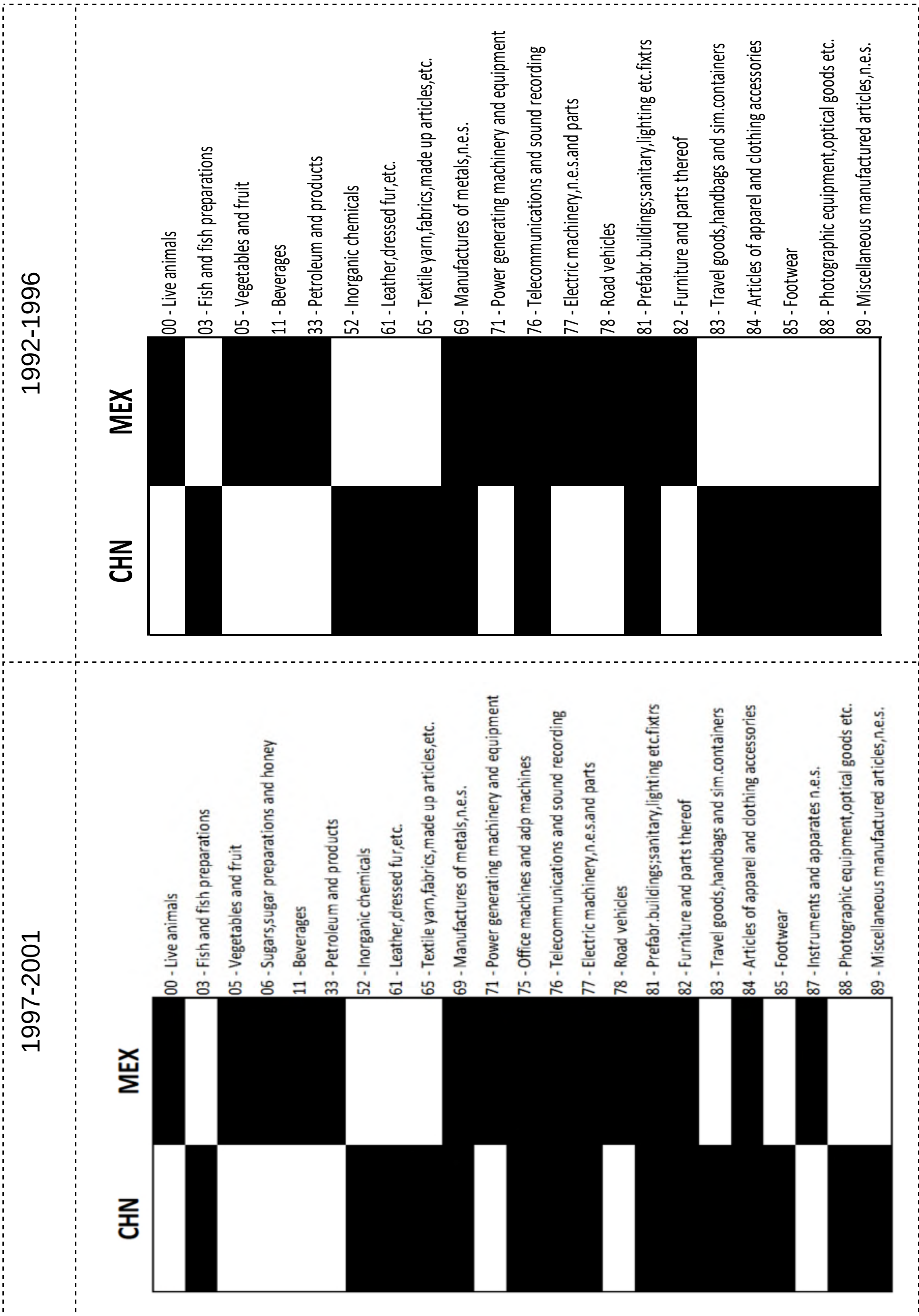


Figure 25. Network centralisation and network density for G3

6.1.1.1 Nestedness analysis

Nestedness analysis is also elaborated as part of the macroscopic analysis. Similar to the nestedness analysis of G1 and G2, adjacency matrices are generated for their analysis. The ‘unpacked’ matrices are presented in Figure 26, and ‘packed’ matrices are presented in Figure 27. Each adjacency matrix contains all the products in which China and Mexico have developed an RCA>1 during that period.

The next step if the analysis of the ‘packed’ matrices aiming at the identification of patterns. Results are presented in Figure 28. Each ‘packed’ matrix is measured by using the following metrics: *matrix temperature, Brualdi and Sanderson (BR) and NODF*. In addition, as elaborated for the developed ecosystems, each packed matrix is then compared with randomly generated networks (PP null models) to assess its statistical significance. Results indicate that China and Mexico bipartite networks are nested and present a higher level of nestedness when compared with randomly generated models. Thus, results reinforce the previous finding by evidencing that distribution of country-products is not randomly distributed. A more detailed discussion and comparison with G1 and G2 are presented in subsequent chapters.



1992-1996
CHN
MEX
00 - Live animals
03 - Fish and fish preparations
05 - Vegetables and fruit
11 - Beverages
33 - Petroleum and products
52 - Inorganic chemicals
61 - Leather,dressed fur,etc.
65 - Textile yarn,fabrics,made up articles,etc.
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
76 - Telecommunications and sound recording
77 - Electric machinery,n.e.s.and parts
78 - Road vehicles
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
82 - Furniture and parts thereof
83 - Travel goods,handbags and sim.containers
84 - Articles of apparel and clothing accessories
85 - Footwear
88 - Photographic equipment,optical goods etc.
89 - Miscellaneous manufactured articles,n.e.s.
1997-2001
CHN
MEX
00 - Live animals
03 - Fish and fish preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
11 - Beverages
33 - Petroleum and products
52 - Inorganic chemicals
61 - Leather,dressed fur,etc.
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69 - Manufactures of metals,n.e.s.
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76 - Telecommunications and sound recording
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82 - Furniture and parts thereof
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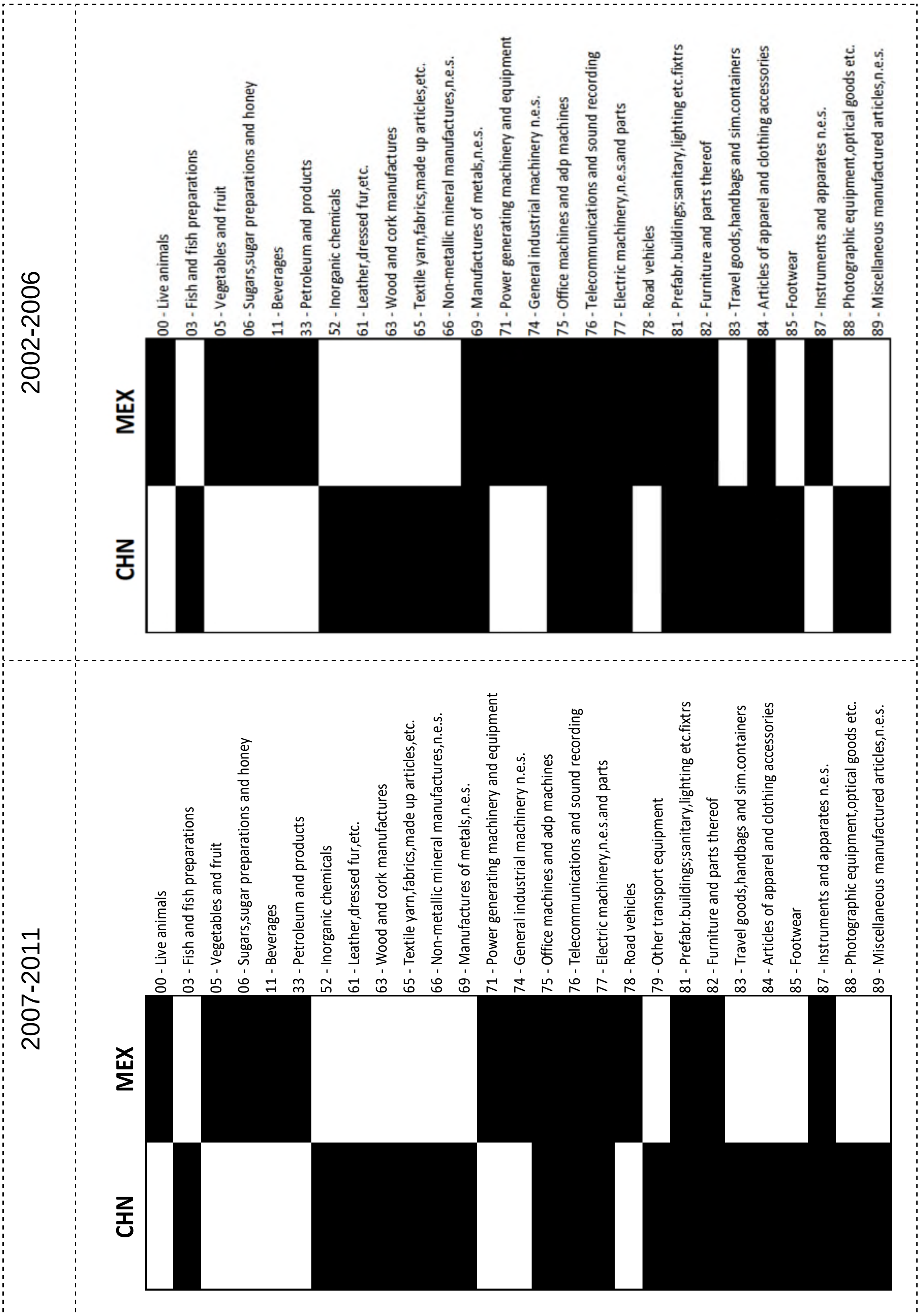
84 - Articles of apparel and clothing accessories
85 - Footwear
87 - Instruments and apparates n.e.s.
88 - Photographic equipment,optical goods etc.
89 - Miscellaneous manufactured articles,n.e.s.


2007-2011
CHN
MEX
00 - Live animals
03 - Fish and fish preparations
05 - Vegetables and fruit
06 - Sugars,sugar preparations and honey
11 - Beverages
33 - Petroleum and products
52 - Inorganic chemicals
61 - Leather,dressed fur,etc.
63 - Wood and cork manufactures
65 - Textile yarn,fabrics,made up articles,etc.
66 - Non-metallic mineral manufactures,n.e.s.
69 - Manufactures of metals,n.e.s.
71 - Power generating machinery and equipment
74 - General industrial machinery n.e.s.
75 - Office machines and adp machines
76 - Telecommunications and sound recording
77 - Electric machinery,n.e.s.and parts
78 - Road vehicles
79 - Other transport equipment
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
82 - Furniture and parts thereof
83 - Travel goods,handbags and sim.containers
84 - Articles of apparel and clothing accessories
85 - Footwear
87 - Instruments and apparates n.e.s.
88 - Photographic equipment,optical goods etc.
89 - Miscellaneous manufactured articles,n.e.s.
2002-2006
CHN
MEX
00 - Live animals
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61 - Leather,dressed fur,etc.
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65 - Textile yarn,fabrics,made up articles,etc.
66 - Non-metallic mineral manufactures,n.e.s.
69 - Manufactures of metals,n.e.s.
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74 - General industrial machinery n.e.s.
75 - Office machines and adp machines
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84 - Articles of apparel and clothing accessories
85 - Footwear
87 - Instruments and apparates n.e.s.
88 - Photographic equipment,optical goods etc.
89 - Miscellaneous manufactured articles,n.e.s.

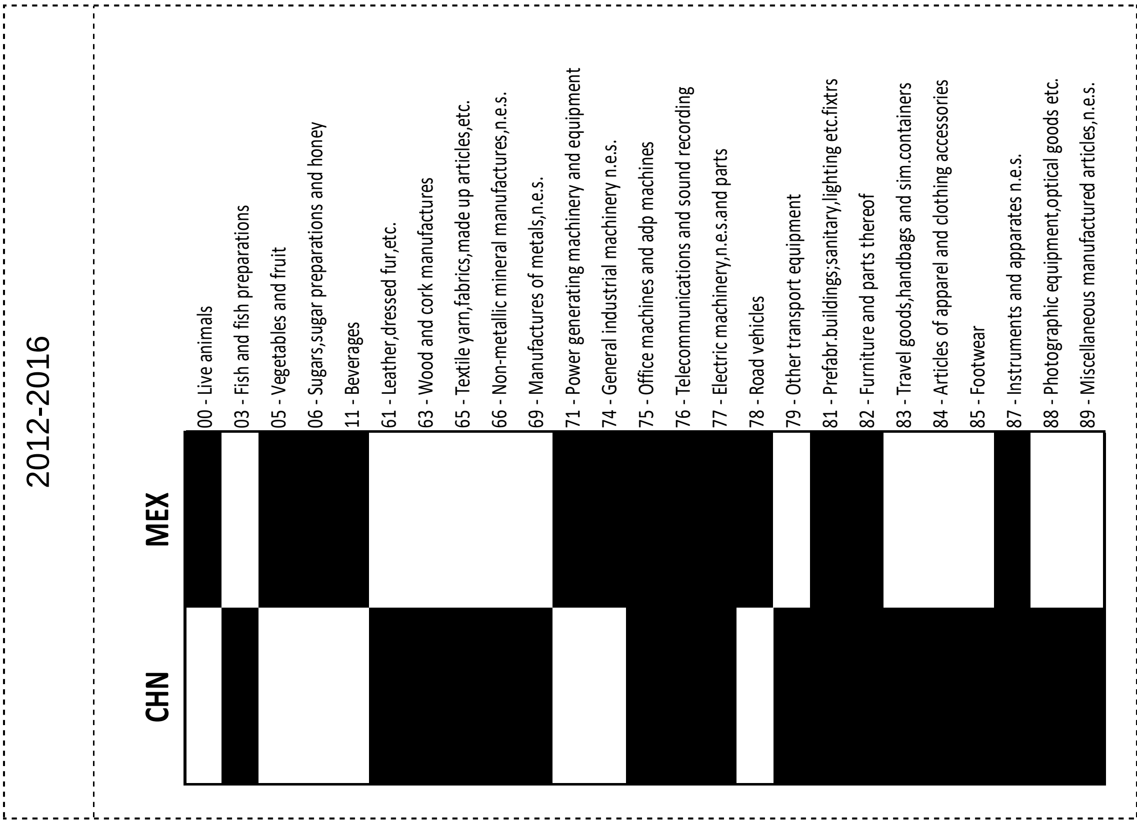
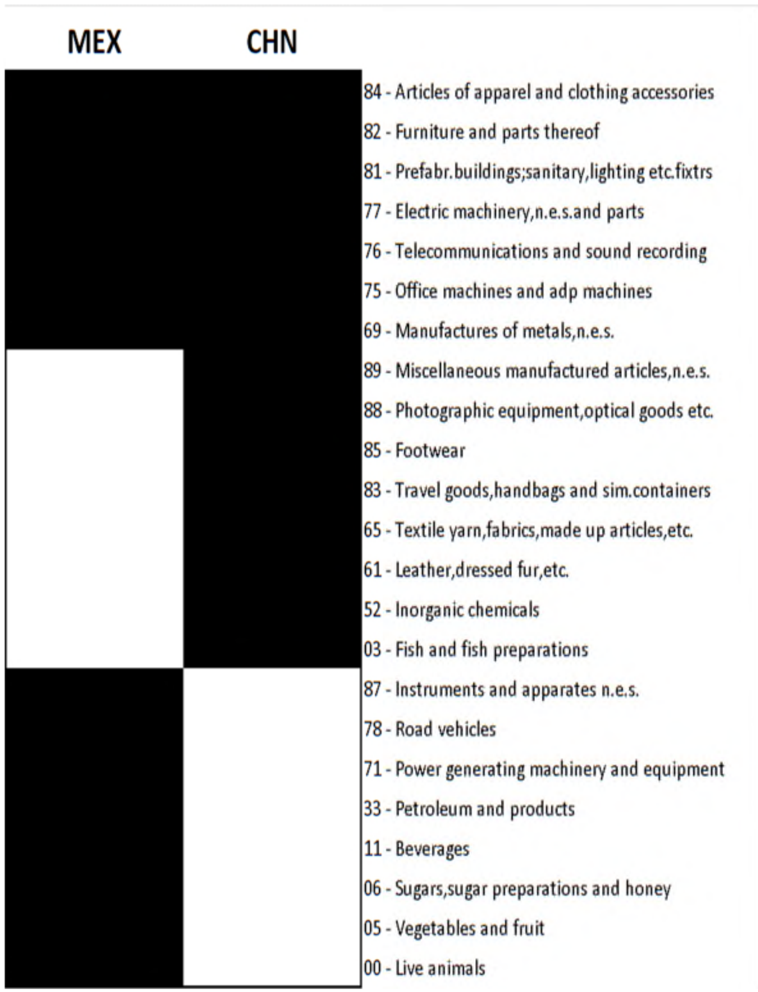
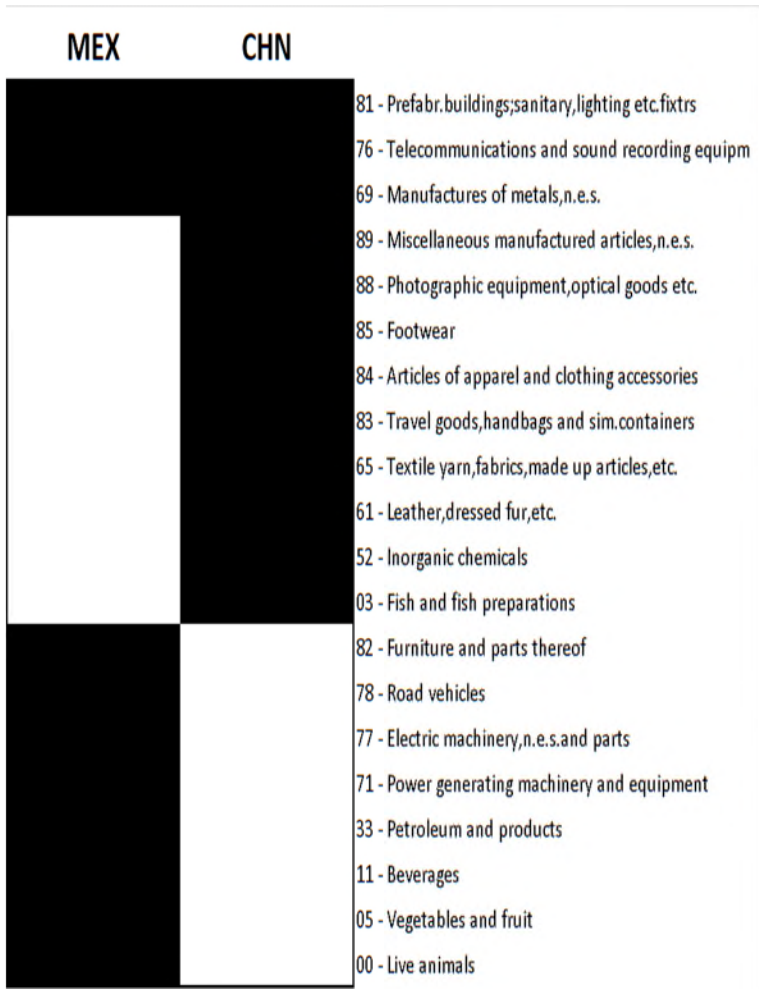
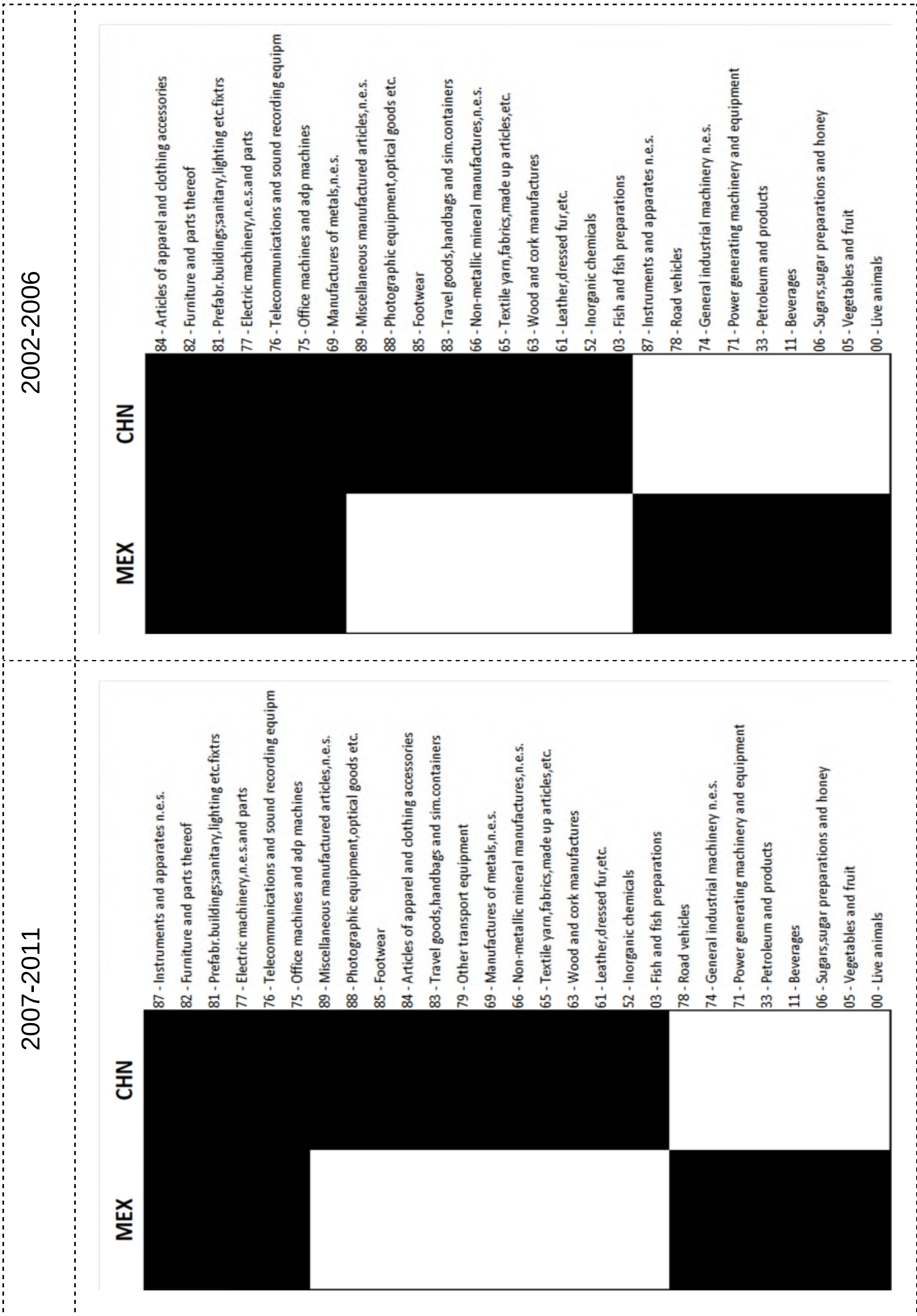


Figure 26. Evolution of unpacked matrices for G3: China and Mexico

1997-2001	1992-1996
	



2007-2011
MEX
CHN
87 - Instruments and apparates n.e.s.
82 - Furniture and parts thereof
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
77 - Electric machinery,n.e.s.and parts
76 - Telecommunications and sound recording equipm
75 - Office machines and adp machines
89 - Miscellaneous manufactured articles,n.e.s.
88 - Photographic equipment,optical goods etc.
85 - Footwear
84 - Articles of apparel and clothing accessories
83 - Travel goods,handbags and sim.containers
79 - Other transport equipment
69 - Manufactures of metals,n.e.s.
66 - Non-metallic mineral manufactures,n.e.s.
65 - Textile yarn,fabrics,made up articles,etc.
63 - Wood and cork manufactures
61 - Leather,dressed fur,etc.
52 - Inorganic chemicals
03 - Fish and fish preparations
78 - Road vehicles
74 - General industrial machinery n.e.s.
71 - Power generating machinery and equipment
33 - Petroleum and products
11 - Beverages
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
00 - Live animals
2002-2006
MEX
CHN
84 - Articles of apparel and clothing accessories
82 - Furniture and parts thereof
81 - Prefabr.buildings;sanitary,lighting etc.fixtrs
77 - Electric machinery,n.e.s.and parts
76 - Telecommunications and sound recording equipm
75 - Office machines and adp machines
69 - Manufactures of metals,n.e.s.
89 - Miscellaneous manufactured articles,n.e.s.
88 - Photographic equipment,optical goods etc.
85 - Footwear
83 - Travel goods,handbags and sim.containers
66 - Non-metallic mineral manufactures,n.e.s.
65 - Textile yarn,fabrics,made up articles,etc.
63 - Wood and cork manufactures
61 - Leather,dressed fur,etc.
52 - Inorganic chemicals
03 - Fish and fish preparations
87 - Instruments and apparates n.e.s.
78 - Road vehicles
74 - General industrial machinery n.e.s.
71 - Power generating machinery and equipment
33 - Petroleum and products
11 - Beverages
06 - Sugars,sugar preparations and honey
05 - Vegetables and fruit
00 - Live animals

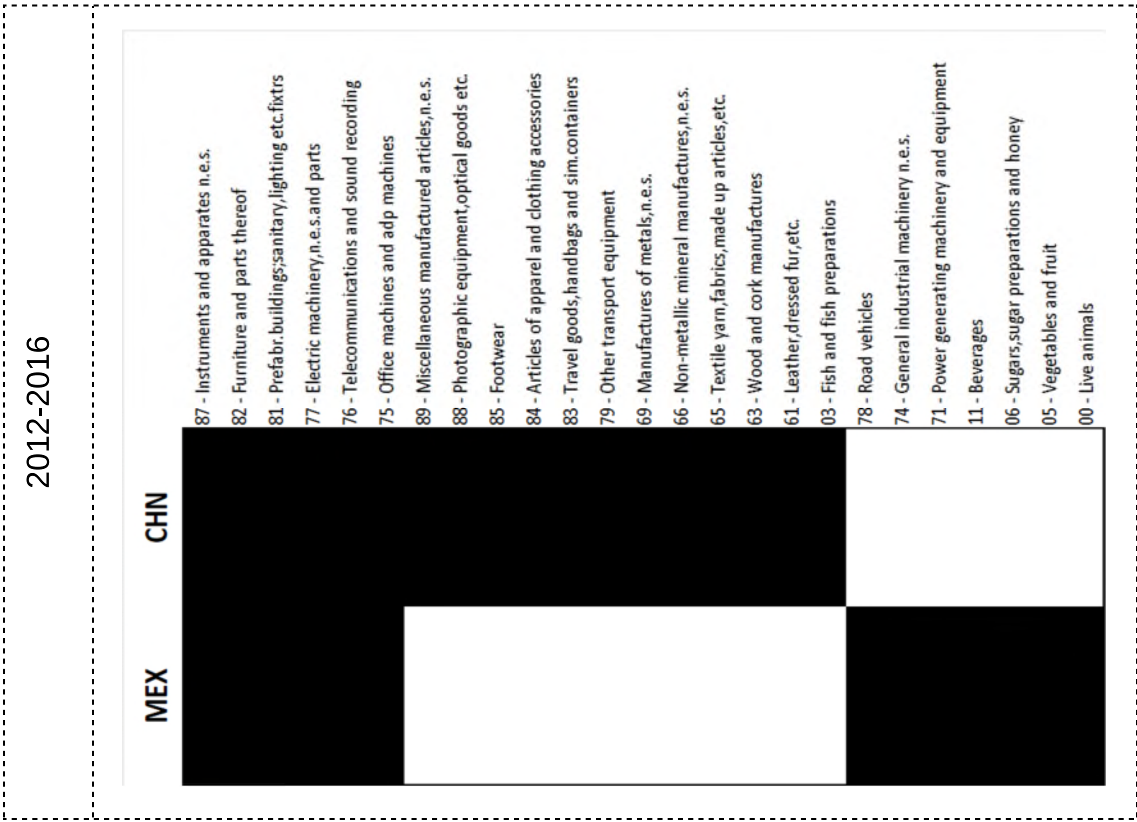
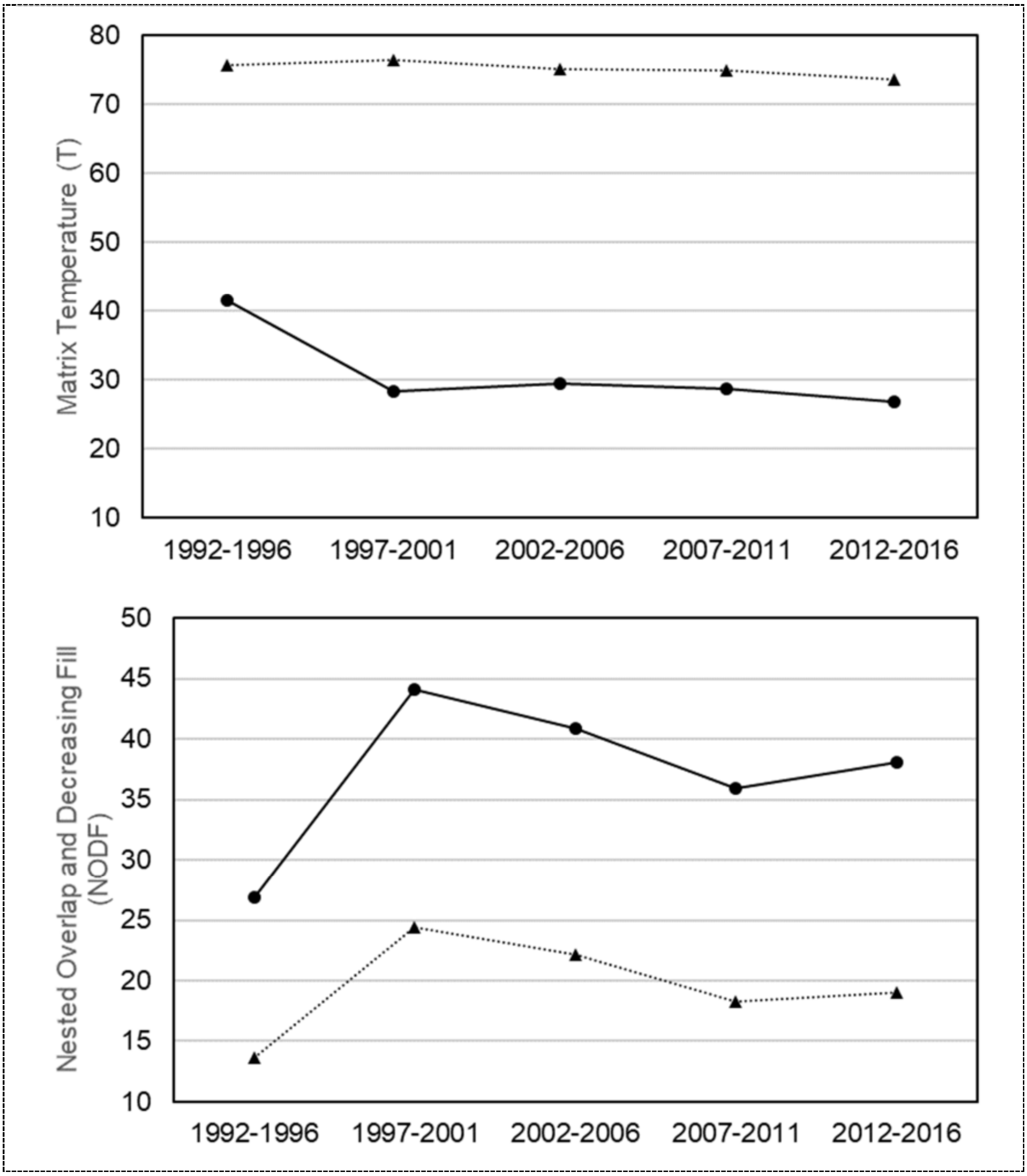


Figure 27. Evolution of packed matrices for G3: China and Mexico



Matrix Temperature (T)
80
70
60
50
40
30
20
10
1992-1996
1997-2001
2002-2006
2007-2011
2012-2016
Nested Overlap and Decreasing Fill (NODF)
50
45
40
35
30
25
20
15
10
1992-1996
1997-2001
2002-2006
2007-2011
2012-2016

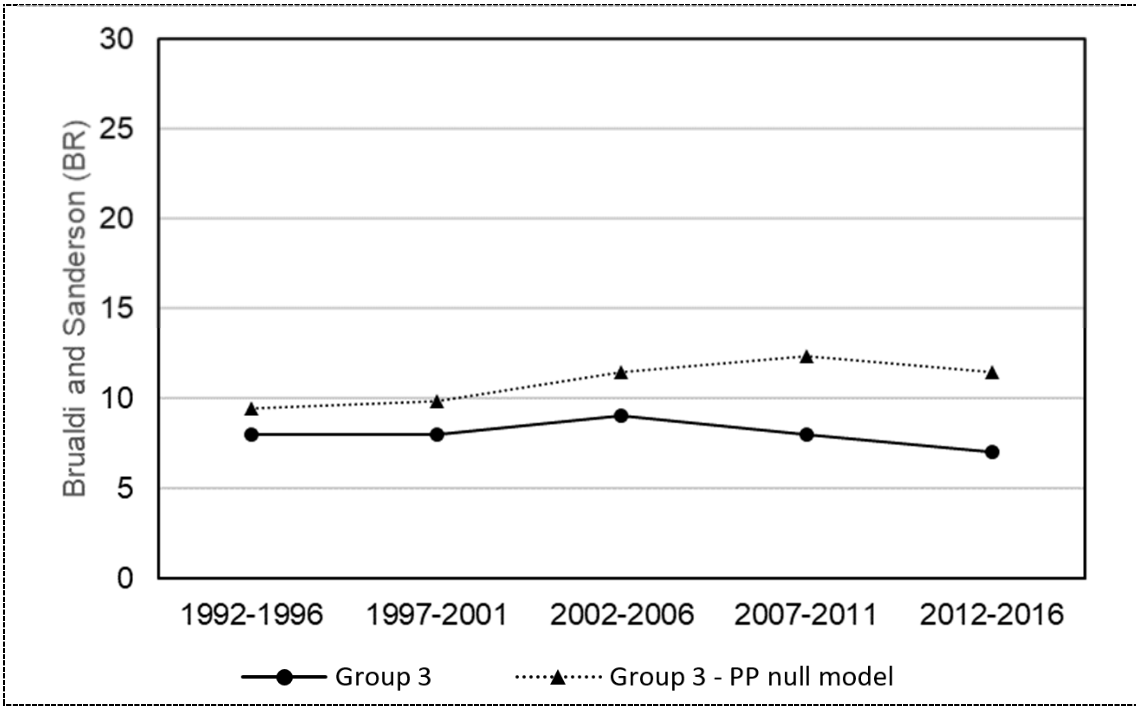


Figure 28. Nestedness measurement and validation with PP null models for G3

6.1.2 Networks analysis: microscopic level

Degree centrality is used to identify the most popular RCA>1 products within China and Mexico's ecosystems. Results are illustrated in Figure 29. In this graph, degree centrality is represented by colours. The highest degree centrality is illustrated with the darkest colour while the lowest by the lightest colour. The value of degree centrality is related to the number of countries that have developed an RCA>1 on that product. For instance, a degree centrality of two (the darkest blue) means that both ecosystems have an RCA>1 on that product; a degree centrality of zero (lightest blue) evidence that no country has developed an RCA>1 on that product. Findings are discussed in the next section.

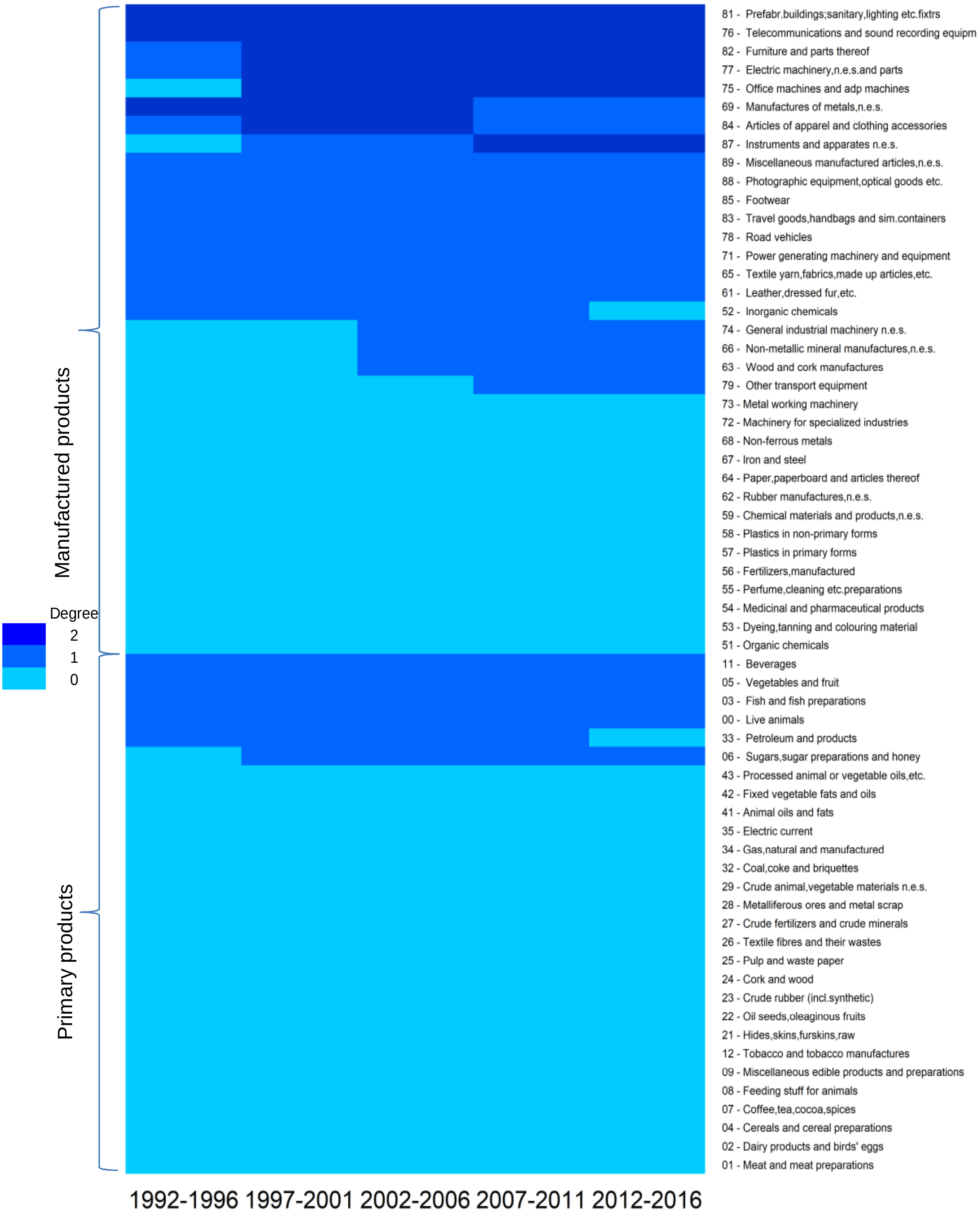


Figure 29. Degree centrality for G3

6.1.3 Interpretation of results and comparison with developed ecosystems

As illustrated in Figure 23, the RCA on aerospace products of China and Mexico has not experienced remarkable fluctuations among all the period of study. China started in 1992 with an RCA of 0.1 in aerospace products and finished at 0.2 in 2016, while Mexico grew from 0.2 to 0.3. Compared to G1 and G2, both countries have demonstrated a considerably lower RCA.

The networks developed for G3, illustrated in Figure 24, are first analysed at a macroscopic level, using network density and network centralisation (Figure 25). Considering both metrics, networks of G1 and G2 increased both, while G3 increased only the network centralisation. Contrary to G1 and G2, network density for G3 decreased among all the period of study. This means that China-Mexico networks decrease their cohesiveness while each country develops more nodes that are isolated. Thus, each country develops an RCA>1 in products that the other country does not have an RCA>1. For instance, in the first period of study, 1992-1996, G3 has 17 nodes connected only to one country. The lowest value of network density is reached in 2007-2011 when they increased the number of isolated nodes to 21. On the other hand, the group of countries with the most developed aerospace ecosystem, G2, decreased from 22 products unique to one country in the first period to 14 over the last period. G2 decreased from 35 to 33 isolated products.

In regards to network centralisation, similar to G1 and G2, China and Mexico´s networks also increased this metric as larger clusters are formed in the centre of the networks. For instance, G3 started with only three shared products and finished with six over the last period. G1 increased from 22 to 23, and G2 increased from 11 to 15.

Previous results evidence that contrary to G1 and G2, China and Mexico develop an RCA>1 more in unique products rather than in shared products. The analysis elaborated for developed ecosystems revealed that although G1 and G2 develop an advantage on unique products, they focus more on increasing competition with each other by developing an RCA>1 on a specific group of products. This leads to the suggestion that perhaps G3 needs to increase the network density in order to enhance its aerospace ecosystem. An increase in network density depicts a higher number of connections between countries and products in a network. In practical terms, it means that countries increase the number of shared products with an RCA>1.

Subsequently, a nestedness analysis is elaborated for G3. The evolution of packed matrices illustrated in Figure 27 and the metrics in Figure 28 evidence a lower level of nestedness than the networks of the groups of more developed aerospace ecosystems. Nestedness results for G3 are aligned to the RCA evolution (depicted in Figure 23): a level of nestedness that slightly increased from the first to the second period of study, but remained practically steady during the other periods. Although it is less evident and inferior than G1 and G2, the evolution of packed matrices for G3 (Figure 27) also shows a typical behaviour of how nestedness patterns are exposed after reordering the original matrices: presences of country-products in the top left corner of each graph. Visually it could be identified that the highest amount of presences in the top left corner of the packed matrices is reached in the second period of study, 1997-2001, and then slightly decreased and remained constant until the last period. The previous behaviour is also evident in the graphs presented in Figure 28, particularly in the matrix temperature and nested overlap and decreasing fill. Here, in Figure 28, nestedness is measured through T, BR and NODF. Results from the three metrics evidence that networks are nestedness and present a higher level of nestedness when compared with null models.

The nestedness analysis shreds of evidence that most common interactions among the group of less developed ecosystems occur over specialist products. This is illustrated by the pairwise relationships on the ‘packed’ matrices: most of the presences are not located in the top left corner. Previous results are contrary to the patterns found on the evolution of G1’s ‘packed’ matrices (Figure 13). This finding evidences that their nestedness evolution depicts a pattern opposing to previous hypotheses developed by (Bascompte *et al.*, 2003; Jordano, Bascompte and Olesen, 2006). They claim that most common relations occur between generalists-generalists and that specialists are mainly related to generalists. Consequently, nestedness results for G3 lead to the suggestion that country-products networks of countries with more developed aerospace ecosystem present a higher level of nestedness than less developed aerospace ecosystems. This means that G1 and G2 have a larger number of generalist-generalist interactions. In practical terms, this means that countries with more developed ecosystems share a larger number of products with an RCA>1.

As elaborated for G1 and G2, the microscopic analysis is used to identify the specific products that have been linked to the evolution of China and Mexico's aerospace ecosystems over the last 25 years. Figure 29 shows the evolution of the product specialisation for G3. In this graph, a degree centrality higher than 0 means that at least one country has developed an RCA>1 on that product. Similar to G1, China and Mexico have more manufactured products with a degree centrality higher than 0 than primary products. Products with the highest degree centrality (equal to 2), meaning that both countries have an RCA>1 on that product, are present only on manufactured products.

Table 22. Most popular products for G3

'81 – Prefabricated buildings, sanitary, lighting, etc. fixtures'
'76 - Telecommunications and sound recording equipment'

Table 22 includes the products with the highest degree centrality of G3's networks. In practical terms, the results evidence that there are only two products with an RCA>1 that have been shared by China and Mexico in the 25 years period. It is relevant to highlight that none of these products is included in the list of popular products for G1 (Table 11) and G2 (Table 12). This means that China and Mexico have not consistently developed an RCA>1 on the same products as G1 and G2. Previous results lead to the suggestion that G3 might have to focus on the popular products for G1 and G2 in order to enhance their aerospace ecosystem. For instance, China and Mexico might have to focus on developing an RCA>1 in products such as ‘78 - road vehicles’ and ‘71 - power generating machinery and equipment’. These two products are the most popular for the developed aerospace ecosystems among the 25 years periods.

In regards to the products that have been correlated with the aerospace sector for G3, a microscopic analysis does not add significant value as the aerospace ecosystem of these countries have not experienced a significant improvement. On the other hand, based on the presented evidence, these countries may need to focus on developing ecosystems similar to the countries of G1 and G2.

6.2 The categorisation of key enablers using ISM – MICMAC methodologies: the Mexican aerospace ecosystem case example

In this section, the process followed for the categorisation of key enablers for the growth of the Mexican aerospace ecosystem is presented. The key enablers are introduced in section 2.3.2. In regards to the categorisation using ISM and MICMAC methods, the only difference from the UK's analysis is the way in which experts' opinion is gathered. Here, individual meetings are held with each participant in which a description of the key factors is 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 23). 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.

In the next sections, the process for the categorisation of the enablers using ISM and MICMAC methodologies is presented.

Table 23. 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 & Development (public sector)	Director	25
Research & Development (public sector)	Director	10
Academia	Professor & Researcher	13

6.2.1 SSIM

After discussing the key enablers, experts' opinion is collected via the SSIM (Table 24). This table includes all the key enablers for the growth of the Mexican aerospace ecosystem. Each expert is individually asked to identify the cause-effect relationships between all the factors by filling the SSIM. As elaborated for the UK, the pairwise relationships are indicated using the symbols described in Table 16. An example of an SSIM filled in by one expert is presented in Table 25.

Consequently, a total of four SSIMs are elaborated (included in Appendix C – Individual SSIMs for the Mexican aerospace ecosystem) containing the suggested cause-effect relationships. The next step is the interpretation of each matrix, using binary code, through an IRM.

Table 24. SSIM for the Mexican aerospace ecosystem

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

Table 25. 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								▼
Non-agricultural products ecosystem	8								

6.2.2 IRM

Each SSIM is converted into an IRM, following the same methodology as described for the UK's aerospace ecosystem in section 5.2.2. The IRMs are elaborated by translating each SSIM into a binary matrix using the rules presented in Table 18. The individual IRMs are included in Appendix D – Individual IRMs for the Mexican aerospace ecosystem.

Then, a final IRM summarising independent opinions for the Mexican aerospace ecosystem is elaborated. This final IRM (presented in Table 26) is generated by using the following rule: 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 following step is the elaboration of the FRM, which is presented in the next section.

Table 26. IRM summarising independent opinions for the Mexican aerospace ecosystem

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	**1**	1	0	1	0	1	1	1	1
Labour: low cost and highly-qualified	**2**	0	1	0	0	1	0	0	0
Investment in human capital development	**3**	0	0	1	1	0	0	0	0
Supporting organisations	**4**	0	0	1	1	0	0	0	0
Foreign investment	**5**	0	0	1	1	1	0	0	1
Automotive ecosystem	**6**	1	1	1	1	1	1	0	1
Agricultural products ecosystem	**7**	0	0	0	0	0	0	1	0
Non-agricultural products ecosystem	**8**	0	0	0	0	0	0	0	1

6.2.3 FRM

The next step is the elaboration of the FRM by adding transitivity relations to the final IRM (Table 26). Following the same methodology as in the UK's aerospace ecosystem (section 5.2.3), transitivity relationships are checked for each pair of enablers. The FRM is generated and presented in Table 27. Here, transitivity is depicted with a 1*.

In addition, the *driving* and *dependence power* is computed as part of the MICMAC methodology.

Table 27. FRM including transitivity for the Mexican aerospace ecosystem

Factor	#	1	2	3	4	5	6	7	8	Driving Power
Geopolitical factors	**1**	1	1*	1	1*	1	1	1	1	8
Labour: low cost and highly-qualified	**2**	0	1	1*	1*	1	0	0	1*	5
Investment in human capital development	**3**	0	0	1	1	0	0	0	0	2
Supporting organisations	**4**	0	0	1	1	0	0	0	0	2
Foreign investment	**5**	0	0	1	1	1	0	0	1	4
Automotive ecosystem	**6**	1	1	1	1	1	1	1*	1	8
Agricultural products ecosystem	**7**	0	0	0	0	0	0	1	0	1
Non-agricultural products ecosystem	**8**	0	0	0	0	0	0	0	1	1
Dependence Power		2	3	6	6	4	2	3	5	

6.2.4 Levels partition

The next step is the levels partition needed for the final ISM model. Following a similar process as detailed in section 5.2.4, the levels partition for the Mexican aerospace ecosystem is shown in Table 28. Here, each factor is categorised according to its position on the final model. 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. 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's column. 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. 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.

Table 28. Summary of levels partition for the Mexican aerospace ecosystem

Factor	Reachability Set	Antecedents Set	Intersection Set	Level
3	3, 4	1, 2, 3, 4, 5, 6	3, 4	1
4	3, 4	1, 2, 3, 4, 5, 6	3, 4	1
7	7	1, 6, 7	7	1
8	8	1, 2, 5, 6, 8	8	1
5	5	1, 2, 5, 6	5	2
2	2	1, 2, 6	2	3
1	1, 6	1, 6	1, 6	4
6	1, 6	1, 6	1, 6	4

6.2.5 ISM model for the Mexican aerospace ecosystem

The following step is the elaboration of the directed graphs based on the levels partitions from the previous step. The levels' partition step resulted in four levels. Thus, the diagraph, Figure 30, is elaborated by positioning all the level 1 enablers at the top of the model (factors 3, 4, 7 and 8). The following two levels, level 2 and 3, includes only one factor: factor 5 and 2, respectively. The bottom level, level 4, includes level 1 and 6; this level is characterised for having the factors considered as the base for enabling all others. The links between the factors are generated from all the 1 and1*'s from the FRM. The directed graph for the Mexican ecosystem is illustrated in Figure 30.

Finally, the ISM model for the Mexican ecosystem, Figure 31, is generated after removing the transitivity links and replacing numbers by statements. In contrast with the UK's 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's ISM model. Results are further discussed in the interpretation of the results section (6.2.7).

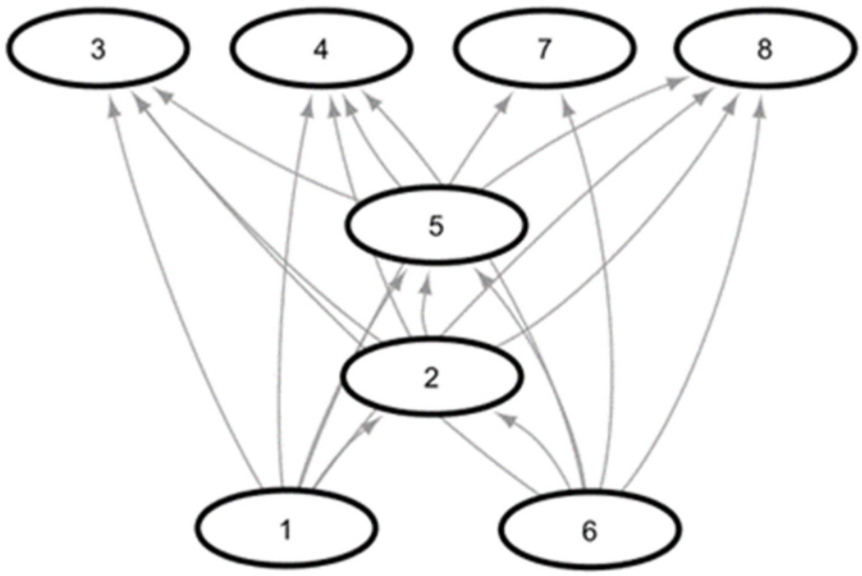


Figure 30. Directed graph for the Mexican aerospace ecosystem

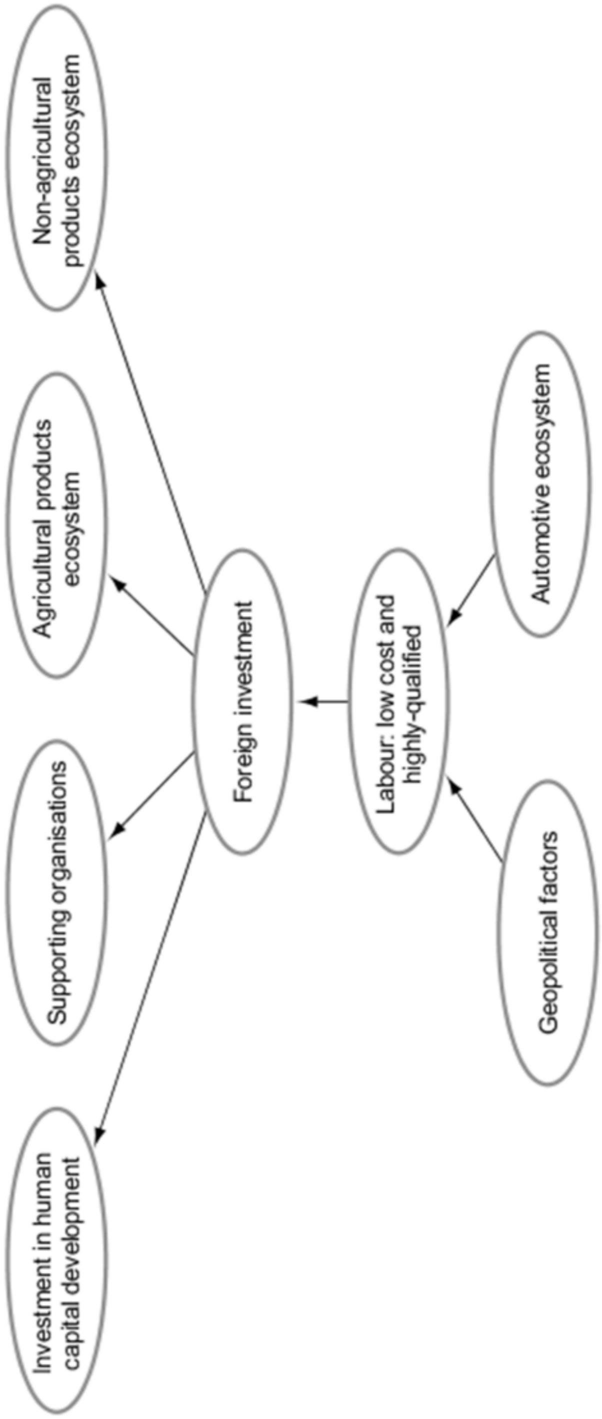


Figure 31. ISM model for the Mexican aerospace ecosystem

6.2.6 MICMAC 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 Figure 32, indicate a contrasting categorisation compared to the UK's ISM 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 in the next section.

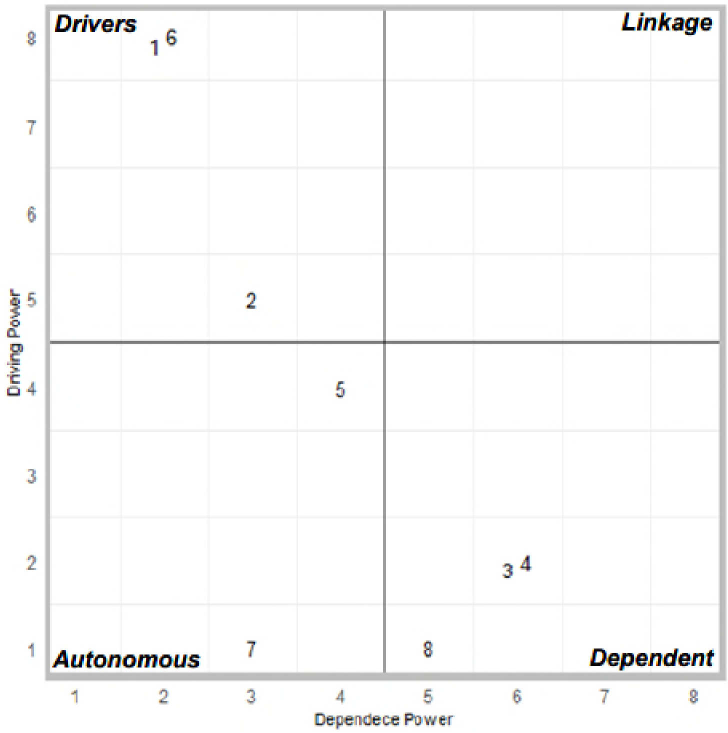


Figure 32. MICMAC for the Mexican aerospace ecosystem

6.2.7 Interpretation of results

As elaborated for the UK's aerospace ecosystem, the key enablers are identified through a literature review and a quantitative analysis, and then validated and enriched with experts' opinion. In this case, only eight key enablers are identified:

g*eopolitical factors, labour: low cost and highly-qualified, investment in human capital development, supporting organisations, foreign investment, automotive ecosystem, agricultural products ecosystem and non-agricultural products ecosystem.*

As part of the ISM methodology, experts' opinion from the Mexican aerospace ecosystem is used for the establishment of cause-effect relationships. The group of experts consisted of professionals working in the private and public Mexican aerospace sector.

The analysis of the Mexican aerospace ecosystem resulted in an ISM model with four levels. The bottom level, level 4, according to Table 28, 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 *non-agricultural 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's 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 *non-agricultural 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's 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. Expert's 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.

6.3 Summary

In this chapter, the methods, sources and results of the study of evolutionary patterns and key enablers for the growth of aerospace ecosystems are presented from an emergent aerospace ecosystems perspective.

In the first part of this chapter, the process for the elaboration of bipartite country-products networks and the identification of evolution patterns using network science are introduced. Here, China and Mexico are used as a case example. An interpretation of results and comparison with developed aerospace ecosystems are also presented in this chapter. Among the main findings are that nestedness evolution of the networks developed for these countries depicts a pattern opposing to a previous hypothesis in which is claimed that most common relations occur between generalist-generalist, and that specialist are mainly related to a generalist. Also, they evidence a pattern in which countries tend to develop an RCA>1 in unique products rather than in shared products. Moreover, although there are specific products like the '78 - road vehicles' in the Mexican ecosystem, in general terms, results also evidence that emergent aerospace ecosystems have not specialised on exporting the same group of products like the developed ecosystems.

The next part continues with the categorisation of key enablers for the growth of an emergent aerospace ecosystem: the Mexican ecosystem. The procedure for the categorisation of key enablers using ISM and MICMAC methodologies is detailed. Finally, a section with the interpretation of results is introduced. Among the main findings is that *geopolitical factors* and the *automotive ecosystem* are considered as the key triggers for the growth of the Mexican aerospace ecosystem.

Conclusions of the analysis presented in this chapter and a comparison with developed ecosystems are presented in the following chapter.

Chapter 7 - Key findings on the evolution of developed and emergent aerospace ecosystems

The aim and objectives of the research programme presented in this thesis have been accomplished by the key findings, which are summarised in this chapter.

The objectives were first accomplished from the developed aerospace ecosystems perspective. Then, a similar analysis was elaborated for emergent aerospace ecosystems.

In the first part of this chapter, the contribution to knowledge is summarised by research area, research methods and research findings. Then, the research findings of the quantitative and qualitative studies are presented in detail. Finally, results are compared, and a number of suggestions are proposed. The ultimate goal of this research is that such recommendations can be used as the foundation for the elaboration of enhancement strategies by any country willing to improve their aerospace ecosystem.

7.1 Contribution to knowledge

This research contributes to knowledge on three key elements: *research area, research methods and research findings.*

In regards to the **research area**, in this research, the gap in the knowledge on the analysis of the evolution of aerospace manufacturing ecosystems is filled to some extent. The previous claim is based on the fact that the literature review, elaborated as part of this study, shreds of evidence a gap in the research for analysing the evolution of aerospace ecosystems. Particularly, a gap on the identification of evolution patterns, other industrial ecosystems and key enablers that have fostered the evolution of developed and emergent aerospace ecosystems. Moreover, no evidence is found on a similar study developed for analysing the evolution of the Mexican or the UK's aerospace ecosystem from this approach.

In regards to the **research methods**, this research contributes to knowledge by the combination of network science, ISM and MICMAC methods for analysing the evolution of aerospace ecosystems. This is based on results from the literature review, which suggest that although network science is a methodology that has recently gained the interest of scientist to analyse industrial ecosystems, there is a gap in the research for analysing the evolution of aerospace ecosystems. There is also an absence of theory to understand in particular which other industrial ecosystems have nurtured the growth of aerospace ecosystems. No evidence is found on a similar study using bipartite country-products networks using trade data from 1992 to 2016 for the UK, the USA, France, Germany, Canada, Brazil, Mexico and China. Consequently, inspired by studies that have developed economic theories and analysed the behaviour of industrial ecosystems by taking a network science approach, this research contributes to broadening the knowledge in the applicability of network science to a particular industrial ecosystem. Furthermore, while ISM and MICMC methodologies have been widely applied for diverse industrial ecosystems, there is a gap in the literature to address the categorisation of key enablers for the growth of aerospace ecosystems. A literature review evidenced that although there is extensive information published on the aerospace sector, there is not a unique study addressing the identification and comparison of key enablers for the growth of the aerospace ecosystem between developed aerospace ecosystems and emergent ones, particularly for the UK's and the Mexican aerospace ecosystem.

In regards to the **research findings***,* results from the analysis elaborated in this research contribute to knowledge as no other study has been found containing similar conclusions. **In practical terms, the contribution of this research could be summarised in two main key findings: the first one is the patterns found in the portfolio of export products that have been linked to the evolution of aerospace ecosystems over a 25 years period. The second one is the identification and categorisation of key enablers that have fostered the growth of aerospace ecosystems.** The novel key findings, part of the contribution to the knowledge of this research, are summarised following.

7.1.1 Patterns found in the evolution of developed aerospace ecosystems

Inspired by studies that have developed economic theories and analysed the behaviour of industrial ecosystems by taking a network science approach, in this work historical trade data and network theory was used to find patterns that have characterised the evolution of aerospace ecosystems.

Bipartite country-products networks were developed for a group of developed (G1: France, the UK, the USA and G2: Brazil, Canada and Germany) and a group of emergent (G3: China and Mexico) aerospace ecosystems. A microscopic (node level) and a macroscopic analysis (network level), including nestedness analysis, was elaborated. The analysis was first done over G1 and G2. Then, a similar analysis was elaborated for the group of countries with emergent aerospace ecosystems. The patterns found in the evolution of developed aerospace ecosystems are presented next.

At a network-level:

- **The relations between the exported products and countries in developed aerospace ecosystems are not randomly distributed:** country-product nestedness analysis in this research contributed to confirm that mutualistic interaction patterns originally found between plants-pollinators & species-habitats networks are also found across networks of different nature.
- **Bipartite country-products networks of more developed aerospace ecosystems present a higher level of nestedness, and their nestedness develops in tandem with the evolution of the RCA on aerospace products:** nestedness patterns found in the country-products networks evidenced that countries with the most advanced ecosystems (G1 and G2) have greater nestedness patterns than the groups of countries with less developed ecosystems (G3).
- **Bipartite country-products networks elaborated in this research are aligned with the claim, suggested by other scientists, that most**

popular interactions occur between generalist-generalist, and that specialist products are mainly produced by generalist countries: the previous finding means that the most popular interactions in developed aerospace ecosystems are between “generalist countries” – “generalist products”, and that “specialist products” are mainly produced by “generalist countries”. Generalist countries are those countries with the broadest portfolio of RCA>1 products, while generalist products are those RCA>1 products with the highest popularity among countries.

- **Countries with developed aerospace ecosystems tend to increase their diversification by developing an RCA>1 on more products rather than specialising on few products**: countries with highest RCA on aerospace products tend to have a higher number of products with an RCA>1.
- **Developed aerospace ecosystems tend to have similar exported products’ portfolio:** countries incline to build an RCA>1 on a specific group of products, meaning that the number of shared RCA>1 products with other countries tends to increase.

At a node-level:

- **‘78 - road vehicles’** and **‘71 - power generating machinery and equipment’** are the most popular RCA>1 products among the countries with developed aerospace ecosystems (G1 and G2). The commodity code 78 embraces all types of vehicles (apart from aeroplanes) and parts thereof, such as cars, buses, tractors, trailers, containers, motorcycles and vehicles not mechanically propelled. The commodity code 71 includes machinery and parts thereof such as all types of engines and turbines (excluding the ones used in aeroplanes).
- **Manufactured products** have depicted a **stronger correlation** with the growth of developed aerospace ecosystems.
- In particular, **the automotive sector** has been the most popular on having a positive correlation with aerospace ecosystem’s evolution.

7.1.2 Patterns found in the evolution of emergent aerospace ecosystems and comparison with developed ones

Similar to G1 and G2, bipartite country-products networks for China and Mexico were developed and scrutinised. Findings are summarised following.

At a network-level:

- **Nestedness analysis of the bipartite country-products networks shreds of evidence opposite results when compared to the developed ecosystems:** the evolution of packed matrices of China and Mexico denotes a pattern in which most common interactions occur over specialist products, and countries decrease their diversification. The previous finding is contrary to the patterns found on the evolution of packed matrices of developed aerospace ecosystems. Moreover, it is also an opposing pattern to previous hypothesis in which is claimed that most common relations occur between generalists-generalists and that specialists are mainly related to generalists.
- **Countries with less-developed ecosystems tend to increase more the number of unique products (with an RCA>1), rather than increasing more the competition within each other.** The previous finding is also contradictory to the pattern found for developed aerospace ecosystems: G1 and G2 tend to focus more on increasing competition with each other by developing an RCA>1 on a specific group of products.

At a node-level:

- **Emergent aerospace ecosystems do not specialise on exporting the same group of products like the developed ecosystems:** results evidence that the most popular products for G3 are '81 – Prefabricated buildings, sanitary, lighting, etc. fixtures' and '76 - Telecommunications and sound recording equipment'. None of the previous products is part of the most popular products for G1 and G2.

7.1.3 Identification and categorisation of key enablers that have fostered the growth of aerospace ecosystems

Results of this research have also contributed to the identification and categorisation of key enablers for the enhancement of emergent and developed aerospace ecosystems. 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's 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 (Cabrera Padilla and Rodriguez Suarez, 2018; Meraz-Rodríguez, Ayvar-Campos and Papadopoulos, 2019). 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's 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, Mexico's 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 (Cabrera Padilla and Rodriguez Suarez, 2018), and it represents the UK's 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's aerospace ecosystem, in the Mexican ecosystem, the *supporting organisations'* key enabler is considered among the least influencer factors. Evidence suggests that the UK's 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 fallouts 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.

- In addition, **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.

7.2 Suggestions for the evolution of emergent aerospace ecosystems

The aforementioned findings lead to a series of suggestions aiming at the enhancement of emergent aerospace ecosystems. Thus, if emergent aerospace ecosystems are aiming at their aerospace improvement, they might need to implement the following suggestions:

- **First:** emergent aerospace ecosystems might need to increase their specialisation's diversification, focusing mainly on developing more generalist – generalist interactions. This means that emergent aerospace ecosystems need to increase the number of products (with an RCA>1).
- **Second:** emergent aerospace ecosystems might need to focus on competing with developed aerospace ecosystems, by generating an RCA>1 on the same group of products. Some of the products that emergent aerospace ecosystems might need to develop an RCA>1 are:
    - '78 - road vehicles'
    - '74 - general industrial machinery'
    - '71 - power generating machinery and equipment'
    - '64 - Paper, paperboard and articles thereof'
    - '63 - Wood and cork manufactures'
    - '62 - Rubber manufactures'
    - '59 - Chemical materials and products'
    - '52 - Inorganic chemicals'
    - '28 - Metalliferous ores and metal scrap'
    - '27 - Crude fertilizers and crude minerals'
    - '25 - Pulp and waste paper'
    - '24 - Cork and wood'
    - '22 - Oilseeds, oleaginous fruits'
- **Third:** emergent aerospace ecosystems might need to focus on fostering key enablers that are lacking when compared to a developed aerospace ecosystem. Particularly, an emergent aerospace ecosystem may need to prioritise first the strengthening of its supporting organisations. Such organisations should be focused on triggering the development of long-

term policies, founded on R&D progression, capable of enhancing the aerospace ecosystem. It could be beneficial for an emergent aerospace ecosystem to emulate policies implemented by the supporting organisations of developed aerospace ecosystems.

As evidenced previously, the aerospace ecosystem is facing a reconfiguration. During the last decades, new aerospace ecosystems have emerged, aiming at coping with the challenges that the aerospace industry is facing. However, the emergence of new aerospace ecosystems has been characterised for being driven by enhancement strategies without scientific foundations. The aim of this research was elaborated based on the idea that enhancement strategies should be founded on a proven point of reference. Therefore, this research aims at the identification to some extent of the point of reference against which emergent ecosystems should base their enhancement strategies. Such point of reference was found by analysing the evolution of developed ecosystems. Thus, the key findings of this research are expected to serve as a scientific foundation for the elaboration of enhancement strategies. The suggestions mentioned in this research might be applied to any country that would like to develop their aerospace ecosystem.

7.3 Limitations

An essential limitation of this study is data availability. The two-digit SITC commodities classification was the most complete database available at the moment when this research was elaborated. A more specific commodities' classification may significantly contribute to propose more specific recommendations.

In regards to the key enablers that have fostered the evolution of aerospace ecosystems, this research pretends to contain some of the most relevant key enablers suggested by recognised organisations and experts. Similar to the UK's aerospace ecosystem, in the literature, there is not an exclusive report containing all the key enablers for the evolution of the Mexican aerospace ecosystem. Consequently, it is assumed that the list of key enablers proposed in this research is not fully comprehensive but is sufficient to some extent for comparison with developed ecosystems and the elaboration of enhancement proposals.

Another important limitation is in regards to the subjectivity of the ISM and MICMAC methodologies, part of the qualitative study performed in this research. These methodologies are based on using experts' opinion. Consequently, results are dependent on the subjective prejudice of the participants. The validation of results from the ISM and MICMAC analyses was performed during two steps, depicted in Figure 19. Firstly, the list of key enablers, coming from a literature review and network analysis, was validated using experts' opinion. The experts contributed with the validation of the proposed key enablers and with the addition of new ones. Secondly, the ISM and MICMAC models are validated by checking conceptual inconsistencies, also using experts' judgement. These inconsistencies refer in particular to the rationality in the categorisation of the key enablers, depicted in the ISM and MICMAC models. In spite of the validity and rationality of results, as judged by experts, further validation may be elaborated by application of statistical validation techniques, such as structural equation modelling (SEM).

Another limitation of this research lies behind the proposed suggestions. It is imperative to highlight that the aforementioned suggestions do not imply that emergent aerospace ecosystems will automatically improve their ecosystems by implementing such recommendations. Consequently, the suggestions discussed in this research should be not considered as fully comprehensive but may be considered as part of the foundation for the elaboration of enhancement proposals. Each country must pursue its growth by developing policies, possibly based on what is suggested in this research.

7.4 Further research

Based on the analysis elaborated in this research, it is suggested that the methodology may be applied to the study of other industrial ecosystems. For instance, if a country wants to foster its pharmaceutical and medicinal ecosystem, it might need first to analyse the patterns and key enablers found in developed ecosystems so they can emulate their evolution.

Based on the aforementioned discussion, an analysis of additional emergent aerospace ecosystems could be used to reinforce the findings resulted from this research. If a similar analysis is elaborated, results are expected to be similar to the ones found in this research, which means that patterns observed on other emergent ecosystems are different from results of developed ecosystems.

Finally, the suggestions mentioned in this research might be applied to any country that would like to develop their aerospace ecosystem. However, the validation of the suggestions may be performed either by using the recommendations at any country with an emergent aerospace ecosystem and by the analysis of its evolution over time or by the judgment of experts. Thus, given the amount of time required for the application and validation of the suggestions in a particular ecosystem, a practical validation process is out of the scope of this research. Further validation will add significant value to confirm the research findings presented in this thesis.

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Appendixes

Appendix A – Individual SSIMs for the UK's aerospace ecosystem

Expert 1:

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
Chemicals ecosystem	9										Ø	↔	↔	▼
Machinery ecosystem	10											▲	↔	▼
Pharmaceutical and medicinal ecosystem	11												Ø	▼
Agricultural products ecosystem	12													Ø
Non-agricultural products ecosystem	13													

Expert 2:

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

Expert 3:

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

Expert 4:

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

Appendix B – Individual IRMs for the UK's aerospace ecosystem

Expert 1:

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

Expert 2:

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	1	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	1	1	0	0	0	0	1	0
Geopolitical factors	**4**	1	0	1	1	0	0	0	0	1	0	1	0	0
R&D public funding	**5**	0	1	0	0	1	1	0	0	0	1	0	1	0
Privatisation of aerospace companies	**6**	0	0	0	0	1	1	0	0	0	1	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	0	0	0	1	0	0	1	0	1
Chemicals ecosystem	**9**	1	0	1	0	0	0	0	0	1	1	0	0	1
Machinery ecosystem	**10**	0	0	0	0	0	0	0	0	0	1	0	0	1
Pharmaceutical and medicinal ecosystem	**11**	0	1	0	0	1	0	1	0	1	1	1	1	1
Agricultural products ecosystem	**12**	1	0	0	0	1	1	0	0	0	0	1	1	1
Non-agricultural products ecosystem	**13**	0	0	0	0	0	1	0	1	1	0	1	0	1

Expert 3:

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	0	0	1
Supporting organisations	**2**	1	1	1	0	0	0	1	1	0	0	1	0	0
Investment in human capital development	**3**	1	0	1	1	1	0	0	0	0	0	0	1	0
Geopolitical factors	**4**	1	0	1	1	0	0	0	0	0	0	1	0	0
R&D public funding	**5**	0	0	1	0	1	0	0	0	0	1	0	0	0
Privatisation of aerospace companies	**6**	0	0	0	0	1	1	0	0	0	0	0	1	0
Strategic alliances of manufacturing firms	**7**	1	1	0	0	1	1	1	0	0	0	0	0	0
Automotive ecosystem	**8**	0	0	1	0	1	0	0	1	0	0	0	0	0
Chemicals ecosystem	**9**	0	0	0	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	1	0	0	0	1	0	0	0	1	1	0
Non-agricultural products ecosystem	**13**	0	0	0	0	0	0	0	0	1	0	1	0	1

Expert 4:

Factor	#	1	2	3	4	5	6	7	8	9	10	11	12	13
Supplier development programs	**1**	1	1	0	1	1	0	1	0	0	0	0	0	0
Supporting organisations	**2**	1	1	0	0	0	0	1	0	0	0	0	1	0
Investment in human capital development	**3**	1	0	1	1	1	0	0	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	0	0	0	1	0	0	0	0	1	0	0	1
Privatisation of aerospace companies	**6**	0	0	0	0	0	1	0	0	0	0	0	0	0
Strategic alliances of manufacturing firms	**7**	1	0	0	0	0	1	1	0	0	0	0	0	0
Automotive ecosystem	**8**	0	0	0	0	0	1	0	1	0	0	0	0	0
Chemicals ecosystem	**9**	0	0	1	1	0	0	0	1	1	0	0	0	0
Machinery ecosystem	**10**	0	0	1	0	0	0	0	1	1	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	1	0	0	0	0	0	0	1	1	0
Non-agricultural products ecosystem	**13**	0	0	0	0	0	0	0	0	1	0	1	1	1

Appendix C – Individual SSIMs for the Mexican aerospace ecosystem

Expert 1:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1		Ø	↔	▼	▲	▲	▲	▲
Labour	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								▼
Non-agricultural products ecosystem	8								

Expert 2:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1		↔	▲	Ø	▲	↔	Ø	▲
Labour	2			▲	Ø	↔	↔	Ø	Ø
Investment in human capital development	3				↔	▼	▼	Ø	▼
Supporting organisations	4					▼	Ø	Ø	Ø
Foreign investment	5						▲	Ø	▲
Automotive ecosystem	6							▼	▲
Agricultural products ecosystem	7								Ø
Non-agricultural products ecosystem	8								

Expert 3:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1		Ø	▲	▲	▲	▼	↔	↔
Labour	2			▼	▼	▲	▼	▲	▲
Investment in human capital development	3				↔	▼	▼	▲	▲
Supporting organisations	4					▼	↔	Ø	▼
Foreign investment	5						▼	Ø	▲
Automotive ecosystem	6							Ø	▲
Agricultural products ecosystem	7								Ø
Non-agricultural products ecosystem	8								

Expert 4:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1		Ø	▲	Ø	▼	▼	▲	▲
Labour	2			Ø	▲	Ø	▼	Ø	Ø
Investment in human capital development	3				▲	Ø	▼	Ø	Ø
Supporting organisations	4					▼	▼	Ø	▲
Foreign investment	5						▼	Ø	▲
Automotive ecosystem	6							▲	▲
Agricultural products ecosystem	7								▲
Non-agricultural products ecosystem	8								

Appendix D – Individual IRMs for the Mexican aerospace ecosystem

Expert 1:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1	1	0	1	0	1	1	1	1
Labour	2	0	1	0	0	1	0	0	0
Investment in human capital development	3	1	0	1	1	1	1	0	0
Supporting organisations	4	1	0	1	1	1	0	1	0
Foreign investment	5	0	0	1	1	1	0	1	1
Automotive ecosystem	6	0	0	1	0	1	1	0	1
Agricultural products ecosystem	7	0	1	0	0	1	0	1	0
Non-agricultural products ecosystem	8	0	1	0	0	1	1	1	1

Expert 2:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	1	1	1	1	0	1	1	0	1
Labour	2	1	1	1	0	1	1	0	0
Investment in human capital development	3	0	0	1	1	0	0	0	0
Supporting organisations	4	0	0	1	1	0	0	0	0
Foreign investment	5	0	1	1	1	1	1	0	1
Automotive ecosystem	6	1	1	1	0	0	1	0	1
Agricultural products ecosystem	7	0	0	0	0	0	1	1	0
Non-agricultural products ecosystem	8	0	0	1	0	0	0	0	1

Expert 3:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	**1**	1	0	1	1	1	0	1	1
Labour	**2**	0	1	0	0	1	0	1	1
Investment in human capital development	**3**	0	1	1	1	0	0	1	1
Supporting organisations	**4**	0	1	1	1	0	1	0	0
Foreign investment	**5**	0	0	1	1	1	0	0	1
Automotive ecosystem	**6**	1	1	1	1	1	1	0	1
Agricultural products ecosystem	**7**	1	0	0	0	0	0	1	0
Non-agricultural products ecosystem	**8**	1	0	0	1	0	0	0	1

Expert 4:

Factor	#	1	2	3	4	5	6	7	8
Geopolitical factors	**1**	1	0	1	0	0	0	1	1
Labour	**2**	0	1	0	1	0	0	0	0
Investment in human capital development	**3**	0	0	1	1	0	0	0	0
Supporting organisations	**4**	0	0	0	1	0	0	0	1
Foreign investment	**5**	1	0	0	1	1	0	0	1
Automotive ecosystem	**6**	1	1	1	1	1	1	1	1
Agricultural products ecosystem	**7**	0	0	0	0	0	0	1	1
Non-agricultural products ecosystem	**8**	0	0	0	0	0	0	0	1