Global and local knowledge dynamics in an industry during modular transition

A case study of the *Airbus* production network and the Aerospace Cluster in Hamburg, Northern Germany

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AECMA	Association Européenne des Constructeurs de Matériel Aérospatial
AEEC	Airline Electronic Engineering Committee
AFDX	Avionics Full DupleX Switched Ethernet (*ARINC* Standard 664)
AIA	Aerospace Industries Association
AIAA	The American Institute of Aeronautics and Astronautics
ASD	Aerospace and Defence Industries Association of Europe (former AECMA)
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
AWC	Aviation Weather Center
BDLI	Bundesverband der Deutschen Luft- und Raumfahrtindustrie
BMBF	Bundesministerium für Bildung und Forschung
BWVI	Behörde für Wirtschaft, Verkehr und Innovation
CASA	Construcciones Aeronáuticas S.A.
CBD	Contract Based Design
CEO	Chief Executive Officer
CFRP	Carbon Fibre Reinforced Plastics
CPS	Cyber-physical system
CSR	Corporate Social Responsibility
DASA	Deutsche Aerospace Aktiengesellschaft
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EADS	European Aeronautic Defense and Space
EASA	European Aviation Safety Agency
EASCG	European ATM Standards Coordination Group
EDA	European Defense Agency
EDIG	European Defense Industries Group
EUROCAE	European Organisation for Civil Aviation Electronics
FAA	Federal Aviation Administration
GLARE	Glass Laminate Aluminium Reinforced Epoxy
GPN	Global Production Network(s)
GRAMS	General Requirements for Aerostructure and Materials Suppliers
GRESS	General Requirements for Equipment and System Suppliers
GT	Grounded Theory
GVC	Global Value Chain(s)

HAV	Hamburg Aviation Cluster e.V.
HAW	Hamburger Hochschule für Angewandte Wissenschaften
HCAT	Hamburg Centre for Aviation Training
HECAS	Hanseatic Engineering & Consulting Association e.V.
HIBB	Hamburger Institut für berufliche Weiterbildung
HSU	Helmut Schmidt Universität Hamburg (Universität der Bundeswehr)
HWF	Hamburgische Gesellschaft für Wirtschaftsförderung mbH
HWWI	Hamburgisches Weltwirtschaftsinstitut
IuC	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITC	Industry Technology Consortia
LaFT	Laboratorium für Fertigungstechnik, Helmut-Schmidt Universität Hamburg
LBA	Luftfahrtbundesamt
NDA	Non-Disclosure Agreement
NIISU	Institute of Standardization and Unification (Russia)
NSF	National Science Foundation (USA)
Open IMA	Open Integrated Modular Avionics
PRI	Performance Review Institute
RTCA	Radio Technical Commission for Aeronautics
R&D	Research and Development
SAE	Society of Automotive Engineers
SJAC	Society of Japanese Aerospace Companies
SME	Small and Medium Sized Enterprises
SOP	Standard Operating Procedure
TUHH	Technische Universität Hamburg-Harburg
U.S. D.o.D.	U.S. Department of Defense
ZAL	Zentrum für Angewandte Luftfahrtforschung (Hamburg)

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Finally, I would like to thank my family for their patience and their support, especially during the last months. You have been wonderful.

This is to Mio.

Foreword

The *Hamburg Aviation e.V.* cluster (formerly Luftfahrtcluster Metropolregion Hamburg e.V.) is a public-private partnership association that won the *Cluster Excellence Award* of the BMBF in 2008 and, in this course, received 40 million euros in public funding. Part of this funding also sponsored my position as a research assistant at the Institute for Production Engineering and Manufacturing Technology (Helmut Schmidt University Hamburg) in the project “Development of a Knowledge Management System for the Aerospace Cluster Hamburg” (2012-2014) that gave me initial access to the field. In a multi-disciplinary team of engineers and social scientists we developed an ambitious socio-technical knowledge management system including a software prototype that did, however, not work out as intended in the end.

The present dissertation has been mainly motivated by investigating and explaining why it was actually supposed to fail – which is not (only) because firms and research facilities simply did not want to share their knowledge and resources and were stratified by severe power asymmetries, but because *something more profound* had happened that had entirely changed the cluster around *Airbus*. During the course of that project and detailed analysis of interviews and observations, I soon figured that despite of the funding, the creation of a corporate identity, the vast amount of sponsored network events and the building of a huge new private applied research center, distrust among the suppliers and service providers around *Airbus* had spread and the development of the location rather declined than further grew. A key to answer why activities of SMEs in the regional cluster are actually declining lies in the top-down strategic implementation of the new modular system policy of the lead firm *Airbus* that started with the beginning of the A380 program. The top-down implemented strategic modularization of product and system architectures as well as related value chain tasks on the global scale also resulted in organizational shifts and alterations on the local level. The motivation to write this thesis has been to understand and explain these profound changes.

Abstract (English)

The thesis examines the interrelations between global and local industrial knowledge dynamics against the background of an increasing digitization and modularization of design and production. It analyzes how the transformation of a knowledge infrastructure in a high technology industry affects a local industry cluster. An infrastructure is a system of organizations, technologies and artifacts. A *knowledge* infrastructure codifies expert knowledge within common standards and design rules that diffuse within production networks. Modularity is a central organizational principle and architectural paradigm that structures knowledge relations in complex product design and production processes. Modularization, however, presupposes the codification of knowledge on the interoperability of separate modules into common technological standards. Hence, the emergence of modular industry structures implicates a change of the knowledge infrastructure underlying design and production relations that also affect spatial industry relations.

In order to explore the multi-dimensional phenomenon of modularization the thesis relies on an engaged instead of a fragmented pluralism combining insights from the theoretical frameworks of global value chains, global production networks, the theory of modular systems and a relational perspective on regional development. The multi-dimensional empirical case study is designed around the aerospace cluster in the *Metropolitan Region of Hamburg* and its local and global embedding in wider structures of the *Airbus* production network including actors that are involved in standard formation and diffusion related activities. The introduction of technological and architectural innovations in the A380 program and its top-down implementation in the 1990s marks the start of the case study. Via integrating the dimension of the artifact the study examines how changes in the design architecture and the accompanying building of a new knowledge infrastructure cause changes in knowledge and production relations on the global and local scale. It relies on a combination of qualitative (interview data, field notes, documents) and quantitative data (supplier lists, cluster data bases) which have been analyzed based on principles of grounded theory building.

The results of the study show how local knowledge relations became disembedded during modular transition and how global industrial and local territorial knowledge dynamics are interrelated. The insights contribute to deepen the understanding of how production networks and value chains change apart from the logics of capital dynamics and transaction cost economics. It, moreover, contributes to the literature on regional knowledge processes by showing how localized knowledge and knowledge processes can become disembedded and devaluated.

Abstract (German)

Die vorliegende Dissertation befasst sich mit den Zusammenhängen zwischen globalen und lokalen Wissensdynamiken vor dem Hintergrund einer zunehmenden Digitalisierung und Modularisierung von Design und Produktion. Im Vordergrund des Forschungsinteresses steht der Einfluss der Veränderung der globalen Wissensinfrastruktur, die den Austauschbeziehungen in einem verteilten Produktions-netzwerk zu Grunde liegt, auf ein lokales Industriecluster.

Eine Infrastruktur bezeichnet ein System von Organisationen, Technologien und Artefakten. Eine *Wissens*infrastruktur bezeichnet ein System aus Standards und Designregeln (als Form kodifizierten Expertenwissens), welches innerhalb eines verteilten Produktionsnetzwerkes für den Transfer von Wissen und Informationen über räumliche und organisatorische Grenzen hinweg sorgt. Modularität wird in diesem Zusammenhang als ein zentrales, organisatorisches Prinzip und architektonisches Paradigma verstanden, das der Struktur von Wissens- und Produktionsbeziehungen in komplexen Produktionsprozessen zu Grunde liegt. Dies gilt sowohl auf Ebene des Artefaktes als auch auf Ebene der relationalen Netzwerkstruktur. Modularisierung als Prozess setzt dabei stets die Kodifizierung von Wissen in Bezug auf Interoperabilität und Kompatibilität in gemeinsame technische Standards voraus. Entsprechend impliziert die Entstehung so genannter modularer Industriestrukturen einen Wandel der Wissensinfrastruktur, die dem Transfer von Wissen in Produktionsbeziehungen unterliegt. Dieser Wandel betrifft auf einer weiteren Dimension auch räumliche Industriebeziehungen.

Der Mehrdimensionalität des Phänomens der Modularisierung wird im Rahmen der Arbeit mit einem pluralistischen Theorieansatz begegnet, der Aspekte aus dem Ansatz der Globalen Wertketten und der Globalen Produktionsnetzwerke mit Ansätzen der Theorie Modularer Systeme verbindet und dabei eine dynamische, relationale Perspektive auf regionale Entwicklung einnimmt.

Die empirische Fallstudie setzt räumlich bei einem Luftfahrtcluster in der Metropolregion Hamburg an und verfolgt dessen Einbettung in lokale und globale Wissens- und Produktionsbeziehungen um das Ankerunternehmen *Airbus*. In diesem Zusammenhang werden Akteure und Strukturen identifiziert, die in die Entwicklung und Verbreitung technischer Standards involviert sind. Auf zeitlicher Ebene setzt die Fallstudie beim Beginn des A380 Programms in den 1990er Jahren an, in dessen Verlauf technologische und vor allem architektonische Innovationen und Standards eingeführt und sukzessive top-down implementiert wurden. Durch die Einbindung der Artefaktebene wird analysiert, wie Veränderungen der Architektur des Artefaktes mit Veränderungen der Wissensinfrastruktur einhergehen, die lokale und globale Wissens- und Produktionsbeziehungen sowie die Entwicklung des lokalen Industrieclusters in Hamburg nachhaltig verändern. Die Fallstudie basiert auf der Kombination qualitativer (Interviews, Feldforschung, Dokumente) und quantitativer Daten (Zuliefererdatenbanken), die entsprechend den

Prinzipien der gegenstandsbezogenen Theoriebildung analysiert und unter Verwendung verschiedener Heuristiken ausgewertet wurden.

Die Ergebnisse der Studie zeigen, wie lokale Wissensbeziehungen in einer Phase der modularen Transition „entbettet“ und gleichzeitig in breitere globale Strukturen eingebunden werden. Die gewonnenen Erkenntnisse tragen insgesamt zu einem vertieften Verständnis von Veränderungs-prozessen in globalen Produktionsnetzwerken bei, die in der bestehenden Literatur vordergründig als Prozesse beschrieben werden, die der rationalen Logik von Inwertsetzung und Wertschöpfung folgen. Darüber hinaus liefert die Arbeit einen Beitrag zur Literatur über regionale Wissensprozesse, indem gezeigt wird wie lokales Wissen entbettet und zugleich entwertet werden kann.

1 Introduction

1.1 Background and research interest

At the beginning of the millennium, *Airbus* initiated its most ambitious project ever – the A380 program, a superjumbo jet that can carry up to 853 passengers. During this time, the company also announced the reorganization of its administrative structure, in order to integrate the prior quite independent, and geographically dispersed organizational structure. This transformation has also subsequently affected the development of regions that are "plugged" into the *Airbus* production network.

After massive delays in production and delivery, technological problems and declining order numbers, the initial euphoria about the A380 superjumbo has certainly passed today. What has remained though are the profound changes in the organizational model of production and design and the underlying infrastructures to govern technological and architectural knowledge that have altered the configuration and socio-spatial dimension of the industry over the last two decades.

An infrastructure is a system of organizations, technologies and artifacts. It is part of the background that makes other things work and is mostly quite invisible to outsiders (Lampland and Star 2009, p. 17). A **knowledge infrastructure** enables knowledge processes while simultaneously having a strong impact upon them. The more complex a product, the more sophisticated the underlying knowledge infrastructures that are necessary for its realization and operation. The A380 can be designated as a highly complex **cyber-physical system** in this regard. In engineering, a cyber-physical system designates an artifact that comprises synergistically interacting physical and computational components[1]. Knowledge, competencies and material resources required to realize a cyber-physical artifact such as an aircraft are spread and dispersed across multiple actors, places as well as scientific and technological fields. Hence, knowledge infrastructures have to be developed that reduce complexity and enable spatially distributed flexible production processes and the transfer of knowledge across places and contexts.

The basic organizational principle of such a complexity reducing system and its underlying infrastructure can be found in the concept of modularity. **Modularity** is a design principle based on insights from complexity theory that can be applied on different dimensions from artifacts to organizations (Langlois, 2002). It is an **architectural paradigm**. On the product or system level, the term modular describes an artifact whose single components (i.e. modules) are interchangeable without adjustments in other components – if module interfaces are clearly defined, standardized and transparent. Whereas in a

[1] The notion has been introduced against the background that IuC technologies diffuse into more and more domains of our daily lives and the artifacts we create, building one of the fundaments of what is termed "Industrie 4.0" in Germany and the "Internet of Things and Services" in English-speaking countries.

tightly integrated design approach each component is specifically designed to work with one another (e.g., a mechanical clockwork), a modular design is characterized by the functional and physical independence of the single components which are linked through universal standardized interfaces enabling a greater variety through recombination (e.g., LEGO modules, motherboard and graphic device). It is a design theory that aims at reducing complexity and making product and process architectures more flexible to adjustments and the integration of complementary knowledge bases (Baldwin and Clark, 2000; Henderson and Clark, 1990).

On the **industry level**, modularity refers to a specific form of organization that partly mirrors the architecture of the artifact that is co-created by the actors that form the production network (Brusoni, 2001; MacCormack et al., 2012). So called modular production networks show a governance pattern, within which knowledge is assumed to get internalized into value chain modules through "specific knowledge codification schemes", that aim at keeping interactions - social as well as technological ones - from becoming highly dense and idiosyncratic (Gereffi et al., 2005; Sturgeon, 2003). Codification is understood here as the process through which information is transformed into a specific linguistic and normative code, it entails the conversion from tacit knowledge into documented information that takes a specific representational format. In sum, modularity is defined as an architectural paradigm and organizing principle of production and knowledge relations that structures product, knowledge and network architectures.

Existing studies in this field assume the existence of modular links in production networks without further questioning how they evolve and become part of more profound knowledge infrastructures and what really happens in an industry during modular transition. Following the logic of scholars of the global value chain approach (Gereffi et al., 2005; Gereffi and Lee, 2016), the actual process of modularization on the industry level must be *per se* accompanied by pervasive codification and standard formation activities that (only in its final stage) result in an "infrastructure" for governing industrial knowledge across contexts and places. As Sturgeon (2003, p. 201 Ftnote) notes:

> *"Standardized protocols do not arise spontaneously, but are part of the historical processes of industrial development. Standards can be agreed upon by committees (open standards), or they can arise from the codification of the routines of dominant firms or from equipment or software vendors […]. Their establishment is often contentious and part of the competitive positioning of firms."*

Hence, technological and industrial standards can be considered as a form of codified expert knowledge (Brunsson and Jacobsson, 2000) here that underlies any process of modularization (Sturgeon 2003). Standards are also dynamic since, they change when new component and process technologies come up. According to Giddens (1984) globalization processes have been enabled by the differentiation and intensification of knowledge transfer practices *over distance* as both a precondition as well as a consequence of modernity. In this sense, the codification of (technological) knowledge is a central practice in governing post-modern industrial systems. In fact, standards - and more specifically interoperability and interface standards - allow parts and systems to come from different technological fields as well as suppliers from all over the world enabling the emergence of global production networks. A **global production network (GPN)** is "an organizational arrangement, comprising interconnected economic and non-economic actors, coordinated by a global lead firm […] producing goods or services across multiple geographical locations for worldwide markets." (Coe and Yeung, 2015, p. 1f.). Within modular industry constellations managing industrial knowledge and codification processes is often achieved by an array of extra-firm practices and institutions designed to balance cooperation and competition (Coe, 2011; Coe and Yeung, 2015; Herrigel, 2009). These actors and practices are, thus, part of the global production network and must be taken into account in any empirical study of industrial change towards modular forms of organization.

There are very few empirical studies that include or integrate a spatial perspective on the formation, diffusion and impact of technical standards in propulsive industries. Although there is consensus among scholars that from a knowledge-based perspective, modularization is per se accompanied by pervasive processes of knowledge codification and diffusion, there are no sufficient insights on *how*, *where* and by *whom* exactly this industry-specific knowledge infrastructure is developed. Thus, there are only few insights on how technological standard formation, diffusion and impact are displayed geographically in high technology industries such as the aerospace industry and how they simultaneously affect global industrial and local economic dynamics and practices.[2] Researchers in (economic) geography are predominantly occupied with "tacit" forms of knowledge and how they enable local or regional advantage (Bathelt et al., 2004; Bathelt and Cohendet, 2014; Malmberg and Maskell, 2002). Hence, they are interested in knowledge that is *protected from external us*e in order to get insights on technological innovations and competitive advantages. Technological (interoperability) standards, in contrast, codify knowledge that is intended to be *shared* in design, development and production processes.

Existing case studies locate the codification of tacit knowledge (i.e. standard formation activities) at the local scale. According to this argumentation, the regional competitive advantage of the Silicon Valley arises from exactly this aspect and the fact that knowledge is produced and codified in this specific place (Saxenian, 1994; Sturgeon, 2003). An empirical analysis of standard formation in the mobile-telecommunications industry describes the emergence of a "pluralistic model of standard setting" that is constituted by "complex networks of state and corporate entities interacting at different spatial scales" (Hess and Coe 2006, p. 1219). These multi-scalar networks of standard setters have been formed as "part of attempts to gain control from the mobile telecommunication business, as well as to ensure

[2] There are few case studies (cf. e.g., Henson and Humphrey (2010); Ouma (2010); Perkins and Neumayer (2010)) that focus however not on propulsive industries and usually investigate the diffusion of a single quality, social or environmental standard rather than the emergence of a knowledge infrastructure and the interrelations between standard formation, diffusion and economic development. An exception is the study of Coe and Hess (2006) on telecommunication standards.

interoperability and convergence.” (ibid., p. 1224). Distinct from the case of the Silicon Valley, codification activities are not reduced to the routines of firms, nor associated to a specific local context. In this case, standards are negotiated by firms and non-firm actors such as nation states on multiple spatial scales (Hess and Coe 2006, p. 1217). That also means that the embeddedness of actors that produce and make use of standards plays a crucial role regarding their impact on different spatial scales. The analysis of global production networks focuses specifically on the **socio-spatial embedding** of relations between actors that constitute a production network (Coe et al., 2008; Coe and Yeung, 2015; Ernst and Kim, 2002; Henderson et al., 2002). Within the analytical framework of Global Production Networks, the key to understand economic development is the sub-national region, since economic actors are situated in particular places with different institutional conditions that shape development and firm practices (Coe and Yeung 2015, p. 18f). Hence, both internal and external linkages such as the functional integration within global value chains and production networks affect the development of regional industry clusters. However, development dynamics within this framework are exclusively described as being driven by capitalist rationales based on transaction cost economics (Coe and Yeung, 2015) or in the context of changing governance structures (Gereffi and Lee, 2016). Knowledge relations and how they are embedded are not explicitly considered.

Technological standards have been predominantly viewed from a functional perspective emphasizing their coordinating and integrating character. But technological standards are also developed in particular places and embedded in the situated practice of their origin. They can become enablers of knowledge exchange, but also constraints considering their normative character. The normative character of standards which can give us further insights on different regional outcomes that develop in the long run has been not enough included in the hitherto existing studies[3]. Hence, the key to understand the dynamics of knowledge processes in global production networks and its different regional outcomes are the different types of embedding of actors that codify knowledge and set technological standards and those that make use of them once they diffuse in the network. The local arena reflects this interplay between endogenous and exogenous factors and the interrelations between different types of embeddedness. It is the place where changes in the trajectory of an industry can be made visible over time.

The top-down implemented strategic modularization of product- and system architectures by *Airbus* that started with the A380 program[4] results in organizational shifts and alterations on the local level. Former case studies, like for instance in the ICT sector, rely on cases where modular approaches have evolved bottom-up over a long period of time (cf. e.g., Sturgeon 2002, 2003). They describe a state of

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[3] This topic has been mainly treated in literature from the field of political economy Ponte et al. (2011) or to describe ideal typical governance forms within global value chains building on insights from convention theory.

[4] Whereas first developmental efforts date back into the 1980s, actual construction started in 2001. I consider the period from the end of the 1990s until today.

what I call “modular maturity” as an ideal-typical governance form. The present thesis goes beyond these insights and explores the dynamics of modularization that enfold over time.

In its core, this thesis assumes that codification and standard formation and the building and transformation of a knowledge infrastructure during phases of modular transition affect the dynamics of global production networks. The main research interest is in the interrelations between global and local development dynamics by asking: How do transformations in the knowledge infrastructure of a production system/global production network affect knowledge and production relations in a local industry cluster?

The main is to identify (central) causal relations between:

- the formation and diffusion of modularity-related technical standards as a form of codified expert knowledge and part of the knowledge infrastructure,
- their role with regard to processes of socio-spatial transformation in knowledge intense, propulsive industries,
- and the related interdependencies between global industrial and local territorial dynamics.

On a theoretical level, therefore, the thesis first of all draws a line to the ongoing debate in geography about the interrelations between knowledge, organizations and territorial industrial development. The thesis aims at broadening the understanding of how global production networks change based on changing knowledge processes and how global and local dynamics are interrelated in this regard.

On a practical level, the results of the analysis have important implications for regional development policies and the strategic positioning of aerospace suppliers in the *Metropolitan Region of Hamburg* in Northern Germany.

1.2 Analytical framework and methodology

A qualitative case study has been chosen as the most appropriate way to explore and analyze the complex causal connections. The study is based on the methodology of Grounded Theory (GT) building, i.e. a reconstructive, interpretative research approach. The research questions have been operationalized in the frame of a single case study using different heuristics and methods for data collection and analysis (including qualitative as well as quantitative data).

The in-depth case study takes the event of architectural innovations in the A380 program, i.e. the introduction of Open Integrated Modular Avionics (Open IMA), as a starting point for an analysis of the different knowledge processes (codification and diffusion) that underlie or enable relational changes on a technological (knowledge) socio-organizational and spatial level. Open IMA is an architectural innovation in systems design that has meanwhile become a technological standard in avionics. It is based on independent and interdependent modules such as a shared AFDX network and standard hardware modules. In order to investigate the interdependencies between global and local dynamics the case study is designed around an aerospace cluster in the *Metropolitan Region of Hamburg* and its embedding in wider structures of the European aerospace manufacturing industry around the lead firm *Airbus* (former *EADS*).[5]

The analytical and conceptual frame of this thesis has four dimensions. First of all, a temporal dimension is necessary, in order to understand how knowledge and exchange relations in global production networks, along with the regions "plugged" into them, change. Thus, on a temporal axis, the thesis considers modularization as a dynamic process and the strategic decision to modularize organizational and product architectures as a major driver for relational changes in a production network.

In order to analyze changing knowledge relations in production systems the thesis choses the entry via the artifact (i.e. the A380) and the relations between its computational and physical components (understood as a cyber-physical system). Distinct from conventional perspectives in economic geography that consider economic exchange relations in production systems against the background of value creation and capture, this allows the researcher to reconstruct the knowledge infrastructure that is necessary to realize a complex cyber-physical system. Changes in the architecture of the artifact (i.e. from integrated to modular) are identified, in order to examine changes in knowledge exchange relations and their embedding in wider socio-spatial structures.

In doing so, the analytical framework considers three interrelated dimensions: the artifact (artifact-as-designed; i.e. technologies/knowledge), the production network that has formed around the artifact (knowledge and production relations) as well as its spatial manifestation. These dimensions relate to different forms of embeddedness, namely the embeddedness of knowledge in situated practice, and the socio-organizational and spatial embeddedness of actors and relations. Hence, change during modularization can be explained referring to different processes of dis- and re-embedding socio-technical and organizational relations from their specific context, which causes different (regional) outcomes.

1.3 Outline and structure of the thesis

The aim of the second chapter is to develop a multi-dimensional conceptual framework that serves as a basis for the following analysis. In order to investigate the interrelations between global and local development dynamics of production one needs a clear understanding of what constitutes a production system. Knowledge is a constitutive feature for production processes, production relations and

[5] The focus of the study is on the aerospace *manufacturing* industry, excluding by definition air transport and other services.

organizational principals. Consequently, the conception of a production system and its inherent exchange relations focuses on knowledge as a central production factor. In order to examine how changes in the knowledge infrastructure of a production system affect the spatial dimension of an industry one needs to focus on a specific territory, since territorial development depends on the geographical agglomeration of actors and specific knowledge and competencies (Asheim, 1996; Malmberg and Maskell, 2002; Saxenian, 1994). It is mostly imagined around the concept of industrial clusters consisting of local internal as well as external linkages between economic actors (Bathelt et al., 2004). Of particular interest to the present analysis is the nature of the external relations that link different places and the knowledge circulation among them.

The aim of **chapter 2.1** is to conceptualize a multi-dimensional production system that integrates the dimension of the artifact. This cyber-physical dimension is necessary in order to get insights into how knowledge flows and relations are organized. In order to conceptualize the social (organizational and network) and spatial dimension of the production system, this chapter draws on the global value chain and the global production network (GPN) approach and its conceptualization of vertical and horizontal exchange relations in production systems. They are based, on the one hand, on theoretical insights from transaction cost economics explaining the efficiency rationale beyond governing and structuring exchange relations; a systemic functional perspective on input-output relations that link tasks and functions in order to produce a common outcome. On the other hand, the GPN approach focuses strongly on the concept of embeddedness of exchange relations derived from economic sociology. This serves as a basis to further conceptualize the social as well as the spatial dimension of the production system via the embeddedness of actors and relations in particular places (2.1.3). Here, different forms of trust serve as a basis for building relational ties as the fundament for exchange relations and knowledge diffusion in production networks (2.1.4). The chapter concludes with a brief summary and conclusion for the further analysis.

Chapter 2.2 explicitly considers knowledge and knowledge relations in production networks. It particularly focuses on the role of codified knowledge and related codification and standard formation processes in global production networks. The context in which knowledge gets codified and how it diffuses in production relations is described with the concept of knowledge infrastructure which will be defined in more detail in chapter 2.2.6. It relates to questions and research on the embeddedness of knowledge in situational practice and socio-organizational contexts of creation and use and integrates the different types of embeddedness introduced throughout chapter 2.1.

Drawing on insights from modular systems and design theory, **chapter 2.3** elaborates on the concept of modularity as an architectural paradigm and organizing principle of production and knowledge relations that structures the artifact and organizational network dimension of a production system. The second part of the chapter describes the knowledge infrastructure in modular production systems based on the definition developed in chapter 2.2.

Chapter 2.4 finally introduces the dimension of time and conceptualizes modularization as a dynamic multi-dimensional process. On the micro level, it is initiated by strategic decisions of designers and managers (chapter 2.4.1). On the macro level, and from an evolutionary perspective, it creates socio-technical path-dependencies that impact the development of industrial structures and its constituting knowledge and production relations and can, thus, be considered as an emergent phenomenon (chapter 2.4.2). Chapter 2.4.3 conceptualizes modularization as a cycle process and identifies three major phases of modularization that are central for the further empirical analysis.

Chapter 2.5 is a synthesis integrating the insights from the prior chapters into a coherent conceptual model displayed in Figure 11 and Figure 12, that illustrates how the different phases of modularization affect knowledge and production relations via multi-dimensional processes of dis- an re-embedding on different scales.

The **third chapter** presents the methodological approach and research design of the heuristic single case study. Chapter 3.1.2 introduces the case and reviews the existing literature and insights on the civil European aerospace industry, the *Airbus* production network, as well as the local aerospace cluster in the *Metropolitan Region of Hamburg*. **Chapter 3.1.2** and **3.1.3** describe the general characteristics of reconstructive, interpretative, qualitative empirical research and the particularities of grounded theory building as well as how the case study design strategy has been combined with the grounded theory approach. Chapter 3.1.4 defines the selection and boundaries of the case example. Throughout **chapter 3.2** the analysis and research questions are operationalized in different methods and heuristics including semi-structured, narrative interviews, semi-overt as well as participant observation, the collection and analysis of documents, technical data and standards documents (chapter 3.2.1). In **chapter 3.2.2** I explain how the heterogeneous data have been analyzed combining the technique of artifact analysis, techniques used to display and spatially map production networks, as well as the coding and grounded theory building process using the Software ATLAS t.i. **Chapter 3** concludes with some remarks concerning the reliability, validity and scope of results.

The empirical part presents the results of the case study. The **fourth chapter** is organized as follows: **The first part** (4.1) introduces the production network around *Airbus* and the local industry cluster in Hamburg (4.1.2) and describes the modular transition and increasing globalization of knowledge and production relations. It is organized along the dimensions of the conceptual model starting with architectural and process innovations that aim towards modularity in design and organization and lead to a reconfiguration and disembedding of existing knowledge and production relations. This results in profound technological and organizational tensions (chapter 4.1.3). Chapter 4.1.4 describes the transformation and building of a new knowledge infrastructure and the re-embedding of knowledge and production relations within this infrastructure that indicates the growing maturity of modular designs and organization. It analyzes how, where and by whom new technological and industrial standards are developed and how this global infrastructure for governing technological knowledge across contexts and places is established, embedded and diffuses in the production network.

The **second part of the chapter (4.2)**, examines the impact of the processes that take place during modular transition on the global scale on the aerospace cluster and the local *Airbus* supply base in the *Metropolitan Region of Hamburg*. After a characterization of the local aerospace sector and the regional cluster (before modularization) (4.2.1), chapter 4.2.2 describes processes of dis- and re-embedding of production and knowledge relations as well as tensions and new challenges for local suppliers. It examines how the institutional embedding of the actors changes in the long run, when they are confronted with distant codes and standards developed elsewhere and how this leads to the destruction of existing trust relations and an increasing alienation of knowledge and production relations on the local level (4.2.3).

The final **chapter 5** further abstracts generalizable patterns from the case- specific empirical data with regard to the impact of modularization and standardization on the overall dynamics and configuration of GPN and also points to limitations of the study. It furthermore discusses the theoretical contribution of the results to the field of economic geography and especially the study of global production networks and reflects upon the practical implications of the research results for regional development policies and the strategic positioning of local SMEs.

2 Theoretical framework and conceptual model

The aim of this chapter is to develop the conceptual model of the thesis based on combining existing theoretical and analytical frameworks in economic geography and related disciplines, in order to develop and relate different dimensions of a production system and explain how it connects to territorial development. In doing so, this thesis argues towards an engaged instead of a fragmented pluralism in theoretical thinking (Barnes and Sheppard 2010, Hassink et al. 2014). Different approaches are not considered as isolated boxes, but are linked to each other in order to explain complex phenomena in an increasingly interconnected world.

First of all, one needs a clear understanding of what constitutes a **production system**, in order to investigate the interrelations between global and local development dynamics of production networks. In the focus of interest stand knowledge and knowledge relations, because they are formative for our definition of (post-)modernist societies and economies. **Knowledge** is a constitutive feature for production processes, production relations and organizational principals. Through the knowledge-based action of actors innovation and emancipation can be achieved (Kirchhöfer 2004, p. 21), and complex production processes can be carried out in globally distributed constellations. Following Giddens, globalization processes have been enabled by the differentiation and intensification of knowledge transfer practices *over distance* as both a precondition as well as a consequence of modernity (Giddens, 1990). Hence, the emergence and spread of the hegemonic discourse of a knowledge-based economy or the knowledge-based view of the firm has significantly influenced the reflection and investigation of knowledge processes - i.e. creation, codification, diffusion, utilization, sharing, transfer - within enterprises, production networks and global industries (Drucker, 1994; Kogut and Zander, 1992; Nonaka and Takeuchi, 1995; Nonaka and Teece, 2001). Consequently, the following conception of a production system and its inherent exchange relations focuses on knowledge and knowledge relations as a constitutive feature.

In order to examine how changes in the knowledge infrastructure of a production system affect the spatial dimension of an industry one needs to focus on a specific territory, since **territorial development** depends on the geographical agglomeration of actors and specific knowledge and competencies. In this regard, the tacit dimension of knowledge described by Polanyi (cf. chapter 2.2.1) made a considerable career in economic geography. As a type of knowledge that cannot be easily transferred and relies on a culture of trust and sharing it became key in explaining local and regional competitive advantage (van Hippel 1993, 1996). Accordingly, the literature on industrial districts (Asheim, 1996), geographical clusters (Porter, 2010), national and regional innovation systems (Asheim and Gertler, 2011; Lundvall et al., 2002), industrial spaces (Saxenian, 1994), learning regions (Maskell and Malmberg, 1999) as well as the literature on different proximity dimensions (Torre and Rallet, 2005) discusses the advantages that arise from permanent geographical proximity based on social relationships and networks. It focuses on localized knowledge networks in production systems that are territorially bounded. Within this stream of literature, regions have been considered as rather “isolated islands” than being part and influenced by external linkages and wider knowledge infrastructures that affect and constitute knowledge relations in production networks. But regional production networks are also embedded in wider networks of exchange relations that span clusters and go beyond the governance structures that are used to explain inter-firm linkages in global value chains (Bathelt and Li 2014). Of particular interest to the present analysis is the nature of these external relations that link different places and the knowledge circulation among them. Recent studies of Gereffi and Lee (2016) reveal how GVCs and localized industrial clusters are linked through a variety of globalization processes and synergistic forms of knowledge governance such as global corporate social responsibility measures. They do, however, not focus on the organization and circulation of technological knowledge within these wider structures and neglect the spatial dynamics of actual processes of codification and standard formation. Those are, however, crucial to any process of modular transition and its implications for territorial development.

2.1 Exchange relations in production systems

The aim of chapter 2.1 is to conceptualize a production system that integrates the dimension of the artifact. This cyber-physical dimension is necessary in order to get insights into how knowledge flows and relations are organized. It is mainly based on literature from (system) engineering, design and systems theory (2.1.1). In order to conceptualize the social (organizational and network) dimension of the production system, chapter 2.1.2 draws on the global value chain and the global production network approach and its conceptualization of vertical and horizontal exchange relations in production systems and their specific forms of embeddedness.

2.1.1 Cyber-Physical Systems

In order to reconstruct the knowledge relations behind a complex production system the entry via the artifact offers the possibility to identify how the numerous components constituting a product interact and how they are integrated. This serves as a basis to identify knowledge relations in the production network and to better understand knowledge and production relations between the numerous actors that are part of the production system.

Against the background of an increasing digitization of artifacts and production systems, tangible and intangible components are increasingly combined. In this regard, cyber-physical system (CPS) research is an emerging transdisciplinary paradigm[6] that is not clearly delimited yet. There exist many definitions and terms such as embedded systems, Internet of Things, etc. The notion of a cyber-physical system has been first introduced by Helen Gill from the National Science Foundation in the US, defining them as:

> *"systems, where physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context."*[7]

The concept relates to the notion of the Internet of Things first employed by Kevin Ashton in 1999 that aimed at describing the potential of RFID technologies[8]. The notion of CPS is, however, more driven by engineering aspects than by computer science and distinct from the Internet of Things has a stronger focus on the physical system behind and the intense link between computational and physical elements (Lee and Seshia, 2017). In Germany, this concept has become popular under the notion of Industrie 4.0. (Kagermann et al., 2013). Industrie 4.0 is, however, more a future vision than an actual phenomenon.

In its core, the different definitions of a cyber-physical system share one common feature; they designate an artifact that comprises synergistically interacting physical and computational components (Baheti and Gill Helen, 2011; Lee and Seshia, 2017).

Conventionally, complex engineering systems such as airplanes or automotives have been designed via decoupling the overall control system (i.e. network and software) from the hardware. Subsystems have been only integrated in later stages. However, a vehicle control system in the automotive industry relies on system components manufactured by multiple actors each using their own software and hardware, hence the final integration is costly and time-consuming. Moreover, the increasing complexity of components and systems and advances in sensor and processing technologies poses immense challenges for the organization of development and production processes especially in terms of integrating independently developed (system) components (Baheti and Gill Helen, 2011).

A common language and a shared infrastructure needs to be developed across disciplines and corporate boundaries to meet these challenges.

Only some aspects of the technological vision of CPS have been realized in contemporary products and production systems. A considerable amount of information is indeed already transferred between smart components via digital channels indicating that they have the potential to profoundly change production relations and how information and knowledge is exchanged in the overall system. Not only need actors collaborate, if they intend to use a common computational core or a shared system infrastructure. Those actors that are involved in setting the technological standards that underlie this infrastructure

[6] It involves various engineering disciplines such as electrical, mechanical and biological engineering, material sciences, as well as networking, control, software, human interaction and learning theory. It combines approaches from cybernetics, mechatronics, design and process science, cf. Suh et al. (2014).

[7] https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.htm

[8] http://www.rfidjournal.com/articles/pdf?4986

will become increasingly important and powerful players (cf. Büthe and Mattli, 2011; Kamps et al., 2017). If one investigates global production networks these aspects must be taken into account beside conventional conceptions of production systems that will be introduced in the following paragraph.
For the present thesis, the concept of cyber-physical systems serves as a foundation for the dimension of the artifact around which a production network and respective exchange relations has evolved. In chapter 2.2 I will explain how knowledge infrastructures for cyber-physical systems are constituted and in chapter 2.3 I will explain how modularity as an architectural paradigm structures and organizes relations between components of a cyber-physical system.

2.1.2 Global value chains and global production networks

In order to clarify the role of knowledge and knowledge exchange relations in production systems, and to conceptualize the socio-organizational dimension of the production system, chapter 2.2 introduces and discusses how economic exchange relations have been conventionally conceptualized based on two contradicting theoretical groundings: the rational transaction cost economics and economic sociology. Whereas the first one refers to how exchange relations are organized, the second one refers to how they are embedded in particular contexts that affect the ideal typical organizational forms identified and described by the transaction cost approach. Both approaches have been integrated in the conceptualization of globally distributed production systems in the frameworks of global commodity chains, global value chains and global production networks.
The transaction cost approach relies on the new institutional economics and analyzes the optimal coordination and control mechanisms of exchange relations and the efficiency of the division of labor between firms and other non-economic actors (Bathelt and Glückler, 2003). Based on earlier work of Coase (1937) on exchange relations and transaction costs, Williamson developed these concepts further based on the premises of bounded rationality and opportunistic behavior into the transaction cost approach. This approach conceptualizes transactions and their associated costs as the central elements for the investigation of organizations. Transaction costs are defined as information-, contracting, coordination or control costs of exchange relations that need to be minimized. These costs occur within hierarchies and markets and determine respective institutional arrangements (Williamson, 1987). According to this view, the complexity of inter-firm relationships as well as the extent to which they involve specific investments (i.e. asset specificity) determines the organization of exchange relations in production systems.
The transaction cost perspective on exchange relations has also deeply influenced the conception of production systems. **Productionist systems** consider vertical and horizontal exchange relations between firms as the primary actors in such systems (Storper and Walker, 1989). **Exchange relations** can be material or non-material, formal or informal, trading or non-trading and can relate to flows of goods

and services, financial flows, technology flows or knowledge. I focus on knowledge exchange relations in production systems (cf. chapter 2.3).

Whereas, **horizontal relationships** between firms in an industry can take various different forms from competition, joint development work (e.g., strategic alliances, joint ventures) to only temporary collusions, **vertical relations** are mostly emphasized within industry research that takes a more abstract systemic perspective (Dicken 2001, p. 349). Vertical relations are predominantly conceptualized around the metaphor of the value chain understood as a temporal sequence of activities or functions that are combined to produce a given output (Gereffi and Korzeniewicz, 1994). These functional units or tasks are bound together by **a network of input-output relations**. Considering and describing the basic structure of production in terms of a division of tasks that are functionally linked by a network of input-output relations has a long tradition in economic analysis and practice (Scott, 1988). The value chain approach is mostly based on theoretical insights of transaction costs economics (Williamson, 1987) and strategic management studies (e.g., supply chain management[9]) that focus on how transaction costs in exchange relations can be reduced within the activities in the chain that, within these conceptualizations, constitute an industry.

General functional *value creation* categories usually entail research and development, production, logistics, operations, marketing and sales, after-sales services etc. depending on the type of industry investigated. Within each stage, value is added or enhanced. The single functions are complementary to each other and are in need of coordination and governance. Thus, a chain maps the "vertical sequence of events leading to the delivery, consumption and maintenance of a particular good or service." (Dicken 2001, p. 349 ff.). These input-output relations between functions and operations also link actors in an industry (for instance through specific types of linkages and governance mechanisms) and, thus, different industrial regions with each other (ibid.).

In attempting to explain how global industries are organized and how governance structures influence development opportunities of firms and regions, a large body of literature has evolved during the last decades (Hess and Coe 2006, p. 1207). The functional perspective on production systems has profoundly shaped conceptualizations of inter-firm exchange relations. With regard to the study of trans-national or global systems of production one can distinguish between three different strands of literature: the global commodity chain approach (Gereffi and Korzeniewicz, 1994), the global value chain approach (Gereffi et al., 2005; Sturgeon et al., 2008) and the global production network approach (Coe et al., 2008; Coe and Yeung, 2015; Henderson et al., 2002; Hess and Coe, 2006).

Linear commodity or value chains concentrate on economic actors (e.g., firms) that interact along the chain. Other non-firm actors and the interaction with different institutional contexts have been rarely analyzed within these approaches (Schamp, 2008). Especially the value chain approach conceptualizes

[9] The logistic consultant Keith Oliver has introduced the term 'supply chain' in 1982.

ideal-typical forms of organization and the configuration and governance of exchange relations. Issues of governance and power are highlighted in this work that focuses on organizational and coordinative routines and broader institutional contexts of transnational global production (Bathelt and Henn, 2014). The global production network approach focuses more on the embeddedness of actors and exchange relations apart from linear input-output relations of the chain approach. Both perspectives give valuable insights on the nature of exchange relations in production systems and will be presented in more detail now.

The concept of **Global Commodity Chains** (GCC) has been developed in the US and dates back to the early 1980s. It has been first announced at the 16th Annual Conference on the political economy of the world system that took place at Duke University (USA) in 1994. Until then nation-state centered analysis had been dominating the research of the global economy. The concept of GCC was, thus, an attempt to develop new conceptual categories in order to deepen the understanding of the spatial organization of production and consumption in an increasingly globalizing economy (Gereffi and Korzeniewicz, 1994).

Global commodity chains were initially defined by Gereffi et al. (1994, p. 2) as "sets of inter-organizational networks clustered around one commodity or product, linking households, enterprises, and states to one another within the world economy." GCC considers four interrelated dimensions:

- the input-output structure (value adding sequence of economic activity);
- territoriality (spatial configuration of the various actors involved);
- regimes of governance,
- as well as the wider institutional embedding underscoring the social embeddedness of economic organization.

Gereffi et al. (1994) made a first attempt to identify different types of CC distinguishing between producer and buyer driven chains. Within *producer* driven chains that are mainly found in propulsive industries such as aircraft, automobile, computer and electronics, semi-conductors and chemicals, technology and production expertise were considered to be the core competencies, whereas in a *buyer* driven chain innovation depends more on product design and marketing which makes the outsourcing of manufacturing easier. Retailers and brand merchandiser are the leading actors here such as in food and fashion industries.

The contestation of value over space is an important analytical category for the **global value chain** framework. It is based on the value chain concept related to the work of Porter (Porter, 1985, 1990; Porter, 2010). Value is defined along notions of surplus value (transformation from labor into goods and services) as well as more conventional understandings of value in terms of economic rent or profit (Coe and Yeung 2015). Whereas a supply chain refers to buyer-supplier relations in a production system, a value chain identifies more general functions of value-added activities such as research and development, production, logistics and sales.

> *"The value-added chain is the process by which technology is combined with material and labor inputs, and then processed inputs are assembled, marketed, and distributed. A single firm may consist of only one link in this process, or it may be extensively vertically integrated, such as steel firms that carry out operations that range from mining ore to fabricating final goods." (Kogut, 1985, p. 15)*

According to the transaction cost theory of Williamson, repeating transactions between firms or organizations are coordinated in a way that minimizes costs, which can explain outsourcing and the vertical disintegration of exchange relations as well as vertical structures in production relations and firms. Hence, from a spatial perspective, the global value chain approach can contribute to explain the decision of firms of whether to invest in production facilities in different countries or whether to organize the production without property rights (i.e. outsource it to contract manufacturers). The latter one demands for complex coordination mechanisms between autonomous economic actors. Nevertheless, despite high coordination costs, outsourcing can be more profitable, if other cost reducing factors occur (Gereffi et al. 2005).

The GVC approach is mostly an attempt to deepen the theorization of *governing* inter-firm exchange relations and advance the concept of GCC. According to Gereffi and Korzeniewicz (1994, p. 97) governance is defined in its broadest sense, as the coordination of different and divergent activities between the interfaces of functions/operational steps in global value chains. The structure of governance is based on relations of power that determine the exchange of commodities, capital flows, human resources/labor, information and the allocation of resources along the value chain. Hence, it also determines the creation and diffusion of knowledge. Each function or step generates value creation and capture to a different degree. The actor(s) that coordinate a value chain can, thus, determine the economic participation of actors in value creation processes. It is important to note here that governance and coordination is not the same thing (Gereffi and Korzeniewicz 1994, p. 113). Whereas coordination refers more to executive forms of governance, governance in a broader sense also entails overall rules and norms. According to (Kaplinsky and Morris, 2000) there are three different types of governance:

- Legislative governance refers to the overall set of rules/rule book of the integration of value chains
- Judicative governance designates the set of rules for the control of institutions
- Executive governance refers to a control function, which coordinates and controls the compliance to the standards formulated in the legislative and judicative rulebooks.

This also implies that actors that take an executive coordinating function need not necessarily be lead firms, but can be located outside of these organizations. Good examples in this regard are market mechanisms, quality standards, corporate social responsibility standards or ecological standards.

Obviously, this approach is influenced by political economy and institutionalism, focusing mainly on macro-institutional structures such as the state or capitalism (e.g., the *Varieties of Capitalism* approach). By examining concrete practices, power dynamics and organizational forms, the analysis of GVC governance identifies patterns that give character and structure to cross-border business networks (Ponte and Sturgeon, 2014). This stream of literature conceptually integrates modularity, as an organizing principle and governance form for exchange relations in productionist systems. I will elaborate on this in more detail now.

The GVC approach distinguishes between three general types of governance. **Governance as "driving"** refers mainly to the former GCC approach and Gereffi's distinction between *buyer* versus *producer* driven chains. **Governance as "linking"** (or coordination, cf. Gibbon et al. 2008) identifies different types of inter-firm linkages and exchange relations in production systems: namely market, captive, relational and modular links. Each linkage type is associated with a different form of governance that depends on:

- what kind of activities or tasks are bundled in one node of the chain (chain configuration),
- how materials, knowledge and information are transferred from one node to another,
- and where specific nodes tend to be located.

Accordingly, scholars of GVC identified three main variables and likely combinations of them that affect asset specificity and therefore influence decision-making and possible inter-firm linkages and exchange relations. Those entail the complexity of information that need to be exchanged between value chain tasks, the codifiability of that information, as well as the capabilities available in the supply base in proportion to the requirements of the actual transaction.

Building on these insights, the traditional **hierarchical** form of organizing production within a single enterprise is increasingly vanishing due to globalization and technological progress. Nevertheless, this form still exists of course. According to Gereffi et al.'s framework, it occurs when product specifications cannot be easily codified (i.e. represented in detailed instructions), for example when products are very complex and there are no suppliers that are able to provide the requested expertise. The decision of firms to keep development and production in-house is motivated "by the need to exchange tacit knowledge between value chain activities as well as the need to effectively manage complex webs of inputs and outputs and to control resources, especially intellectual property." (Gereffi et al. 2005, p. 86).

Exchange relations in **market links** are, in contrast, assumed to be governed by price and product specifications. This relates to the conventional view of trading or buyer-supplier relations in which rules and conventions inherent to market mechanisms coordinate the exchange of commodities. Since the complexity of information that needs to be exchanged is considered to be low, they can be easily codified such as in agricultural production. There is no need for external governance mechanisms

(Gereffi et al. 2005). Knowledge is transferred via imitation and so-called spillover effects (Pietrobelli and Rabellotti, 2004).

Captive links are referring predominantly to hierarchical types of governance by power and the vertical integration of exchange relations (Ponte and Sturgeon 2014). According to Gereffi et al. 2005, they occur when the complexity of product specifications and the ability to codify are high, but available capabilities in the supply base are low. Hence, lead firms will seek to establish captive links.

> *"This is because low supplier competence in the face of complex products and specifications requires a great deal of intervention and control on the part of the lead firm, encouraging the build-up of transactional dependence as lead firms seek to lock-in suppliers in order to exclude others from reaping the benefits of their efforts." (Gereffi et al 2005, p. 85f.)*

This makes them extremely dependent or "captive". Examples can be found for instance in export-oriented textile production such as shoes or the organization of global sports ware brands (Donaghu and Barff, 1990; Kortum 2013; Schmitz, 2006). Knowledge transfer within this form of governing exchange relations is limited to the tasks and operations of the manufacturer. Lead firms are coordinating the diffusion of knowledge and information (Peitrobelli and Rabelotti 2004, p. 9).

Relational links are governed by trust and reputation. Long-term relationships and spatial embeddedness are playing a central role for this type of governance (Ponte and Sturgeon 2014, p. 212). In this case knowledge/or product specifications cannot be codified and supplier capabilities are considered to be high. Exchange relations between buyers and sellers involve the transfer of tacit knowledge. The high expertise and capabilities of suppliers set strong incentives for lead firms to outsource certain activities, in order to gain access to complementary competencies. It results in a mutual dependence that, according to this framework, is regulated via social and spatial (or relational) proximity, reputation, social ties (e.g., family, ethnic etc.). The exchange of knowledge and information is facilitated by frequent face-to-face interaction and direct coordination (e.g., managerial authority). As a result, the costs of switching to new partners increases (Gereffi et al 2005, p. 86).

Finally, **modular linkages** are assumed to be governed by standards and codified links, since they are "typically enabled by industrial conventions and the de facto and de jure standards that underlie them." (Ponte and Sturgeon 2014, p. 212). Analyzing the US electronics supply chain, Sturgeon (Sturgeon, 2002, 2003) conceptualizes a modular production network as one in which the coordination of (priced) transactions of goods and services is achieved through standards that codify industrial conventions and make idiosyncratic social relations - considered as a problem here instead of a relational asset - rather obsolete. Hence, modular exchange relations are considered to be more flexible and anonymous. Within modular value chains or modular production networks highly codified technological knowledge and information is exchanged between lead firms, system suppliers and suppliers on lower tiers of the chain. The system supplier or, more generally speaking, the strategic partner focuses on his role of developing partial or complete (systems) solutions to lead firms. According to (Gibbon et al., 2008) the number of system suppliers is usually low whereas their size and financial power is immense. This modular form of organization aims at producing a variety of products according to customer specifications within the existing highly automated production process. On a lower tier and value-added stage, exchange relations between system suppliers and specialized suppliers as well as generic suppliers (usually component suppliers, service providers and contract manufacturers) are assumed to be governed by price. Nevertheless, the intensity of information and knowledge exchange (and the complexity of information that need to be exchanged) is higher than in pure market relations.

Table 1 summarizes the primary economic actors in modular chain configuration, their role, scope of value-added activity based on Coe and Yeung (2015, p. 41) and gives examples from the aerospace (manufacturing) industry.

Table 1: Firms as actors in global production networks

Primary actors in modular value chains/production networks	Role	Scope of value-added activity
Lead firms *(Other names:* multi-national corporation, anchor firm, OEM*)*	Coordination and control	Product and market definition, architectural integration, platform assembly
Strategic partners (*Other names*: turnkey suppliers, system suppliers, first tier suppliers, prime contractors, full package suppliers)	Partial or complete (system) solutions to lead firms	Co-Design and development in manufacturing and advanced services, large scale system integration
Specialized suppliers (industry specific) (*Other names*: 2nd-tier suppliers, component suppliers)	Dedicated supplies to support lead firms and/or their partners	High value modules, components, products, component system integration
Specialized suppliers (multi-industrial) (*Other names*: 2nd-tier suppliers, component suppliers)	Critical supplies to lead firms and partners	Cross-industrial intermediate goods and services, value-added parts and assemblies
Generic suppliers (*Other names:* n-tier or lower tier suppliers, contract manufacturers, service providers, component suppliers)	Arms' length providers of suppliers	Standardized and low-value products and services, design-to-print parts and assemblies

Key customers[10]	Transfer of value to lead firms	Intermediate or final consumption

According to the existing literature, this network form of modular value chains with a low numbers of big producers that supply a high number of global brands can be found in the consumer electronics as well as the automotive industry (Gereffi et al. 2005). Knowledge is transferred in a codified form. According to Pietrobelli and Rabelotti (2004), the lead firms and producers are, however, neither the distributors nor the creators of knowledge. Knowledge is created mostly in public-private R&D laboratories (ibid., p. 8) and distributed by certifiers and consultant firms (Kortum, 2013).

To sum up, on the industry level and from the GVC perspective, modularity refers to a specific form of organization within which knowledge gets internalized into (value chain) modules through specific knowledge codification schemes, that aim at keeping exchange relations and interactions from becoming highly dense and idiosyncratic (Gereffi et al., 2005; Sturgeon, 2003). Modular linkages establish a form of governing through standards or governance as normalizing (Ponte et al. 2011).

Following this causality, pervasive processes of knowledge codification and related standard formation activities must per se accompany the actual process of modularization. This is, however, not part of the GVC approach, which suggests the following causal connection: the complexity of knowledge that is part of a(n) (inter-firm) transaction impacts whether it can be easily codified or not. Codified knowledge can get easily transmitted between different actors, thus transaction costs are considered to be low. This enables either market or modular linkages and exchange relations that are either governed by price or in the latter case by standards making idiosyncratic relations and relational assets based on trust rather obsolete. The aim of the GVC approach is to develop ideal-typical (and thus simplified) forms of governance that characterize exchange relations in production systems. The *transformation costs* arising during modularization are not part of this rather static approach. It focuses mainly on the question to what degree knowledge can be codified, in order to reduce transaction costs in decentralized exchange relations rather than *how* knowledge gets codified and standards evolve, *who* develops them *where*, through which mechanisms do they diffuse and how are they received and understood and affect the configuration of production relations on different spatial scales.

Whatever its precise form, ranging from hierarchically organized to more flexible, open networks, production needs to be coordinated, either through visible or less visible forms such as governing through a standards pattern. Although, the distinction between different forms and levels of organizational coupling sharpens analytical approaches, it is quite obvious that this broad categories of governance types and mechanisms are reductionist and over-simplified for analytical purposes and have

[10] The role of the customer is not part of the present analysis.

often only weak empirical evidence.[11] One cannot clearly align one type of governance mechanism to a specific industry or a specific spatiality. Hybrid forms of governance and coordination (Foss, 2001; Foss et al., 2010; Grandori, 1997, 2001) and multipolar value chain configurations (Kawakami and Sturgeon, 2011) are most likely to be found in empirical case studies. They are characterized by various kinds of linkage types as well as multiple foci of power. “[This] plurality acknowledges that not only firms, but also other actors such as standard-setting bodies, international NGOs, social movements, certification agencies, labor unions and consumer associations can have a bearing on GVC governance.” (Ponte and Sturgeon 2014, p. 215).

Geographical implications of the global value chain approach are considered to be rather weak (Ponte and Sturgeon 2014), because value chains are, first of all, an ideal-typical organizational structure. However, each linkage form (captive, relational, modular, market) can enable or foster distinct geographic possibilities from clustering to dispersal of industries or a rapid versus a gradual relocation of work. Modular and market linkages are more anonymous, less idiosyncratic and, hence more flexible and interchangeable. Consequently, two aspects make modular production networks more likely to be globally dispersed and less dependent on relational assets and long-term relations of trust that occur in local agglomerations: knowledge is codified in standards and can be easily exchanged (modular linkages enable a governing through standards pattern); components, systems and assemblies that are standardized and exactly specified can be outsourced to external suppliers (for instance in countries with lower production and labor costs)

Nevertheless, aligning one type of linkage to a specific geographical manifestation has only weak empirical evidence (Ponte and Sturgeon 2014). Empirical studies often investigate the level of individual transactions, single value chain nodes or bilateral relationships rather than the level of overall governance of knowledge and the territorial diffusion of knowledge. Moreover, the interdependencies between global and local dynamics are rarely addressed. An exception can be found in the study of the dynamics of local learning in global value chains (Kawakami and Sturgeon, 2011). The authors examine the development of capabilities of East Asian local manufacturers leading to their exceptional rise in the domain of industrial production in the last decades.

Another approach to analyzing exchange relations in production systems in an interconnected world that is deeply intertwined with GCC and GVC analysis is the **global production network approach** (GPN). GPN analysis focuses on the organizationally and geographically complex webs of intrafirm, interfirm and extrafirm networks that characterize contemporary production systems (Hess and Coe, 2006, p.1207). The GPN perspective has its roots in the field of economic geography and builds upon insights of GCC and GVC approaches as well as actor-network theory. It is mostly concerned with how production

[11] There has also been a misassumption in earlier literature that has conceptualized the network as a different organizational form between hierarchies and markets. The network organization is not something entirely novel. (cf. e.g., Dicken et al. 2001, p. 353).

networks are embedded in, and intertwine with institutions and the social and cultural contexts extant in specific locations. (Ponte and Sturgeon 2014, p. 219, note 5). Instead of the metaphor of a chain (as a linear sequence of input- output relations), it envisions the contemporary production of goods and services as networks consisting of multiple economic and non-economic actors that are interconnecting multiple locations in a highly complex way (Coe et al. 2008). Scholars following this approach do not consider the concept of the "network" as being *new* or some hybrid form of economic organization that exists between the poles (or artificial dichotomy) of markets and hierarchies. Networks "reflect the fundamental *structural* and *relational* nature of how production, distribution and consumption of goods and services are – indeed always have been – organized." (Coe et al., 2008, p.272).

Authors that prefer the "network" to the "chain" approach argue that the concept of a network is more suitable to contemporary economic phenomena, because "networks […] are spreading from local domestic national trading environments, becoming regional as more countries are involved in strategic sourcing and/or distribution strategy, and ultimately global." (Gattorna, 2013, p.226) The consequence is the emergence of "networks-of-networks" and, simultaneously, the complexity increases with the widening of the geographical scope and the growing number of relations and interconnections as well as entities and actors involved.

More recent work in this field has also broadened the conceptualization of value creation and the underlying notion of value. Value is not reduced to, for instance, market value, but can vary in constitution and significance among firms and extra-firm institutions. According to the specific interests of the organizations embedded in the GPN (i.e. tax revenue of state agencies; social standards and wages of labor organizations; civil society organizations for ethical and fair production), the production and constitution of what is considered as value is perceived differently (Coe and Yeung 2015). The authors therefore speak of "value activities," when they refer to practices that are related to creating, enhancing and capturing value regardless of the varying constitution of value that underlies any organization's purpose and strategic interests.

Another difference between GCC/GVC and the GPN analysis, that has been pointed out by (Coe and Yeung, 2015) is the necessary presence of a global lead firm for the constitution of a GPN. Instead, GCCs focus on commodities/products and cannot be (analytically) organized around a single firm. Accordingly, the definition of a GPN depends on the presence of one (or multiple) lead firms (cf. also De March et al. 2014). The lead firm is considered to be essential since it "has the power and capacity to coordinate and control directly its production network – be it in the role of a buyer, producer, coordinator, controller or market maker, or a composite of one or more of these roles." (Coe and Yeung 2015, p. 40). Nevertheless, the GPN approach integrates multiple actors beside firms. Non-firm actors such as the state, NGOs, labor organizations and other institutions play a crucial role in terms of the organization and control of their activities (Cumbers et al., 2008). Growing attention is being paid to extra-firm practices and extra-firm actors in GPN (e.g., international organizations, labor groups, consumers, civil society organizations), since governmental and non-governmental institutions can have a significant impact on firm’s behavior and value activity (Coe and Yeung 2015, p. 47f.). Knowledge diffusion and interactions/exchange relations in global production networks are not taking place in a vertical linear process, but are circulating in space within a complex network of relations.

In summary, taken all together, these multiple actors and organizations constitute the GPN within a permanent negotiation process, which is why Levy (2008) also refers to GPN as *contested fields* (Levy, 2008). Actors constantly operate between relations of cooperation/collaboration and competition and conflict since they follow different intentions, objectives and strategies. This is why GPN are considered to be inherently dynamic. They are always “in the process of becoming – both organizationally and geographically.” (Coe et al., 2008)

Similar to GVC studies, GPN approaches have mostly analyzed the underlying spatiality of value creation, enhancement and capture in different GPN configurations rather than having explicitly analyzed the role of knowledge and the formation of architectural standards and related knowledge infrastructures for the configuration of GPN. However, distinct from the concepts of GVC and GCC, this approach explicitly aims at identifying causal linkages between GPNs and territorial development.

The analysis of local and global knowledge and exchange relations demands for a stronger focus on the socio-cultural environment and on knowledge, institutions and conventions that are bounded, changed, produced and reproduced locally. Different institutional and operational frameworks and multiple spatial scales determine the actions and strategies of economic actors (Hess, 2004; Izushi, 1997).

2.1.3 Embeddedness of actors and relations

The rational and efficiency oriented perspective on exchange relations, sees them as disembedded from broader institutional and socio-cultural frames as has been criticized by Granovetter and his new economic sociology (Granovetter, 1973, 1985). Embeddedness refers to the impact of non-economic institutions and relations on economic activity. The notion can be traced to Karl Polyani’s substantivist approach, which argues that in non-market societies without purely economic institutions, formal rationalist economic models cannot be applied (Polanyi, 1977). Economic activity such as reciprocal barter trade relies on kinship, political and religious institutions (i.e. on more general social institutions), whereas in market societies economic activities have been rationalized and “disembedded” from the broader social realm. Mark Granovetter further developed the concept arguing that also in market societies economic activities and relations are embedded in social relations, rational economic models are not entirely disembedded from society (Granovetter, 1985). Granovetter’s concept of social embeddedness (1985) has been widely used to explain how economic activities are shaped by the social relationships they are embedded in. Whereas the transaction cost approach demonstrates the rationale behind organizing exchange relations in the given economic system, the theory of embeddedness shows how they are constrained and shaped in empirical reality. This is central, in order to explain how external linkages can lead to a socio-spatial disembedding of knowledge and production relations (cf. also chapter 2.5.2).

The concept of social embeddedness has also found its way into economic geography resulting in a new institutional regionalism or regional institutionalism around the turn of the centuries (Malmberg and Maskell, 2002, 2006; Uzzi, 1997). The term *relational* has been predominantly used to describe a specific mode of interaction, economic coordination and governance that is characterized by long-term reciprocal relationships building on a high level of mutual trust, informal face-to-face communication and collaborative, cooperative behavior rather than anonymous market competition. Accordingly, these embedded or "strong ties" are assumed to be building the basis for inter-firm knowledge transfer and learning. According to this perspective, idiosyncratic relational contracts are embedded in social relationships and it is these social networks building on kinship and friendship that are constitutive for economic relations and institutions (Granovetter 1985).

Seminal studies by Storper (1997) or Malmberg and Maskell (2002) have adopted these conceptualization of relationality assuming a territorial form of embeddedness based on local/regional institutionalism that associates relational closeness to spatial proximity (Malmberg and Maskell, 2002; Storper, 1997; Storper and Venables, 2004). Within this rationale tacit knowledge and shared cognitive frames depend on localized interpersonal networks[12]. The local or regional scale within these conceptualizations is considered to be the most effective place for coordinating socio-economic activity. Thus, localization economies emerge out of the pooling of resources in local agglomerations that create cost-savings via the sharing of capacities, their optimal utilization and reduced search costs. Spatial proximity also increases the possibility of knowledge diffusion and fosters the formation of local institutions and trust (Boggs and Rantisi, 2003). Accordingly, theoretical explanations (often grounded on empirical case studies) for territorial development have been stressing the significance of relational assets, the embeddedness in networks, and spatial proximity thereby focusing mainly on local and regional scales (Yeung, 2002; Yeung 2005). The institutional regionalism characteristic for these studies has provided valuable insights concerning local knowledge relations. Inter-personal trust, co-location and proximity are important concepts in this stream of literature (Murphy, 2006).

Global knowledge relations and the relations between the local and the global sphere have been widely neglected in this stream of literature that is not able to explain the dynamics of economic disparities and uneven economic development. The actual processes of knowledge creation and especially knowledge codification and modes of knowledge diffusion have been treated as black boxes in most of

[12] Evolutionary approaches in Economic Geography have, however, shown with the concept of related variety that in order to be successful in the long run, the right balance between cognitive distance and proximity has to be found (Boschma and Iammarino, 2009).

these studies and the concepts developed within (Bathelt and Cohendet 2014, p. 880). Exchange relations and network structures are, however, embedded in local, national and global contexts via production, distribution and the transfer of knowledge. This aspect requires for a change in perspectives from localized industry relations to trans-regional relations of value creation.

The concept of "**relational embeddedness**" of actors, firms and organizations within global networks of production that spans across regions and links different localities has gained growing attention in recent years and decades (Coe et al., 2008; Dicken and Malmberg, 2001; Henderson et al., 2002).

The GPN approach emphasizes the multi-dimensional and multi-scalar nature of production networks stressing that each stage or each node in the network is embedded in much broader complex and especially non-linear horizontal relationships.

> *"Every element in a GPN – every firm, every function – is, quite literally grounded in specific locations. Such grounding is both material (the fixed assets of production), and also less tangible (localized social relationships and distinctive institutions and cultural practices)." (Coe et al. 2008, p. 279)*

In this sense, (Hess, 2004) has broadened the view on the phenomenon of "embedding" or "embeddedness" in the field of economic geography with its often "overterritorialized" conception.

The embeddedness of production networks (and its relations and actors) refers to the question of how they are constituted and changed by the economic, institutional and politic context in which they are located. Usually, three types of embeddedness are considered. **Societal embeddedness** refers to how actors and their socio-cultural and institutional background shapes the interaction and actions of individuals and collective actors. This type of embeddedness comes closest to what Polanyi originally meant in his famous writings. It also reflects the history and imagination of business ideas within a specific institutional or regulatory framework that determines cognitive frames (cf. DiMaggio, 2001) and actor's behavior such as firm strategies and decisions (Hess 2004, p. 176 f.).

The **network embeddedness** refers to the structure and durability of network relationships between an individual or an organization (cf. also Granovetter, 1985).

> *"It is most notably the* ***'architecture', durability and stability of these relations****, both formal and informal, which determines the actor's individual network embeddedness (the relational aspect of network embeddedness) as well as the structure and evolution of the network as a whole (structural aspect of network embeddedness)." (Hess 2004, p. 177, emphasis added).*

The relational aspect of network embeddedness points to the actual relationship between actors. The structural embeddedness is broader and takes non-firm institutional networks into account. In terms of network evolution and creation **trust** (cf. chapter 2.1.4.) plays a significant role. Network relations and the degree of network embeddedness is an outcome of trust building processes between actors on an individual and a more systemic level (i.e. trust in norms and institutions). The structure of intrafirm networks is mostly based on contracting relations and ownership integration, but is at the same time determined by the level of interpersonal trust among its actors and units.

Finally, economic activities are anchored in particular places, which refers to the notion of spatial or **territorial embedding** (Hess and Coe 2006, p. 1208). “Economic actors become embedded there in the sense that they absorb, and in some cases become constraint by, the economic activities and social dynamics that already exist in those places.” (Hess 2004, p. 178). If a firm locates in a particular region, it can take advantage of the existing local networks and labor markets and vice versa. The existing local networks can take advantage and grow based on the new external actors. Hence, embeddedness can become a key driver of regional growth through “capturing global opportunities” (Amin and Thrift, 2001), but also result in a spatial lock-in for the anchor firms (Scott, 2000; Scott and Storper, 2010).

The three dimensions are of course closely connected and interrelated. Territorial embeddedness produces relations of geographical or spatial proximity. It is, however, only one type of a number of categories of proximity (Torre and Rallet, 2005) or types of relations and embeddedness affecting economic interaction (Massey et al., 2007; Yeung, 2005). Spatial metrics themselves have no causal power without social action (Bathelt and Cohendet, 2014). The potential of territorial embeddedness and spatial proximity can, for instance, only be enabled by institutional proximity in production and knowledge relations. At the same time, it can be constrained by institutional or cognitive distance (Nooteboom et al., 2007). Here it is important to again highlight that actors in GPN are embedded in multiple networks on different spatial scales. There are local, regional and trans-regional or global networks, which might overlap. Spatial proximity or territorial embeddedness creates a variety of opportunities that can enfold their potential via the active building of relational ties (cf. Amin and Cohendet, 2004; Bathelt and Glückler, 2011). These interrelating proportions of different types of embeddedness produce, bridge and reduce distances among actors and regions (Menzel, 2015). The inter-dimensional links and connections are able to provide valuable insights into the structures and dynamics of change that characterize contemporary industries (Sturgeon, 2002, 2003; Sturgeon et al., 2008). The heterogeneity of regional and global development can be explained through this multiscalar embeddedness. Actors are embedded in their specific cultural, political and social backgrounds and are at the same time linked in networks of relations with individuals and organizations via economic and social action in space.

2.1.4 Individual and systemic trust

Trust has for long been an important aspect for establishing and maintaining economic and inter-firm production relations in post-Fordist economies, in order to avoid opportunistic behavior and malfeasance (Dyer and Chu, 2000). Cooperation between firms is based to a high degree on mutual trust.

Economic sociology and the literature on embeddedness emphasizes the central role of mutual trust in generating inter-personal relations and social networks that underlie economic (exchange) relations. The literature on local or geographical embeddedness emphasized that spatial proximity facilitates the building of trust-based relationships that require for direct face-to-face interaction (Hess 2004, Murphy 2006). There is, however, neither a consistent theoretical foundation, nor significant empirical proof for the correlation or mutual dependence of spatial proximity and trust. Giddens (1990, p. 33) notes for instance that there is no need to trust at all, if the actors involved had complete information/knowledge about one another and their activities. Consequently, trust is related to an absence in time and space and cannot be attributed to one particular spatial scale (Hess 2004). Instead, it is important for the following analysis to distinguish between different forms of trust, namely inter-personal or individual and systemic forms of trust.

From a micro-perspective, **individual or inter-personal trust** is the basis for any situation of economic and social interaction/transaction (Rousseau et al., 1998) and, thus, also the basis for knowledge relations between actors in the context of production. Since the decision to trust another person is associated with an ambiguous outcome, trust can be considered as the result of a subjective-rational calculation. The trustor is always taking a risk. In this sense, interpersonal trust always implies the expectation of an (intangible) equivalent value. Therefore, it can be also referred to as a reliance on reciprocity.

On a more abstract and aggregated level, the concept of **systemic trust** relies on the idea of having trust in a system of norms, values and institutions (e.g., the monetary system, the traffic regulation system, capitalism etc.) (Coleman, 1994). This type of trust relates directly to codified forms of knowledge and knowledge infrastructures. It can be also referred to as trust in the functionality of a system/institution and its norms. It relates to a more identity-based form of trust that emerges when actors share common values and standards that foster social cohesion (Lewicki and Wiethoff, 2000). In the case of a (global) production system, that would mean that actors also share the same knowledge infrastructure (cf. following chapter). Imagine for example an Open Source Software Community that develops a product without ever meeting in person. Knowledge is exchanged in a highly codified form and exchange relations are based on systemic trust, i.e. trust in the codes and standards of the developed infrastructure[13]. According to Luhmann, systemic trust reduces social complexity, since no individual is able to process and assess all the information available (Luhmann, 2000), thereby also addressing the "problem of the utilization of knowledge not given to anyone in its totality" (Hayek, 1945, p.520).

Nevertheless, systems or organizations are represented in most of the cases by people (e.g., officials, managers, politicians, the police, etc.). Hence, systemic trust always implies a personalized component

[13] This conceptualization of systemic trust and the networked relationships between artefacts and humans can be also found in the sociological approach of actor network theory Latour (2017) in science and technology studies.

and both types are mutually interdependent. In order to assess the trustworthiness of a person, an organization or a system of rules and norms, people rely on the experience with trusted representatives of and experiences with that system they have gained during previous interactions. Consequently, a trustor is in need of information about the trustee to be able to trust. If the trustor had complete knowledge, he would not need to have trust at all (cf. Giddens, 1990, p. 33). The decision to have trust in someone or something depends on the particular experiences and the associated risk with regard to future interactions and their expected outcomes and, thus, on knowledge gained during prior experience and interaction. This also counts for the more abstract form of systemic trust in norms and conventions. A lack of systemic trust can, therefore, be associated with missing experiences or a misunderstanding of the underlying knowledge, norms and rules.

Identity-based and systemic trust is of central importance for long-term inter-organizational relations in production and knowledge networks. Exchange relations and an open knowledge transfer directly depend on the level of trust between the actors. Finally, trust is very fragile, it is developed in a longitude process and can be, in both cases, destroyed within seconds, if an expectation is disappointed and the expected behavior or outcome does not occur.

2.1.5 Summary and conclusions for the further analysis

Conceptualizing production systems around the artifact illustrates how components relate to each other and how these relations shape exchange relations in the production network. Apart from proprietary and strategic factors, it enables scholars to identify what information and knowledge need to be exchanged in the overall system and how physical and digital modes of transfer interrelate. This aspect will be more clearly elaborated upon throughout the following chapters. The concept of a cyber-physical system is used here to describe the dimension of the artifact as part of the overall production system (cf. Fig 1).

Moving from relations between components in complex systems to the social relations of exchange, analyzing industrial value chains and production networks enables scholars to identify relevant actors, the linkages that tie them together into a larger whole, and the nature of exchange relations that give shape to their structure and governance. Inter-firm linkages and exchange relations in post-Fordist production systems are understood as the creation of value-added through sharing knowledge, expertise and resources rather than market competition. Whereas the transaction cost approach illustrates the rationale behind organizing exchange relations in the given economic system, the theory of embeddedness shows how they are constrained and shaped in empirical reality. Both theoretical backgrounds are applied to different degrees in the concepts of global value chains (2.2.2) and global production networks (2.2.3). Vertical exchange relations are based on a functional, linear input-output logic. They are able to explain processes of vertical specialization and the functional differentiation and structure of value chains and production networks. Here, the nature and degree of "coupling" of inter-firm linkages and exchange relations depends on the codifiability of knowledge and routines. Modular linkages and exchange relations are based on the codification of knowledge into technological and industrial norms. Knowledge is exchanged via a codified link. I will elaborate on this topic in detail in the following chapter 2.2.

The analysis of local and global knowledge and exchange relations demands, however, for a stronger focus on the socio-cultural environment and on knowledge, institutions and conventions that are bounded, changed, produced and reproduced locally. Different institutional and operational frameworks and multiple spatial scales determine the actions and strategies of economic actors. The embeddedness of actors significantly influences the structure and nature of exchange relations. Actors also engage in horizontal exchange relations apart from the functional production units and value adding functions. Non-firm actors and institutions such as governments, international standard setters etc. are part of global production networks and play a crucial role in terms of governing technological and industrial knowledge and knowledge diffusion. In order to conceptualize the social (i.e. organizational and network) and spatial dimension of a production system, insights from both approaches have been integrated, in order to describe the vertical embeddedness and functional integration as well as more horizontal forms of socio-spatial embeddedness. Figure 1 summarizes and integrates the hitherto developed dimensions of a production system.

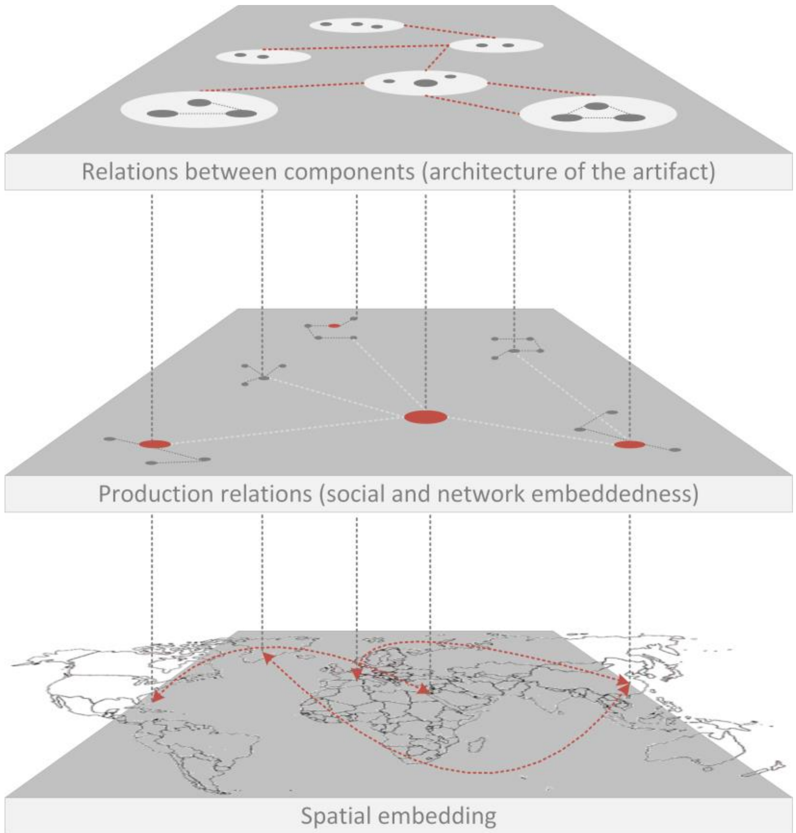

Figure 1: Dimensions of a production system I

2.2 Knowledge and production

This chapter aims at defining and clarifying the understanding of **codified and tacit knowledge**. Since modular production networks are assumed to be enabled by the codification of technological and industrial knowledge, it particularly focuses on the role of codified knowledge and related **codification and standard formation processes in production networks**. It integrates functional as well as normative perspectives on standards and their dual nature for the development and building of knowledge and network relations. Chapter 2.2.4 examines how the functionalist and normative dimension of standards have been integrated in existing concepts of GVC and GPN. The focus of interest is, thus, *not* on the role of knowledge and knowledge relations in terms of creating technological and product innovations,[14] but on the way knowledge is organized and diffuses in trans-national and rather decentralized, modular production networks**.** The context wherein knowledge is codified and how it diffuses in production relations is encapsulated in the concept of **knowledge infrastructure**, which will be defined in more detail in chapter 2.2.5. It relates to questions and research on the embeddedness of knowledge in situational practice and socio-organizational contexts of creation and use.

2.2.1 Explicit and tacit knowledge

The most popular and widely used definition of knowledge comes from Karl Polanyi (Polanyi, 1967), who distinguishes between implicit or *tacit* and explicit knowledge.[15] The implicit-explicit distinction refers to the form through which knowledge is represented. Explicit knowledge can be represented and articulated (i.e. expressed and communicated) linguistically (Davies, 2015). It is basically information written or spoken in a code. The code is the symbolic representation of an information, whereas meaning can only be assigned in the (cognitive) context in which the code appears and is received (Cowan et al., 2000). Thus, the cognitive context afforded by the receiver of the message determines, whether and what kind of meaning he or she assigns to the specific code[16]. Polanyi's notion of ***tacit knowing*** refers to knowledge that cannot be captured linguistically, which does not mean that it cannot be communicated at all. Tacit knowledge refers more to skills and experiences or to "know-how" (e.g., riding a bike, speaking a language). It is the transmission mechanisms that are considered to be different. Whereas explicit knowledge can be transmitted via telling and understanding, tacit knowledge is rather transferred via performance and imitation (Polanyi and Sen, 2013). It cannot be captured in language without relying on the immediate context and other demonstrative forms of action (Davies, 2015). That

[14] Hence, the entire stream of literature dealing with innovation systems Lundvall et al. (2002, 2002) and the geography of innovation Liu et al. (2013) is not considered here.
[15] It is valuable to note that the notion took its origin in the psychology of visual perception and human motor skills.
[16] In this sense, knowledge can be also considered as a "state of the agent's entire cognitive context." (Cowen et al. 2000, p. 216).

does, however, not mean that it cannot be transmitted *over distance* at all, since virtual devices and advances in IuC technologies provide valuable tools to do so as the success of You Tube tutorials and advances in augmented and virtual reality devices indicate[17]. New visualization and communication techniques severely challenge the role of tacit knowledge and common ground (Cumbers et al. 2008). As a result, the different forms in which knowledge appears or is "stored" also refers to different forms of relations between actors and their embedding in specific contexts that facilitate or enable knowledge exchange and diffusion.

2.2.2 Codified knowledge and knowledge embodied in artifacts

The major challenge is how to define and operationalize knowledge within research on economic development and industrial change that combines micro and macro-perspectives and the interrelations between places. Focusing only on the micro-level, for instance on how knowledge is created or transferred on an inter-individual or inter-firm level would neglect broader knowledge relations and how knowledge diffuses in trans-national production systems. Focusing only on meso or macro-structures, on the other hand, would ignore the social and cultural embeddedness of actors that create, exchange and make use of that knowledge on a local scale. For analytical and empirical purposes one needs to limit the understanding according to what is relevant for the subsequent analysis of the dynamics of knowledge in time and space respectively how knowledge affects industrial network evolution and regional change.

The dynamics of knowledge in space can only be captured and analyzed on a broader scale, if knowledge is given in a representational form that can be easily captured and compared. In other words, it needs to be explicit, that means information written in a code (Cowan et al. 2000), or objectified, that means information embodied in an artifact. The term artifact refers to everything that is intentionally created by an individual or a group of humans. It is an explicit object (e.g., an airplane, a software) embodying the implicit knowledge that is necessary in order to create and make use of it. An artifact (whether tangible or intangible, physical or cyber-physical) is, thus, always also an epistemic object (Gagliardi, 1990a, 1990b; Guliciuc and Guliciuc, 2010; Yanow, 2006). It builds a good starting point for defining the frame of the analysis of knowledge in production relations. The challenge, however, is to identify the explicit knowledge that is necessary to create that artifact, since the notion of explicit knowledge is very broad and it basically refers to any form of linguistically represented information, it needs to be further limited.

According to the conventional view, industrial and technological expert knowledge is usually linked exclusively to human beings (Gertler, 2003) and is, therefore, often described as being tacit (i.e. also hard or impossible to capture). But such knowledge can also be "stored" in machines, computational

[17] In later publications Polanyi emphasized that all knowledge is somehow rooted in tacit knowledge Polanyi and Sen (2013).

codes, or written rules such as technological standards (Brunsson and Jacobsson, 2000). From this view, industrial and technological standards can be considered as expert knowledge embodied in a code (Brunsson and Jacobsson, 2000) and technological and industrial standards as a set of codified rules (Lampland and Star, 2009).

2.2.3 Industrial and technological standards as a form of codified knowledge

Behind virtually *any* artifact created these days - from a simple screw to software protocols – stand industrial standards that define product, system and process architectures and specify manufacturing guidelines. More than half of the technological information required to design and manufacture an aircraft are based on standards that codify technical knowledge (AIA, 2005).

2.2.3.1 The functional character of standards

From a technical and functional point of view, a standard is a set of characteristics that describes features of a product, process, service, interface or material (AIA, 2005). It describes any set of agreed-upon rules for the design and production of tangible and intangible artifacts "deployed in making things work together over distance and heterogeneous metrics" (Bowker and Star, 1999). Hence, standards are intended to provide solutions for matching problems (Vries, 1999). They are intended to solve an (engineering) problem by lowering transaction costs mainly through reducing cognitive complexity and information costs (Simon, 1962). Industrial standards address a broad range of fields from interoperability and quality to safety, social and environmental issues. Referring to complex modular systems coordination is mostly achieved through technical standards that codify specifications about the components of a technology and the interfaces that connect them them (Garud and Kumaraswamy, 1993). Thus, in the case of complex modular product or service systems (e.g., aircraft, automobiles, machine tools), interoperability and interface standards play a significant role in order to make the single elements, modules and systems work together (David and Greenstein, 1990; Tassey, 1982, 2000).. This functionalist perspective on standards particularly stresses their coordinative character for supporting the governance of industrial knowledge. However, this view on standards often dismisses their inherent normative dimension.

2.2.3.2 The normative character of standards

From a normative perspective, standards are "norms selected as a model by which people, objects or actions can be judged and compared, and which provide a common language to evaluators, the evaluated and their audiences." (Ponte et al., 2011). This also indicates the inherent ambivalent nature of standards: they simultaneously enable and constrain social interaction (Botzem and Dobusch, 2012; Giddens, 2006).

Standards are a form of codified rules that include behavioral norms, social conventions as well as legal rules or de jure standards. The basic feature of a rule as compared to a convention is that a rule is potentially codifiable. Members of a community can share either tacit or explicit knowledge of these rules[18]. That means that the aspect of codifiability is crucial and also helps to identify the community or group of actors that *shares and understands* the rules. Hence rules also imply constraints and can indicate membership, inclusion and exclusion (Hodgson, 2016). Such codified knowledge can, thus, be both: a reference point and a possible authority, because a common notation or rule can be either "promulgated by authority or may acquire 'authority' through frequency of usage and common consent, i.e. by *de facto* acceptance." (Cowan et al. 2000, p. 225). In practice, manufacturers, their customers and regulatory authorities can assess the conformity to these standards. Conformity assessment designates any measures carried out by manufacturers, their customers, regulatory authorities and/or independent third parties to assess conformity to existing standards and rules (e.g., audits, quality management, and certification and qualification procedures). If firms or other actors do not comply with a certain standard (e.g., by achieving formal certification) they might not be able to enter a specific production network. Standards, therefore, deeply affect the modes of engagement a firm or actors in production relations can relate to. Insights from convention theory and the sociology of regimes suggest that the imposition of specific "information formats" or specific architectures of knowledge infrastructures serve as a frame for getting engaged (Lampland and Star, 2009) or what Thévenot refers to as "regimes of engagement" (Thévenot, 2001).[19]

A technological standard is nothing more than a piece of codified information, if no one understands, uses and commits to it. Formal rules and standards have only limited potential for guiding actions, since they underlie the interpretation of single subjects, which brings me back to the tacit and subjective dimension inherent to any form of knowledge. One person's standard, can be another one's mess or in other words, what is meaningful for one person or a group may be tacit or impenetrable for someone else (Lampland and Star, 2009). This also illustrates that the line constructed between implicit/tacit and explicit knowledge is blurry and transitions from one state to another are fluid.

2.2.4 Standards in global value chains and global production networks

The literature on organizational modularity, global value chains and related global production network approaches, usually takes a **functionalist perspective on standards**. According to the GVC framework, knowledge exchange relations are determined by the complexity of knowledge and information that

[18] It is important to stress that semantic (design) rules and standards do not equalize institutions. They are the elements that constitute institutions and upon which institutions develop based on repetitive conduct.

[19] The metaphor of "standards wars" also illustrates the increasing emergence of standards as the outcome of battles for dominance.

needs to be exchanged in production relations its codifiability and the capabilities or competencies resident in the respective supply base (cf. chapter 2.1.2).

A rather positivist perspective underlies this perspective emphasizing that firms are autonomous and formative in their actions acting and not reflexive non-autonomous actors. They adopt strategies to reduce the complexity of (knowledge) transactions through the development of technical and process standards (Gereffi et al. 2005).

> *"When standards for the hand-off of codified specifications are widely known, the value chain gains many of the advantages that have been identified in the realm of modular product design, especially the conservation of human effort through the re-use of system elements – or modules – as new products are brought on stream […]. In the realm of value chain modularity, suppliers and customers can be easily linked and delinked […] Institutions, both public and private, can both define grades and standards and (in some cases) certify products comply with them. The development of process standards and certification in relation to quality, labor and environmental outcomes perform similar functions." (Gereffi et al. 2005, p. 85)*

Within the GPN literature and the revised GPN 2.0 approach a new focus is put on the role of so-called intermediary functions of standards, logistics and finance for the formation and organization of GPN, since they enable their efficient functioning (Coe and Yeung 2015). This shifts the attention from exchange relations between dyadic pairs of firms (dominant in the GVC approach, e.g., lead firms and system suppliers) to intermediary functions that coordinate exchange relations in the overall network. Standards coordinate knowledge flows, logistics coordinate material flows and finance coordinates capital flows (Coe and Yeung 2015, p. 47f.).

Hess and Coe 2006 (p. 1208) emphasize that it is important to recognize the factors that underlie processes of standard formation, especially in an era of liberalization and deregulation (cf. also (Nadvi, 2008). The role of the state in governing GPN is that of promotion and regulation. But within propulsive industries such as the IT, automotive and aerospace manufacturing industry the power and impact of non-state extra-firm actors has often been overlooked. Industry standards are developed and negotiated by a variety of different actors that might build strong ties among each other, in order to capture benefits that arise from participation in standard setting activities. At the same time, they create entry barriers to outsiders of those technological or epistemic communities. (ibid., cf. also Galvin and Rice, 2002).

Since state actors often lack technological knowledge (and technological progress runs fast) regulation gets increasingly privatized as (Büthe and Mattli, 2011) describe in their book "The New Global Rulers". Private standard setting actors developing technical standards and specifications promote them industry-wide in order to gain market dominance (Kamps et al., 2017). Hence, industry consortia in global industries such as *SAE* (Society of Automotive Engineers) play a significant role in governing inter-firm relations. Coe and Yeung refer to these "new players" as *intermediaries*, because they often intermediate diverse interests and objectives of firms and extra-firm actors in GPN. The function of standards as intermediaries in GPN is to establish, enforce and harmonize protocols, knowledge and specifications as well as to provide (and distribute) information. Associated value (adding) activities are in the areas of private regulation in terms of certification, approval and creating compliance (Coe and Yeung 2015, p. 51, 54). They enable the effective functioning of a GPN (Coe and Yeung 2015, p. 50). The authors also emphasize that past research has paid not enough attention to these specific actors and their role as intermediaries is undertheorized in research on GPN (ibid.). It cannot be ignored that a whole new industry has emerged around the setting, diffusion, interpretation of and compliance to (technical) standards (i.e. certifiers, accreditors, consultants, accountants etc.)(Brunsson and Jacobsson, 2000; Schoechle, 2009). Brunsson and Jacobsson emphasize that, for instance, European standardizing organizations include representatives of firms, public agencies as well as other interest groups and are often linked to (mandatory) directives (ibid.) A quite popular example in this regard is the provision of the EU directive that prescribes manufacturers to follow the ISO 9000 quality management standards (ibid., p. 47). (Ponte et al., 2011). They relate the increasing importance of standardization in the EU to the intention of creating a free market (Brunsson and Jacobsson, 2000, p. 46).

Additionally, the GVC and GPN literature has emphasized the critical role of industrial standards for the vertical specialization of key actors. “Without common technical interfaces and modularity standards in constituent components and subsystems, it is doubtful that the world of production in electronics and automobiles could be as highly globalizing as they are.” (Coe and Yeung 2015, p. 55f.). It is, in fact, standards that allow components and parts to come from actors all over the world. As a consequence, technical standards are being introduced in an increasingly wide range of fields, which can be explained by a growing need for coordination and supervision within increasingly decentralized productionist systems (Brunsson and Jacobsson, 2000). The empirical problem with standards and standard setting actors is that they are harder to capture (standards are rather intangible) and their impact is less visible at first sight, although authors such as (Nadvi, 2008) have emphasized that any economic actor must comply to industrial and technological standards in order to participate in specific GPN.

The **normative dimension** of standards has been far less addressed within this stream of literature. An exception can be found in recent work that strongly relates to political economy and convention theory, in order to explain the governance of global value chains (Ponte et al., 2011; Ponte and Cheyns, 2013; Ponte and Sturgeon, 2014). From a normative perspective, standards establish a form of governance as “normalizing”. Governing through standards is understood as aligning a given practice to be compatible with a standard or norm (Gibbon et al., 2008). Most of the literature addressing this area relies on theoretical foundations that can be found in the economics of conventions or convention theory and the establishment of quality conventions (Ouma, 2010; Ponte et al., 2011). A very popular example is, for instance, the establishment and diffusion of the EN ISO 9000 quality management standards that are widely applied. The ISO 9000 quality standard has become an EU directive that manufacturers of machinery have to follow. In this regard Brunsson and Jacobbson note that:

> *"Standardization may be regarded as a way of regulating in a situation where there is no legal center of authority […] people voluntarily conform to the decisions of authorized expert knowledge. But while order is being established, responsibility may be vanishing." (Brunsson and Jacobsson, 2000, p. 48)*

However, most of the existing empirical studies in this regard have focused on what is referred to as corporate social responsibility (CSR) measures including social and ecological standards (Gereffi and Lee, 2016) or the numerous studies on the diffusion and adoption of international (quality) management standards such as the popular and wide spread ISO 9000 series. There are some studies on the impact of standards in the agro-food industry (Lee et al., 2012; Morgan et al., 2009; Mutersbaugh, 2005; Neilson and Pritchard, 2009; Ouma, 2010; Ponte and Gibbon, 2005) and the textile industry (Quark, 2013). Moreover, there is research on the general role of international standards in terms of value chain governance (e.g. Kaplinsky, 2010; Ponte et al., 2011).

Such a governing through standards pattern also evolves in decentralized modular forms of organizing production. However, the standards considered in existing empirical research on this topic do not codify and distribute *technological* or *architectural* knowledge and conventions.

2.2.5 Knowledge codification and standard formation processes

An ongoing debate has evolved about the actual codifiability of knowledge that can be separated into two main positions. One is based on the phenomenological approach of Polanyi and his tacit dimension inherent to any form of knowledge and the other one is based on the pragmatic information-processing approach of Simon (Simon, 1962). Authors in economics and innovation studies have mostly adopted the first position. Here, tacit knowledge has been reduced to a type of knowledge that cannot be easily codified and transferred (i.e. is "sticky") (cf. Hippel, 1993, 1994). It enfolds only through a culture of trust and knowledge-sharing (ibid.). The marginal costs of knowledge transmission are assumed to rise quickly with distance from the context in which "new" technological and scientific knowledge is generated. This "stickiness" of knowledge (especially scientific and technological knowledge) is assumed to benefit local enterprises, nations and entire regions. Developing a strong and innovative manufacturing sector requires applied and basic research facilities in spatial proximity to the production operation. Accordingly, the co-location of applied research facilities and potential commercial developers is assumed to facilitate regional innovation activities (cf. e.g., Patel and Pavitt, 1994; Brusoni et al., 2001). Hence, a new innovation strategy perspective formed around the concept of tacit knowledge that is influencing industry and regional cluster policies and development promotion until today.

The second position is based on insights from systems and complexity theory (Simon, 1962). It has influenced authors in economics to question the boundary between tacit and codified knowledge. According to this position, the boundary is determined by the costs and benefits of knowledge codification and can be removed by information technology, which is able to turn tacit into codified knowledge (Cowan et al., 2000). This is certainly an oversimplified assumption, if tacit knowledge is understood more in terms of capabilities, skills and “know-how”. Although related assumptions locating the transfer of tacit knowledge only in face-to-face interaction and relations of socio-spatial proximity are evidently challenged by advances in IuC technologies.

The GVC/GPN frameworks adopted this latter perspective particularly with regard to the conception of modular value chain linkages in which technological knowledge gest codified and exchange relations are only loosely coupled (cf. chapter 2.2.2). Certainly, both perspectives have their strength and weaknesses (for a detailed insight into the codification debate (cf. e.g., Nightingale, 2003) in explaining the nature of exchange relations, knowledge transfer and economic development.

Nevertheless, both perspectives often neglect or do not recognize the complexities of sharing/exchanging codified knowledge (such as standards) across places, disciplines and different socio-cultural contexts. In order to shed light into the factors that influence the exchange of codified knowledge it is important to identify those practices that are used to codify technological and industrial knowledge and to examine the emergence of linguistic and normative codes. How do they emerge and diffuse and how are they embedded in broader technological and social infrastructures. Hence, I am not interested here in whether and to what degree certain types of knowledge can be codified at all, since this leads to a controversial epistemological debate, which is still open and not in the focus of the present thesis.

Knowledge codification can be understood as the process through which information is transformed into a specific code. In linguistics it designates the process and the result of the (common) formulation and standardization of a consistent general language norm. Other authors also describe it as the conversion from tacit knowledge into an explicit and “usable” form (Nonaka and Takeuchi, 1995; Nonaka and Teece, 2001).. With regard to the quite problematic nature of the tacit dimension of knowledge and Polanyi’s understanding of tacit knowledge as a form of knowledge that cannot be simply expressed in a linguistic code without an immediate context (Davies, 2015), I rather understand it as the conversion into documented information that takes a specific representational format.

The fact that knowledge is made explicit in a linguistic code, does however not mean that it becomes a technological standard. Yet, knowledge codification and standard or rule formation are interwoven processes. The process of standard formation itself entails the codification of knowledge, but is always accompanied by the negotiation on consensus on what kind of information should be fixed in a common technical document. Moreover, there always exist some tension between the interests that underlie the need to codify and those that underlie the need to leave it tacit – "leave the work tacit, and it fades into the wallpaper […] Make the work explicit, and it becomes a target for surveillance." (Lampland and Star 2009, p. 22).

There are different mechanisms of industrial standard formation and one can classify standards according to the institutional environment within which processes of codification and formation take place. With regard to industrial standards one can distinguish between *de jure* standards developed and enforced by governments (e.g., safety, environmental, social standards), *de facto* standards that arise from the selection of market participants and are widely accepted and used without formal review and approval from a standards organization (e.g., PDF file format for printing, DVD format, assembly lines in mass manufacturing) as well as so called *voluntary consensus-based standards* (e.g., Wi-Fi, FireWire) set by multi-stakeholder committees (e.g., industry consortia) of standards developing organizations such as ISO, IEEE or *SAE* (*Society of Automotive Engineers*). Hence, standardization can be embedded in different institutional contexts (i.e. markets, states) (Murphy and Yates, 2009). Against the background of an increasing deregulation and liberalization of economic activity, voluntary-consensus-based standard setting and the actors involved play an ever increasing role in global high technology industries. Hence, the focus here is mainly set on standards that are set through industry consortia in so-called voluntary consensus based standard setting. This is a very knowledge intense process that requires for an epistemic community of experts, which defines standards for a specific field of technology apart from a competitive market setting (Murphy and Yates, 2011). In terms of knowledge exchange and diffusion, these standard setting platforms provide forums of exchange and negotiations for a set of sometimes quite heterogeneous actors (e.g., state and market actors form different countries and/or industrial sectors). These forums are arenas for the competition between different models and the vocabulary of the "specific language" to be developed (Cowan et al 2000).

> *"Until this competition is resolved, the community of potential knowledge generators and users will have difficulty communicating, and the value of knowledge codification that arises from dissemination will be reduced." (Cowan et al 2000, p. 247)*

Hence, strategic interests and the idea that a certain standard might diffuse and become an industry-wide convention also motivate the participation in standard setting activities within industry consortia. Regarding the legitimacy of standards, Botzem and Dobusch (2012) stress the interdependence of standard formation and standard diffusion and the interrelations and feedback loops between them. They differentiate between input legitimacy that is related to standard formation processes and output legitimacy related to standard diffusion processes and their inherent recursive relationship that is based on network and crowd effects (Botzem and Dobusch, 2012, p. 743).

The formation, diffusion and adoption of industrial and technological standards can give valuable insights on industrial development. Actors participating in industrial/technological standard formation activities can direct the formulation of standards and cognitive frames, thereby also affecting technological trajectories (popular examples can be found in VHS standards, or mobile telecommunication standards (Hess and Coe, 2006). Once a standard base is created and has been established scholars from the field of industrial and business research have shown that technological or market lock-in situations may occur (Arthur, 1989). Users tend to stick to the established infrastructure and the related standard base and might get locked into that base, although the technology becomes inferior over time. In this sense, standards can also become constraints and a threat to the development of expert knowledge, if standardization is carried too far. A good example is the ICT classification in medical systems (cf. e.g., Brunsson and Jacobsson, 2000; Bowker and Star, 1999). Actors, nevertheless, prefer the lock-in situation, because it reduces uncertainty and secures returns (Vries, 1999).

This argumentation is associated with research on so-called dominant designs defined as a "generic service or function that has achieved and maintained the highest level of market acceptance for a significant amount of time" (Lee et al., 1995, p.6). Thus, a dominant design is set, when a market accepts a particular technology that defines the specifications for products, services or processes of an entire industry (e.g., jet engines in aviation). Due to network externalities, the lock-in effect that maybe created by dominant designs applies to the whole production network, since changing to a new technology is only profitable, if a large number of actors will follow (Vries, 1999). Thus, the innovative capacity or performance of an industry is assumed to correlate negatively with the emergence of dominant designs in the long run (cf. also (Brem et al., 2016)), since from an engineering perspective, standards temporarily "freeze" solutions concerning interoperability and matching problems (Vries 1999, p. 213).[20] As a result, codified knowledge can become "a source of "lock in" to obsolete conceptual schemes, and to the technological and organizational systems that are built around those." (Cowan et al. 2000, p. 248). On the other hand, for empirical purposes this also means that, "codified knowledge can be a potent carrier of history – encapsulating influences of essentially transient and possibly extraneous natures that were present in the circumstances prevailing when particular codes took shape." (Cowan et al. 2000, ibid.). Cowan et al. (2000) state that it is during periods of technological and organizational change that new infrastructure is developed and situations of "excess codification" can be expected (p. 248).

The chapter has demonstrated that the formation of technological standards and the organization build around those are deeply intertwined. I will elaborate in more detail on this connection in the following chapter on what I refer to as knowledge infrastructures as an emerging interdisciplinary field of research that has a strong influence from social and cultural anthropology.

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[20] If the interface itself stays stable, modules/entities can be easily changed (i.e. the rails in the railway system and the trains making use of the rails).

2.2.6 Knowledge infrastructures

As has been already pointed out, industrial standards are often presented from a functional perspective as universal intermediaries that operate in an ideal-typical homogenous space of global production and the world market and as a form for effectively governing industrial knowledge across contexts and places. The issue of infrastructure is rarely or at all raised in related research on industrial and regional development. Yet, standards need a certain infrastructure in order to enfold their potential. Although several authors use the term infrastructure with regard to specific standard bases and the organizational practices build around them, they do not give a more detailed definition.

Unraveling technological infrastructures often reveals how knowledge and the architecture of knowledge systems is built and how knowledge is at the same time constrained, stored and embodied in artifacts and the processes used to create them (Lampland and Star 2009, p. 18). In the common understanding and use of the notion, infrastructure is "something that other things run on", for instance railroads, highways, canalization systems, electricity or the "information highways" underlying data transfer in the internet. A good infrastructure is usually invisible (at least to the end user). It is part of the background that makes other things work (Lampland and Star 2009, p. 17). In order to understand more complex technological systems and how they are created and produced, one needs however a more profound understanding of infrastructure and how technological, knowledge and social infrastructures are interrelated in production systems.

Star and Ruhleder (1996) define infrastructure "as a fundamentally relational concept, becoming real infrastructure [only] in relation to organized practices." (Star and Ruhleder, 1996, p.116). In this sense, technological infrastructures (e.g., the internet) embody standards (e.g., meta data and language standards for communication) that relate to/codify certain conventions of practice. They are being learnt of as part of membership. That means that the emergence and shape of technological infrastructures also relies on the social infrastructure and its specific governance systems, institutions and norms.

The sociology of science as well as research on standards and ontologies, systems science and design define a knowledge infrastructure in its broadest sense as robust internetworks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and the natural worlds (Edwards, 2013; 2017). Considering a cyber-physical infrastructure for production and knowledge circulation, it consists roughly of three layers (cf. Figure 2). The material technological infrastructure entails physical manufacturing facilities (e.g., machine tools, assembly lines, robotics etc.), data and communication networks. The codification infrastructure relies on a specific standard and documentation architecture that specifies how technical standards on manufacturing, materials and processes, interfaces and interoperability, meta-data etc. are created and organized. The social infrastructure determines practices and contexts of codification and standard formation influencing how codes take shape and diffuse based on existing conventions and institutions.

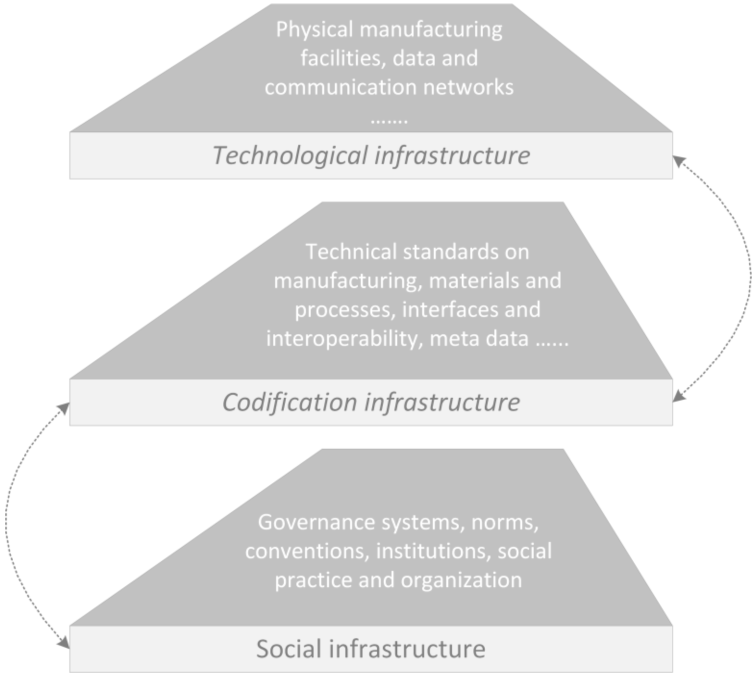


Figure 2: Dimensions of a knowledge infrastructure

2.2.6.1 Development and formation of knowledge infrastructures

Taking a closer look on standards development, Millerand and Baker (2010) identify different phases of development and local implementation based on an empirical study of the development of IT-standards. Integrating insights from other studies on standard formation and diffusion, one can identify three major phases. Throughout the **development phase**, codification and negotiation processes take place (Cowan et al., 2000; Nonaka and Teece, 2001). This phase is often characterized by competition of different standards and standard languages. The **phase of implementation or diffusion** depends on the reach and scope of the standard (is it intended to be a global or national standard), the modes of diffusion (coercion or de facto acceptance via market selection) (Botzem and Dobusch, 2012) and network as well as crowd-effects (Arthur, 1989; Tassey, 2000; Vries, 1999). Finally, the **enactment phase** describes the phase in which a standard reaches a specific local context. The compatibility with local conventions and the ability to learn has an impact on how a standard will be received and interpreted and whether it will be adopted (Lampland and Star, 2009).

2.2.6.2 Embeddedness of knowledge infrastructures

The development of a cyber-physical, socio-technical knowledge infrastructure for production as displayed in Figure 2 requires for the cooperation of an often very heterogeneous set of actors. Their embeddedness in particular spatio-temporal contexts illustrates how the existence and reality of a standard can vary, in line with the engagement/disengagement of the actors that are part of the development of these standards (Lampland and Star 2009, p. 151). In order to understand how the perception and impact of a standards varies the distinction between “objective” and “enacted” technology is quite useful.

The notion of “objective” technology or, in other words, the artifact-as-designed refers to a set of technical, material/physical and computing components, whereas “enacted” technology (or the artifact-as-used) refers to how it is perceived, conceived and used in practice in particular context (Lampland and Star, 2009; cf. also Weick, 1979). This also counts for standards that codify technological knowledge. The way in which actors are engaged and enact technological standard formation depends on the socio-cultural and institutional structures they are embedded in. These organizational arrangements of routines, conventions, standards and norms, mediate the development of standards on the one hand, and contribute to the reconfiguration of the organizational arrangement on the other hand (Lampland and Star, 2009, p. 152). “Each standard in practice is made up of sets of technical specifications and organizational arrangements.” (ibid., p. 165). Or to put it differently, **technical specifications cannot exist outside specific organizational contexts.** In this sense, standards must constantly interact with the infrastructure from which they emerge shaping the way they actually affect production (Cullen Dunn, 2009).

> *“In many cases, having a certain sort of infrastructure – usually the same set of technologies that the people who originally wrote the standards had – is a prerequisite for entering the market in the first place. Rather than being governed by a set of complex rules that dictate how and what they will make and trade, producers without the right infrastructure are forced out of the market altogether.” (Cullen Dunn 2009, p. 118).*

This distinction between objective and enacted technology and the embeddedness of actors who create and make use of them also highlights the power asymmetries between standard setters controlling the language of science and technology, and (local) producers/manufacturers who are coerced to follow these standards lacking the power to create or change them (ibid., p. 118ff).

This aspect also relates to the distribution of an infrastructure along a global-local and a socio-technological axis (cf. Figure 3). On the local technological level the question of whether new standards built upon an already installed standard base is important in order to be able to connect to them (e.g., certain manufacturing technologies, pipelines, electricity, etc.). A breakdown of that infrastructure would become visible on a local scale. On a global scale, the level of transparency of that infrastructure and the degree to which it is actually codified and embodied in (open) standards impacts its wider diffusion. This in turn affects its reach and scope on the global-social scale and the overall opportunities to link to existing conventions of practice. On a local-social scale, conventions and standards are learned of as part of membership, depending on the embeddedness of users and creators. If creators and users of codified knowledge/standards are embedded in different socio-cultural and economic backgrounds this obviously affects the distribution of such infrastructures and the transfer and diffusion of related knowledge. In an abstract sense, the sharing of knowledge *across* localities and contexts always entails:

> *"linking experience gained in one time and place with that gained in another, via representations of some sort. Even seemingly simple replication and transmission of information from one place to another involves encoding and decoding as time and place shift. Thus, the context of information shifts in spite of its continuities; and this shift in context imparts heterogeneity to the information itself." (Bowker and Star, 1999, p. 290)*

The following figure (based on Millerand and Baker 2010) illustrates infrastructures as distributions along a socio-technical and a local-global axis.

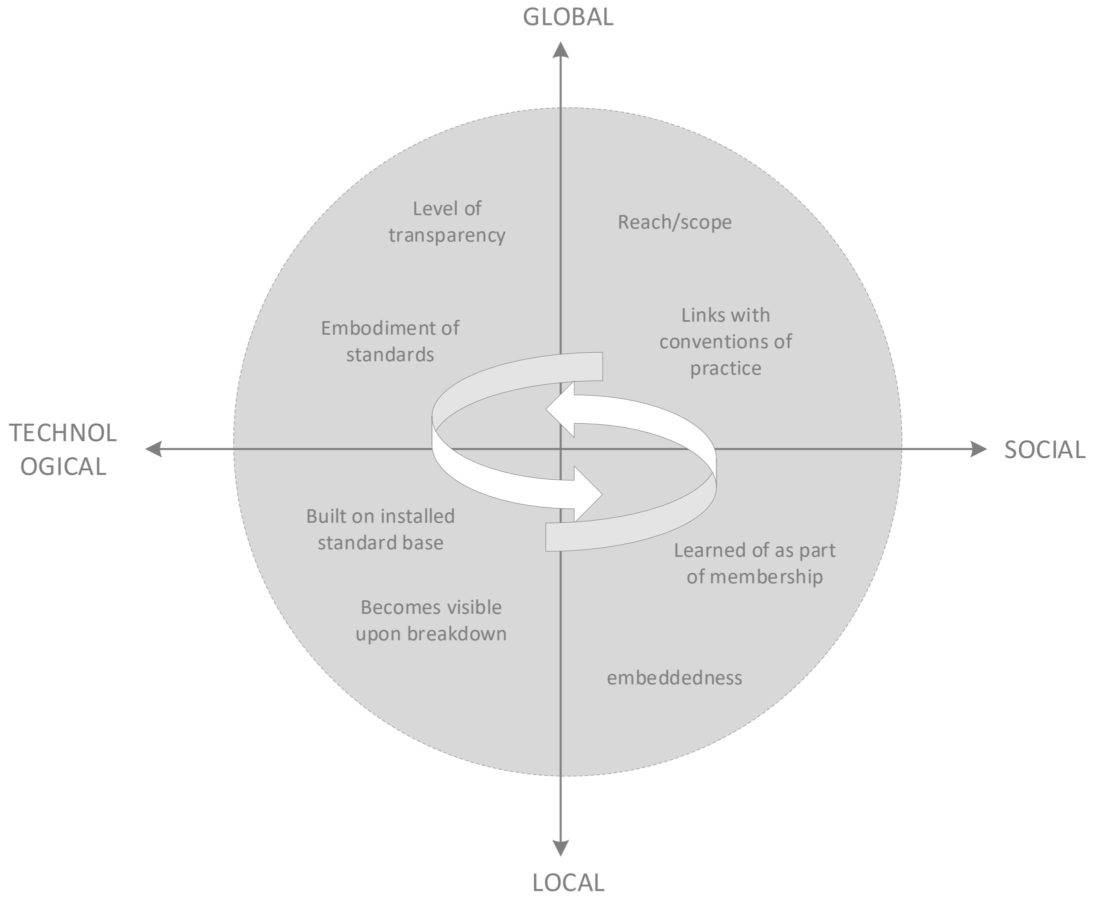


Figure 3: Infrastructures as distributions along a technical/social and global/local axes

In summary, a knowledge infrastructure in production can be considered as a set of technical specifications embodied in standards that relate to specific conventions of practice and are developed in and for organizational contexts in particular places by actors that have a specific institutional embedding. Any form of knowledge in production relations is embedded in situated practice and specific socio-cultural contexts. Tacit knowledge is embedded in situated practice and codified technological knowledge embodied in standards and artifacts is embedded in specific infrastructures that reflect organizational and social practice and shared cognitive and normative frames.

2.2.7 Summary and conclusions for the further analysis

The previous chapter has defined the role of codified knowledge in production relations. Industrial standards codify expert knowledge that addresses matching problems across different metrics and contexts. They have an intermediary and functional character and enable the coordination of industrial knowledge across places. The literature on GVC and GPN has predominantly adopted a functional perspective on standards that is not able to show their inherent ambivalent nature. By showing how knowledge codification and standard formation are carried out, it became clear how technological standards and organizational practices and routines are intertwined and embedded in particular contexts stressing their normative dimension. These interconnections have been captured in the concept of knowledge infrastructures. A knowledge infrastructure has been defined as a set of technical specifications embodied in standards that relate to specific conventions of practice and are developed in and for organizational contexts in particular places by actors that have a specific institutional embedding. They are distributed along a global-local and social-technological axis.

Technological and industrial standards can be both: an intermediary and a constraint given their functional and their normative character for social (inter-)action as well as technological and industrial evolution and development. Standards serve as the basis for the development of institutions, which can develop upon them based on stable and repeated interactions. Hence, the dual nature of standards as a form of codified expert knowledge influences the institutional as well as the creative frame (i.e. the frame for the search for solutions or the solution space) in which economic actions (can) take place. On the one hand, standards enable exchange and interaction, on the other hand they can constrain participation and creativity and create immense entry barriers to an industry (e.g., via lock-in situations and the creation of regimes of engagement) on different spatial scales. Insights from convention theory and the sociology of regimes suggest that the imposition of specific information formats or specific architectures of knowledge infrastructures serve as a frame for getting engaged. Hence, actors participating in standard setting also set the frame for processes of inclusion, exclusion and marginalization. Chapter 2.1.4 has stressed the role of inter-personal and especially systemic trust for the building of relational ties and exchange relations. In the case of a (global) production system, systemic trust means having trust in the functionality of a system its institutions and norms, which also means that actors need to share the same knowledge infrastructure regardless of where they are located. A lack of systemic trust can, therefore, be associated with missing experiences or a misunderstanding of the underlying knowledge, norms and rules, for instance when standards have been developed in distant locations and institutional contexts and implemented elsewhere.

Whereas knowledge codification is the process through which information/knowledge is transformed into a specific code and language norm (i.e. its conversion into a documented (explicit) form, standard formation is the process through which codified knowledge becomes a rule or an industrial/technological convention. Phases of standard formation entail its development, diffusion and enactment. The process of standard formation, can take different forms, but it always entails the codification of implicit/expert knowledge into de jure, de facto or voluntary-consensus based standards. The distinction between these three types of standards refers to the institutional context in which they are formed (i.e. governmental institutions, market selection, or voluntary consensus-based organizations such as industry consortia, citizens initiatives etc.) and highlights different degrees of liability. The phases of standard formation will be related to phases of modularization throughout Chapter 4.

For the conceptual model, it is important to distinguish between the embedding of production and knowledge relations although both are intertwined. In this sense the knowledge infrastructure is part of a GPN. It displays more horizontal exchange relations based on cooperation rather than competition that exist apart from vertical buyer-supplier relations that are usually considered in the conventional conception of production systems (cf. Figure 4).

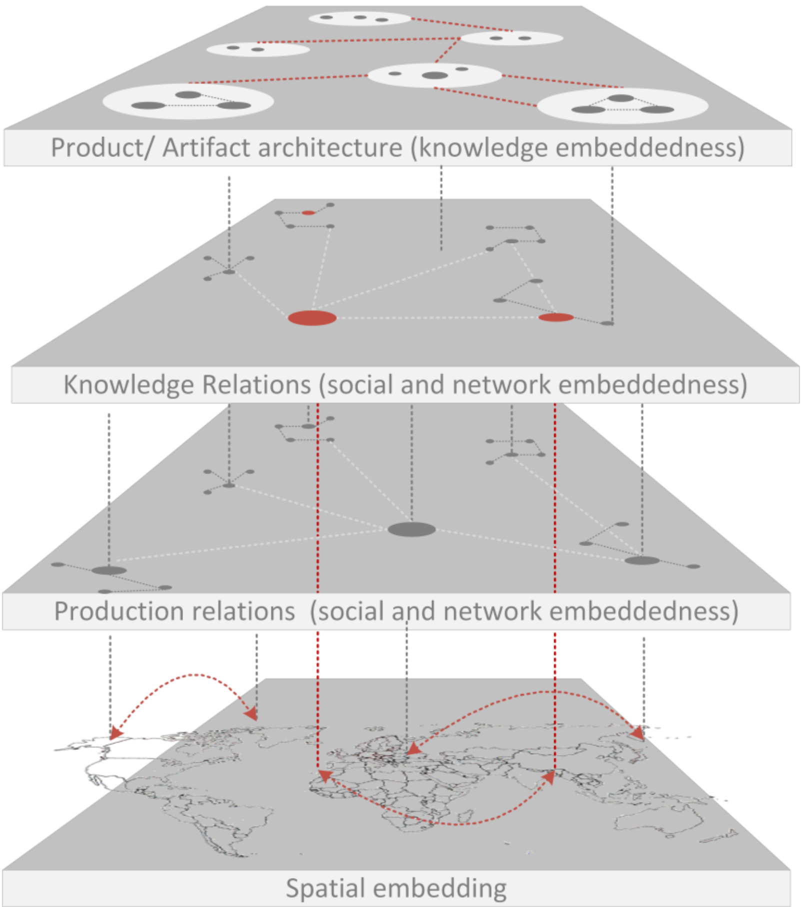


Figure 4: Dimensions of a production system II

2.3 The architecture of knowledge exchange relations in modular production networks

The dual nature of technological standards and its embedding in wider infrastructures of social organization does not only point out to specific institutional contexts in which standard formation is embedded, but also to specific architectures of how knowledge is organized in production relations and how it is inscribed in the artifact and the processes used to create it. The following chapter introduces the architectural paradigm of modularity as a fundamental principle for organizing knowledge infrastructures. The concept also helps to clarify how architectural knowledge is embodied in artifacts. Based on the definitions and insights from the prior chapter, the aim of this chapter is to define the characteristics and organizational principles of modular design, production and knowledge network architectures (2.3.1). Section 2.3.2 draws conclusions on what this means for the knowledge infrastructure inherent in modular organizations. It discusses the interrelations between knowledge relations, the configurations of standard and product architectures and how they are reflected in the configuration of the production network; aiming to answer the question of whether or to what degree modular product architectures are mirroring or affecting knowledge relations in production networks.

2.3.1 Modular product and design architectures

Modularity has become one of the major organizing principles of high technology and technology driven industries (Baldwin and Clark 1997). The basic principle of modularity is not as new as some authors assume. In terms of production, it can look back to a long history. Manufacturing processes of complex artifacts have been divided into more manageable modules or units of assembly for centuries. Modular approaches rely primarily on open and shared standards. Hence, the development of interoperability and interchangeability and standardization of parts, processes and materials is considered to be the precursor to modern forms of product modularity in many ways (Arnheiter and Harren, 2005). Whereas the term "modular production" has been first employed by Martin Starr in his paper "Modular Production – A new Concept" in 1965 (Doran and Starr, 2010; Starr, 1965), standardization and modularization can be already found in the construction of buildings in ancient Rome 2000 years ago or the building of warships and guns in Italy, France and Germany in the early 15th century.[21] However, conditions and environments in which this type of architectural knowledge occurs and evolves have changed over time. It is the modularity in *designing* products and systems (i.e. the modularity of product

[21] It is, thus, deeply influenced by military use (Arnheiter and Harren, 2005).

architectures) that found its way from the computer and electronics industry into more and more industries during the end of the 1990s (Baldwin and Clark 1997).

Modularity can be considered as a special form of architecture, a way of defining and describing a system (Sanchez and Mahoney, 1996). The intended system design can refer to a product or process as well as to an emergent system design for an organization or an entire industry (Boisot and Sanchez, 2010; Sanchez, 2008). Modularity is a specific way of representing a system design by defining the functional component structure of the design and the interfaces that specify or determine how the functional components interact.

Product architecture is the scheme by which the functions of a product are allocated to its constituent physical and non-physical components (Ulrich, 1995)[22]. It has been shown "to be an important predictor of product performance, product variety, process flexibility and even the path of industry evolution." (MacCormack et al., 2012, p. 1309). In product and systems design one usually distinguishes between integrated and modular product architectures. I will explain in more detail now, what this exactly means.

Principles of modular designs and modularity as architectural knowledge

If we assume that knowledge accumulates over time and gets more complex, modularity, first of all, is a response to the increasing complexity of existing knowledge and artifacts (Simon, 1962). At a point, where an artifact can no longer be made neither be comprehended by a single person, the division of knowledge and efforts becomes a necessary precondition (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996). Knowledge and competencies required to design and build a complex cyber-physical artifact such as the A380 (as one of the biggest passenger aircrafts in the world) are spread and dispersed across multiple actors, locations as well as scientific and technological fields.

> *"Modularity is a very general set of principles for managing complexity. By breaking up a complex system into discrete pieces – which can then communicate with one another only through standardized interfaces within a standardized architecture – one can eliminate what would otherwise be an unmanageable spaghetti tangle of systemic interconnections." (Langlois 2002, p. 19)*

(Product) modularity is a concept that enables us to describe and characterize different types of designs by referring to the way an artifact can be decomposed into different parts and modules. Whereas there are numerous definitions of modularity these days, they share at least one commonality "the notion of interdependence *within* modules and independence *between* modules" (MacCormack et al., 2012, p. 1311; Ulrich, 1995). The independence between different modules or components is often associated with the notion of "loose-coupling." In the same sense as there are different levels of coupling between

[22] I do not refer explicitly to the economic implications that come along with the notion of the "product" here. The product is the artifact/the outcome intentionally created by a collective of actors.

actors of an organization (Orton and Weick, 1990) there are different degrees of modularity in product design.

Accordingly, on the **object level**, the term modular describes an artifact (either tangible, intangible or a combination of both referred to as cyber-physical systems) whose single components are interchangeable without adjustments in other components – provided that interfaces are clearly defined, standardized and transparent, so that new components can simply "plug into" the existing architectures (Henderson and Clark, 1990). Transferred to the **process level**, it means that manufacturing processes are broken down into standardized subunits (i.e. process modules or assemblies), in order to enable the rearrangement of different process configurations (Arnheiter and Harren, 2005)[23]. It becomes obvious that product and process modularity are deeply intertwined. It is a design theory that aims at reducing complexity and making product and process architectures more flexible to adjustments and the integration of complementary knowledge (and products), thus, accelerating incremental and parallel product development (Baldwin and Clark, 2000). Modular designs can, therefore, be considered as a form of **architectural knowledge** that specifies in which way the components, modules or assemblies of a given system are linked to each other. Consequently, an architectural innovation designates an innovation that changes the way in which the modules of a system are linked to each other without making significant changes in the core design concepts (i.e. the basic knowledge underlying the components) (Henderson and Clark 1990).

Parnas was the first to study software modularity and proposed a concept of hiding information in order to divide code into modular units (Parnas 1972; Parnas et al., 1985). In the following years and decades different metrics have been proposed in order to capture the degree of coupling *between* as well as the cohesion *within* software modules (MacCormack et al., 2012). Meanwhile, modular systems design is increasingly diffusing into ever wider fields ranging from systems and software engineering, to mechanical and machine engineering, including the design of manufacturing machines themselves, building one of the fundaments of the contemporary highly interconnected and automated industry landscape. Software modularity as well as the independence between software and hardware modules (e.g., in computer systems) is very well studied, whereas complex physical and cyber-physical systems (such as aircrafts or complex machine tools for manufacturing) naturally show a higher degree of coupling between its elements. There exist far less studies in this regard, mostly because respective product or production system data are not easily accessible and demand for in-depth technological and industry knowledge.

[23] In the case of process modularity, task interdependencies between process units are determining module boundaries.

Decomposition of complex cyber-physical systems

The design theory of modular systems is, first and foremost, an attempt to master the growing complexity of artifacts and the processes used to create them by reducing complexity through decomposition (Simon, 1962; Ulrich and Eppinger, 1995). In order to decompose a complex cyber-physical system, as for instance an aircraft, the system building blocks (i.e. modules) can be divided along a functional and a physical dimension (Kossiakoff, 2011). Understanding the functional aspects of the system allows the designer to partition them into a physical and a logical hierarchy which can then be decomposed into single elements. The basic functional elements can be categorized into four classes according to the respective operating medium. Signal elements are sensing and communicating information; data elements are interpreting and communicating information; material elements are providing structure and process material; and finally, energy elements are providing energy or power. Within this functional system perspective, components/modules can be considered as “the physical embodiment of functional elements”, which can be further categorized into several classes according to the materials of construction: electronic, electro optical, electro mechanical, mechanical, thermomechanical and software (i.e. information/data) (Kossiakoff, 2011, p.42ff). Obviously, knowledge bases and scientific fields involved in creating the artifact are heterogeneous, posing challenges with regard to issues of cross-sectoral communication and knowledge diffusion.

Shifting the attention from the functional system domain to the structural system configuration, one is interested in how the elements that constitute the system are interrelated. According to the literature on design hierarchies, complex cyber-physical artifacts are always structured in terms of a “hierarchy of nested parts” (Murmann and Frenken, 2006) or a “nested hierarchical structure of interrelationships” between different functional elements (Baldwin and Clark, 2000, p.11). A system, thus, consists of several sub-systems, i.e. smaller second- and third-order systems until the level of the basic components and parts being recursively nested. The hierarchical order is determined by two aspects: the hierarchy of the inclusion of parts as well as the hierarchy of control (Murmann and Frenken, 2006; Whyte and Wilson, 1969). The hierarchy of inclusion of parts is mainly determined by the assembly order. In the case of modern aircrafts the overall system can today be roughly divided into four hierarchical levels of inclusion of parts (cf. Figure 5/left side). Each level corresponds to a respective level of integration. At the component level, raw materials and semi-finished parts are the basis for component manufacturing. The second-order subsystem level corresponds to component system integration, the first-order subsystems corresponds to platform systems integration and the so-called architectural integration takes place in a final step at the overall system level. Data provided by the online database *Airframer* illustrates which subsystem integrates which other subsystem in its production process using purchasing data from aircraft manufacturers, programs and key suppliers. According to this database, the overall system can be divided into 88 subsystems consisting of 1.723 different components (cf. also Cagli et al., 2012).

The hierarchy of control refers to the point that - analogously to the brain in the human body or an operating system in a computer - there are different functional parts that are sub-ordinated to sub-systems that control “how all other first-order subsystems interact to perform a well-functioning system” (Murmann and Frenken, 2006), as for instance in the case of avionics within an aircraft or more generally in the field of control engineering.

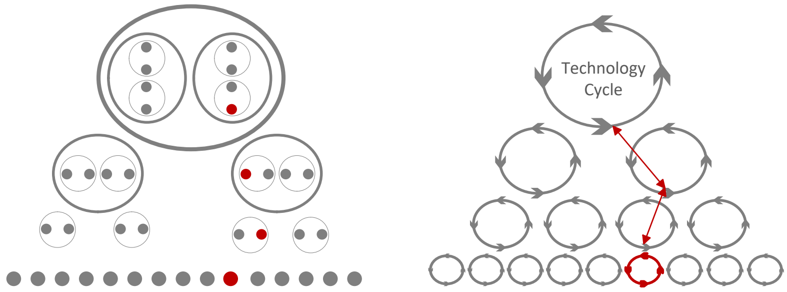


Figure 5: 4-level system architecture from a static (left) and dynamic perspective (right) based on Murmann and Frenken (2006)

The left side of Figure 5 illustrates a static perspective. Since scientific and technological progress and related innovation and product life cycles are more rapid than ever, technologies applied in the modules and subsystems are each subject to an on-going change. In coping with these dynamics the peculiarity of modularity as a design principle results from a different aspect and goes beyond the mere decomposition and hierarchical partitioning of systems. Modularity (at the system level) aims at minimizing the interdependence of functional elements within and between hardware as well as software components. Within a tightly coupled integrated product architecture (cf. Figure 6/left side), any changes within a module are likely to provoke changes in each of the other surrounding modules. Instead, within an ideal modular product architecture (illustrated at the right side), the “loose” coupling simply refers to the fact that interactions (e.g., signal interfaces) and interdependencies between modules are reduced to a minimum. An artifact (e.g., software) “can be complex (i.e. have many parts) and at the same time modular (i.e. have few interdependencies between these parts).” (MacCormack et al., 2012, p. 1312). Consequently, from the designers or engineer’s point of view complexity is being reduced. Modular product architectures have also been described as “instances of independent rules with high combinatorial potential.” (Boisot and Sanchez 2010, p. 385, FN 8).

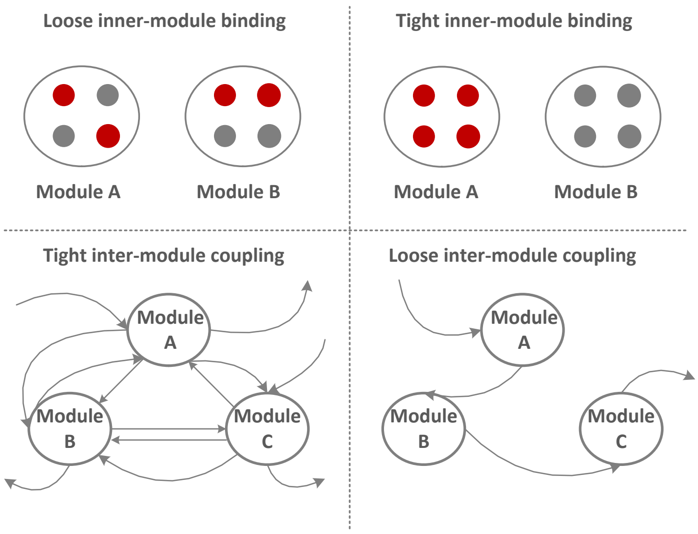


Figure 6: Integrated system architecture (left side) versus modular system architecture (right side) based on Kossiakoff (2011, p. 379)

It is important to note that modular designs are far more difficult to develop than interconnected or integrated systems. Components or modules are only able to connect and perform as a whole, if interfaces are well-defined, transparent and stable, since the interface is the part of the system that enables interaction between its elements and, it is the point of interaction between modules and coupled systems (Halbach, 1994).[24]

> *“The designer of modular systems must know a great deal about the inner workings of the overall product or process in order to develop the visible design rules necessary to make the modules function as a whole. They have to specify those rules in advance. And while designs at the modular level are proceeding independently, it may seem that all is going well; problems with incomplete or imperfect modularization tend to appear only when the modules come together and work poorly as an integrated whole.” (Baldwin and Clark, 1997, p.86)*

The higher autonomy of modules envisioned by modularity as a design principle enables the following: modules can be matched in a greater variety of configurations; modules can be developed and approved upon in parallel, thereby accelerating incremental innovation and giving new opportunities for the division of knowledge, labor and responsibilities within the production network.

This also points to a different organization of knowledge relations and a specific knowledge infrastructure that is necessary, in order to realize modular design and production.

[24] The term “interface” (etymologically) originates in the field of systems and control engineering. As a technical feature interfaces have a translating and mediating function between two coupled systems (sub-systems). http://www.etymonline.com/index.php?term=interface

2.3.2 Knowledge infrastructures in modular production

The prior chapter illustrated that modularity as a form of architectural knowledge is a fundamental approach of organizing complex cyber-physical systems and production processes. The principles of modularity are, however, not limited to the technical domain (i.e. complex technical systems). They apply also to organizing economic and wider social systems and, thus, shape the nature of exchange relations between its constituting elements. The aim of this subchapter is to identify the peculiarities of knowledge infrastructures in modular production and how they relate to the configuration of production relations in a global network.

The impact of modularity as a design principle and architectural paradigm has been predominantly investigated by scholars of organizational and strategic management studies (Baldwin, 2008; Brusoni, 2001; Ethiraj and Levinthal, 2004; Langlois, 2002; Miozzo and Grimshaw, 2005; Sanchez and Mahoney, 1996; Schilling, 2000). Hence, the organizational and economic implications and consequences of modularization are described quite well in the respective literature that mostly draws on transaction cost economics (Baldwin, 2008; Baldwin and Clark, 2006; Jacobides, 2005) and addresses predominantly relational changes on the product or network level. In associating modularity explicitly with industrial change and evolution some authors have been able to show that the increasing modularization and global division of labor and knowledge within and especially across firms becomes evident in an increasing vertical specialization along the value chain (Hobday et al., 2005). This is accompanied by an extensive outsourcing and vertical disintegration of production processes. It caused the rise of powerful system suppliers and intermediary markets and has together resulted in the emergence of extensive more flexible forms of organizing production in propulsive high technology industries, which has been described with the concepts of flexible specialization (Herrigel, 2009) and modular linkages in the global value chain (Piore and Sabel 1984; Sturgeon, 2002, 2003) (cf. chapter 2.1.2).

From a **socio-organizational perspective**, the technical interface is the point where design information and process knowledge need to be exchanged between actors in the production network. Imagine a technical interface between two modules and assume that both modules are designed and manufactured by different actors. In this case actor A has to have information on the interdependencies between module A and B and how to integrate the component manufactured by actor B. If one intends to modularize the architecture of a given design (e.g., an aircraft) it implies a reconceptualization of the overall interdependencies in order to define module boundaries and interface standards. So if each module is created by different actors than who ensures the architecture's overall integrity and how is it done? In this case, the designer(s) can make all the design information available to everyone involved as for example in the cases of radical Open Source Soft- and Hardware approaches.[25] As a consequence,

[25] Examples are Open Source Software such as Linux, Mozilla and Open Source Hardware such as the Arduino Boards (electrical engineering).

the designer might possibly fail to capture any economic value, but more importantly for the given analysis, he would also partly or entirely lose the control of the overall structure (i.e. the architectural integrity and design sovereignty). Another possibility, initially described by Parnas (1972, 1985), is that the architecture's integrity is maintained by controlling the distribution of knowledge and information about the design. Accordingly, Parnas distinguishes between visible and hidden information, whereas the visible information is included within the interface between modules and the hidden information refers to design parameters not included in the interface. As a consequence, each module is regarded as a black box – also referred to as "hidden modules" by Baldwin and Clark (2000). In an ideal modular design information and knowledge on interoperability becomes only visible at the interface. This profoundly affects knowledge and exchange relations in a production network. The definition and design of interfaces as well as module boundaries is, therefore, probably the biggest challenge that comes along with modularization (Baldwin and Clark, 2006). Technological and system interfaces must be harmonized with existing or to be developed organizational interfaces as well as the specific property structure of the actors involved in the production process as illustrated in Figure 7.

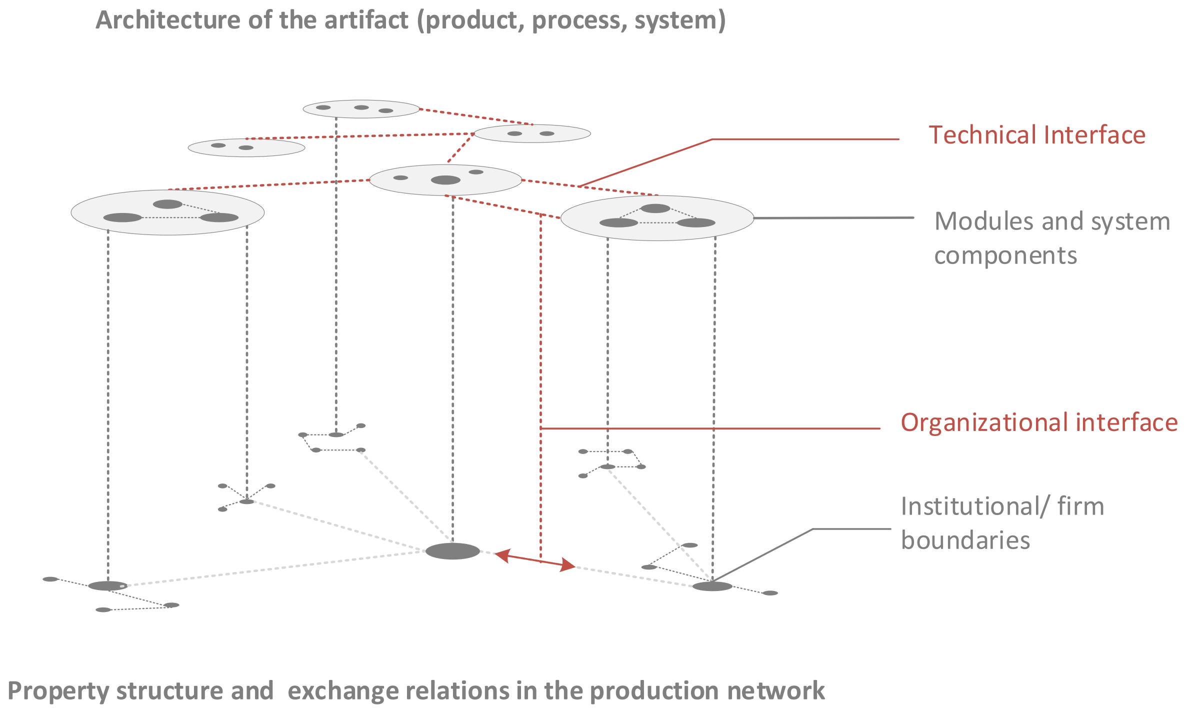


Figure 7: Technological and organizational interfaces in modular systems

Problems occur, when technological, proprietary and organizational interfaces do not match. When technical module boundaries are drawn between competitors or across different institutional contexts, actors might not be willing to share knowledge and design information, if they affect or are assumed to affect intellectual property that is for instance protected through patents hold by others. In order to cope with this challenge, design rules and interface/interoperability standards must be established and respective knowledge must be codified into common open standards. From a systemic stand point, all standards concern “systems of interrelated entities.” They specify features of internal aspects of a module or the interfaces between the modules (Vries, 1999). In the same way the entities of a complex artifact can be recursively nested (modules, sub-modules etc.), **a standard’s architecture can mirror the architecture of the artifact**, since the standard’s structure is often intended to correspond to the technology structure (Henderson and Clark, 1990).[26] This means that a modular product or design architecture also requires for a modular standard architecture. On a technical level, this refers mainly to the structure and architecture of the documentation of technological specifications. The *ideal* knowledge architecture in modular design and production consists of a cyber-physical system with standardized interfaces and components and a standard’s architecture that mirrors the architecture of the artifact. The question is how does a corresponding organizational form and the constitution of exchange relations looks like in such a system?

In their seminal paper on modularity, Sanchez and Mahoney (1996) assumed that standardized interfaces in modular product architectures can provide essential embedded coordination of loosely-coupled development and production processes. They enable new kinds of modular organizations that lead to “self-organizing” industry structures. Relations between actors are only loosely coupled enabling a (globally) distributed production and development process (cf. also (Brusoni et al., 2001; Brusoni, 2001). It is based on the conceptualization of organizations as complex systems, comprising many elements with different levels of coupling between them (Orton and Weick, 1990; Williamson, 1983). **Organizational coupling** can be analyzed according to various different dimensions. Considering only the opposite ends of a continuum organizations can be tightly (dense/tight linkages) or only loosely coupled as in the organization of technical components in modular systems. According to Sanchez and Mahoney (1996), the more actors adapt modular product and process architectures, the more it influences the development of industry structures towards a “modular industry architecture” of globally dispersed, loosely coupled organizations (Sanchez and Mahoney 1996). Thus, the modular systems approach (within the field of organizational studies) grounds the **structure of relations** in productionist systems around architectural relations of the artifact that is co-created by the actors that form the production network as well as task interdependencies in the production process. The nature of relations is classified as being only loosely coupled and hence easily interchangeable and manageable. This argumentation can also be found in the literature on GVC and the concept of modular linkages and governing through standards (cf. chapter 2.1.2).

One of the main hypothesis that has been discussed in the field of organizational studies in recent years is the so-called “**mirroring hypothesis**” that assumes that the architecture of the product and process

[26] In the case of the aerospace industry the ATA chapters classify and categorize the systems of an aircraft into groups and sub-groups based on ATA 100 a common referencing standard for commercial aircraft documentation.

entirely or at least partly “mirrors” the structure of the production network (Hoetker, 2006; MacCormack et al., 2012; Sanchez and Mahoney, 1996). This implies that modular architectures lead to modular organizations. The studies that have investigated the relation between product architecture and the organization developing it rely predominantly on transaction cost economics and consider modularity as a specific organizational structure for the coordination and division of labor that aims at minimizing transaction costs (Baldwin, 2008; MacCormack et al., 2012). This perspective relies on an efficiency rationale that is interested in optimizing organizational designs.

More recent work by Sanchez, however, demonstrates that the development of a modular architecture requires for collaboration of firms in order to set and agree on industry standard product architectures (Sanchez, 2008; Sanchez and Mahoney, 2012). This means that horizontal exchange relations are crucial for the development of modular knowledge infrastructures. Modularity standards and standard architectures are often developed within industry consortia. These actors set the rules for getting engaged. They form knowledge networks and epistemic communities that negotiate on what is going to be fixed in a common technological standards. Whereas mass production and concepts of lean production arose out of standardization of products and processes, “modular systems standardize something more abstract: the rules of the game.” (Miozzo and Grimshaw, 2005, p. 1422; cf. also Langlois 2003). They define the technological framework or in other words the technological and codification dimension of the knowledge infrastructure. Horizontal knowledge relations apart from conventional input-output relations in production networks are needed in order to develop such an infrastructure.

In the case of cyber-physical systems, knowledge gets codified and embedded in standards and the transfer of information and knowledge between components gets increasingly embodied in the artifact and its virtual transmission channels. Consequently, most of the studies implicitly or explicitly assume that the information infrastructure or design rules inscribed in the product and process architectures would ensure system coherence and compensate any explicit managerial authority (Brusoni et al., 2001; Brusoni, 2001, 2005; Jacobides and Winter, 2005; Kechidi, 2013; Langlois, 2002; Sanchez and Mahoney 1996). If at all, this is only the case once they are successfully established. This perspective neglects the fact that the knowledge infrastructure, on which this form of knowledge governance and nature of exchange relations runs, needs to be developed in a collaborative process first and it entirely neglects the embeddedness of knowledge and actors.

The analysis of the design and production of modular cyber-physical systems as well as the development and evolution of the underlying knowledge infrastructure must be separated in empirical research, in order to gain a better understanding of what happens during modular transition and how modularization impacts the organization of industries.

The following table distinguishes production relations and knowledge relations according to the key actors involved, the structure and nature of exchange relations, the element or output they create and/or exchange and the boundaries in terms of their property structure.

Table 2: Production versus knowledge relations in modular production systems

	Production of a modular artifact (product, system, design)	**Development of the corresponding knowledge infrastructure**
Key actors	Firms	Standard setting organizations, industry consortia
Structure of exchange relations	Hierarchically nested, rather vertical	Horizontal
Nature of exchange relations	Loosely coupled, non-idiosyncratic, interchangeable, buyer-supplier relations	Collaboration apart from market competition, tightly coupled, knowledge exchange relations
Elements/Output	Heterogeneous components and subsystems, design and manufacturing processes	Interface and interoperability standards, standard product and process architectures, information infrastructures
Boundaries in terms of property structure	Closed (commercial), e.g., I-Phone	Proprietary standards De Jure Standards
	Open as in Open Source Soft- and Hardware (e.g., Open Source 3D Printer)	De Facto standards Voluntary consensus-based standards

This distinction also clarifies how actors in a production network need to oscillate between cooperation and competition - between exchanging and sharing knowledge.

A knowledge infrastructure has been defined as a set of technical specifications embodied in standards that relate to specific conventions of practice and are developed in and for organizational contexts in particular places by actors that have a specific institutional embedding. Hence, infrastructures stretch along local social – technical and global –axes. Knowledge is always embedded in situational practice and the socio-organizational context of creation and use. Knowledge relations are embedded in the knowledge infrastructure that is determined by the product or artifact architecture and the social environment in which they are created.

They can involve different actors and institutions and, therefore, also have a different spatial manifestation and impact. The formation of standards as well as the associated value activities (i.e. certification, accreditation) that are necessary for the design and production of complex cyber-physical systems can have a different geographical embedding than the actual production processes and the value captured form it. This multi-scalar embeddedness of knowledge and knowledge relations also highlights power asymmetries between the producers and users of such codified knowledge and standards. One person’s standard can be another one’s mess, or, in other words, what is meaningful for one person or a group may be tacit or impenetrable for someone else (Lampland and Star, 2009). Technological modularity standards and the knowledge infrastructure they are embedded in can enfold their full potential only, if actors and regions are able to connect to codification schemes developed in different socio-spatial and institutional contexts. Figure 8 summarizes these multi-dimensional interrelations of different types of embeddedness of knowledge and production relations.

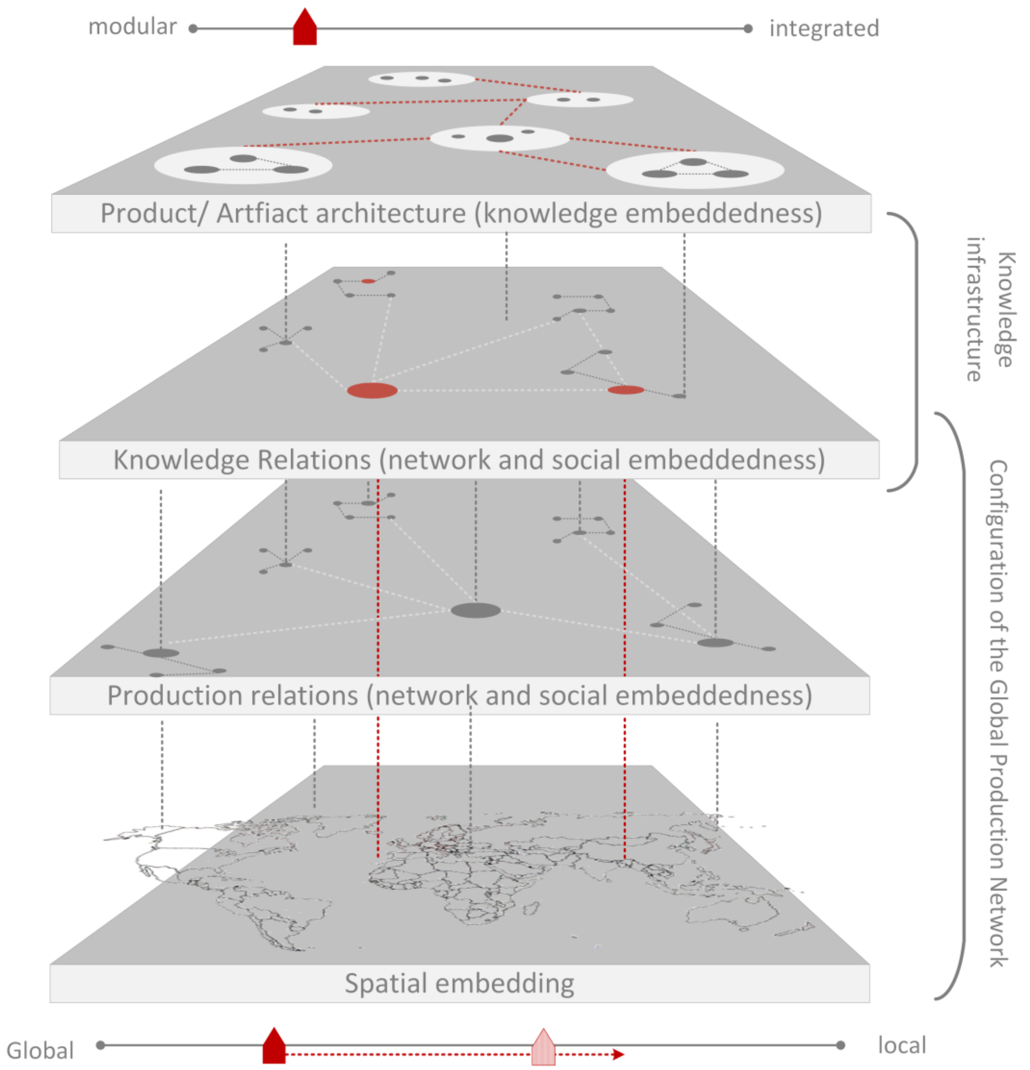


Figure 8: Dimensions of a production system III

2.4 Modularization as a dynamic multi-dimensional process

The aim of this chapter is to conceptualize modularization as a dynamical process and identify main phases and their characteristics based on processes of standard formation and diffusion (cf. chapter 2.2.5). In doing so, modularization is considered as a process based on strategic decisions of designers and managers (2.4.1) as well as an emergent and path-dependent phenomenon (2.4.2). Finally, commonalities between these two perspectives are identified and put together. The final chapter (2.4.6) gives a summary and draws conclusions for the further analysis.

2.4.1 Modularization as a strategic process

The decision of whether or whether not to modularize is a strategic one and modularity has become a key strategic choice variable for firms (MacDuffie, 2013). Modularity can be strategically implemented via what Sanchez (2008) refers to as strategic partitioning sometimes also referred to as variety management in production engineering (ElMaraghy et al., 2013). The economic advantages arising from modular architectures can be summarized as follows. It is a design strategy that: reduces transaction costs in exchange relations; reduces system and process complexity; facilitates parallel development of modules; increases the recombination of modules (i.e. enhancing the number product and process variants); increases incremental innovation; and creates opportunities for a redistribution of labor and responsibilities along the value chain.

A lot of prior work in the field of organizational and management studies has pointed out to the critical role that modularity plays in terms of successfully developing a new product, the competitiveness of a firm's product portfolio or the evolution of organizational capabilities (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996; Schilling, 2000; Ulrich and Eppinger, 1995). In these terms, the economic and organizational costs and benefits of modularity have been emphasizing different aspects (cf. MacCormack 2012, pp. 1311) such as:

- Managing complexity (Simon, 1962),
- Designing and managing inter-firm product lines and product family architecture (Sanderson and Uzumeri, 1995),
- Manufacturing (Ulrich, 1995; Ulrich and Eppinger, 1995),
- Process design (e.g., MacCormack 2001) and process improvement (e.g., Spear and Bowen 1999) analyzing the Japanese "Toyota" production system (e.g., concepts of lean engineering and lean management) (Womack et al., 2007)

- Modularity and innovation (Ethiraj and Levinthal, 2004; Fixson and Park, 2008; Hofman et al., 2016; Langlois and Robertson, 1992; Murmann and Frenken, 2006) [27]
- the increasing role of system integration and system integration as a business model (Hobday et al., 2005)

Whereas a great deal of work points to the benefits of modularity such as the reduction of complexity, speeding up innovation, facilitating the division of labor and promoting flexibility, there are also latent costs and implicit tradeoffs (Yoo, 2016). First of all, a modular design must be developed and constructed upfront. This also means that a certain level of uncertainty always prevails concerning the performance of the final system in which the different modules are integrated. “The architects must know a great deal about the relevant tasks and must incorporate their insights into design rules specified long in advance.” (Yoo, 2016, p. 25; Baldwin and Clark 2000, p. 86 supranote 8). Respective knowledge must be codified into generalizable standards and a knowledge infrastructure must be developed that integrates or adapts organizational routines and the configuration of network and exchange relations. The result is a tradeoff between flexibility (an actual aim of strategic modularization) and generality (Yoo 2016). Standards and design rules create conformity and once a standard base is installed, it is often quite volatile (cf. chapter 2.3.5) and can be a constraint for change and the further development of knowledge and technological innovation. From a strategic perspective, component or module interfaces determine the firm’s range of strategic flexibility. They must give enough space for innovation, but at the same time ensure the protection of intellectual property (Ethiraj and Levinthal, 2004); (Baldwin and Henkel, 2015; Henkel et al., 2012). This points to an inherent conflict of objectives that comes along with strategic modularization with regard to knowledge and production relations. This conflicts becomes evident in the need to disclose competitive knowledge and, on the other hand, the strong need for transparency and sharing knowledge.

The major limitation of most of the empirical studies on modularity and strategic modularization is that they do not consider the *transformation* costs arising when a production network is reorganized due to strategic decisions to change the design of the product architecture (Garud and Munir, 2008). This also counts for the case when modularization is strategically implemented top-down in a production network. The efficiency rationale considers modularity as a strategic choice variable and modularization as a strategic process. This perspective cannot explain differing developmental outcomes on different spatial scales. Within the next chapter, modularization is viewed from an evolutionary perspective as an emergent and especially as a path-dependent phenomenon.

[27] It is worthy to note that ‘modularity in design’ fosters incremental, modular often peripheral innovations rather than radical innovations, once a modular architecture has been established as a dominant design

2.4.2 Modularization as an emergent and path-dependent phenomenon

Apart from the micro-decisions of designers and firms to develop and implement modular architectures for strategic reasons, on a macro level, modular industry structures are often described as being the outcome of an *emergent* self-organizing process (Boisot and Sanchez, 2010; Sanchez and Mahoney, 2012) without however specifying how it is indicated in empirical research.

Within developmental systems theory, a process of emergence is one in which “system forms at one level emerge from interactions of components at lower levels as well as interactions with the surrounding environment” as a major generator of emergent evolutionary novelty. (Martin and Sunley 2015, p. 719). Hence, the new system forms or entities exhibit properties not inherent to the entities from which they actually evolve. Self-organization and emergence play a central role in theories of complex systems as well as evolutionary perspectives on industrial development. Both terms are borrowed from evolutionary biology and system theory and are often used as a metaphor to describe socio-economic change. As distinct from a biological system, “self-organization” and emergence in socio-economic systems arise from relationships between individuals (e.g., power relations) relations (Lawson, 2011; Sayer, 2010). In a similar sense, socio-technical systems emerge from the relationships between individuals and the interaction with technological systems applied to achieve a certain goal. The processes of emergence in such systems are reflexive, because actors are aware of the context and environment in which they operate and are able to adapt and modify it to changing conditions and circumstances (Martin and Sunley 2015, p. 723). Considering modularization as an emergent phenomenon, Boiset and Sanchez (2010) suggest that modular industry structures emerge as the result of firm-level managerial choices. Due to network externalities, more and more firms adopt modularity principles, because of the benefits that arise from collaboration with other firms that apply modular principles. “In this way, in product markets in which effective use of modularity bring competitive advantages, modularity may emerge as the dominant logic for economic organizing in an industry.” (Sanchez and Mahoney 2012, p. 22; cf. also Prahalad and Bettis, 1986).

This does however not explain how a modular knowledge infrastructure evolves. Foster (2010) emphasizes that emergence in the social realm is an essentially knowledge-based and knowledge-driven process, since actors combine, select and build upon past knowledge and the knowledge that exists at that time and particular place (Foster, 2011). Henderson and Clark (1990) were the first to show that changes and innovation in architectural knowledge involve significant changes in the way components are linked to each other. These changes deeply challenge firms, because they destroy the usefulness of the architectural knowledge embedded in their organization and routines reflecting the current “dominant design” (Suárez and Utterback, 1995). The modularization of product and process architectures always implicates a change of the existing knowledge infrastructure and the associated knowledge relations in a production network.

Modular industry structures and organizational forms are based on architectural knowledge that diffuses within a given production network and which further evolves into new forms. Consider, for example, its origin in the construction of buildings thousands of years ago to its contemporary application in the design and production of complex cyber-physical systems. This also suggests that modularization is a path-dependent process in which existing technological and socio-organizational trajectories intertwine. “A path-dependent process or system is one whose outcomes evolve as a consequence of the process’s or system’s own history.” (Martin and Sunley 2006, p. 399). This very general concept has been widely applied in different disciplines. In economics, it is mostly associated with technological “lock-in” (Arthur, 1989; David, 1994) (cf. also chapter 2.3.4).

But what does that mean exactly for the configuration of knowledge relations in production networks? How are technological and organizational trajectories intertwined in modular industry structures and their underlying knowledge infrastructures?

The existing literature has described the transformation towards what is referred to as modular industry structures predominantly as a change in industrial organization from the hitherto dominating paradigm of the vertically integrated corporate firm that is based on a centralized authoritarian governance pattern (i.e. hierarchy) to more horizontal, modular, “loosely coupled” production networks. Those “new” organizational forms are indicated by vertical disintegration, the emergence of intermediary markets (Brusoni, 2001; Langlois and Robertson, 1992; Sturgeon, 2002, 2003; Sturgeon et al., 2008) and new industry roles such as system integrators, hub firms, pivot firms or knowledge intermediaries (Gilly et al., 2011; Kechidi and Talbot, 2013). Accordingly, standards are only considered as intermediaries here (cf. chapter 2.2.4) that enable coordination across contexts and places in loosely coupled network relations. Hence, in this stream of literature, modularity is understood as moving activities out of hierarchy (Gereffi et al. 2005). The assumption that modular architectures lead to loosely coupled horizontal production relations and vertical disintegration has, however, been problematized in recent years (Brusoni, 2001, 2005; Sosa et al., 2004) and the “mirroring hypothesis” has been increasingly questioned. Regarding the organization of production relations, Fixson and Park (2008) note that modularization changes the structure of an industry towards higher degrees of vertical specialization (Fixson and Park, 2008), because modularization in design and in manufacturing hierarchizes the system elements and the assemblies that connect them into a whole. In his empirical study, Hoetker (2006) comes to the conclusion that modularity “enhances reconfigurability of organizations more quickly than it allows firms to move activities out of hierarchy” (p. 501). This is not astonishing against the background that modular systems theory is highly influenced by hierarchy theories and the structure of a modular system is based on a nested hierarchical structure of interrelationships (cf. chapter 2.3.1). A more recent empirical study carried out by MacCormack et al. (2012) explores the duality between product and organizational structures through once more testing the “mirroring’ hypothesis.” They compare software products that have basically the same functionality, but a different organizational context. They are either produced by tightly coupled commercial software firms or by only loosely coupled Open Source Software Communities with horizontal exchange relations. The results show that a product's architecture is "not wholly determined by function, but is influenced by contextual factors. The search for a new design is constrained by the nature of the organization within which this search occurs." (MacCormack et al. 2012, p. 1317). This also underlines the importance of embeddedness within specific contexts. The authors conclude that the relation between designs and their development environment have a dual nature. Designs may on the one hand reflect the environment in which they evolve (i.e. Open Source Software and Open Source Software Communities as loosely coupled forms) and on the other hand, they may be the outcome of purposeful choices made by managers and designers (e.g., more tightly coupled forms within commercial firms).

The concept of emergence also highlights both: the role of environment in creating novelty (i.e. system forms at one level emerge from interactions between sub-ordinated components and their interaction with the surrounding environment) and the interactions between system elements. Transferred to the social realm that means the interactions and different decisions of the actors that constitute the production network impact technological and trajectories and vice versa. Thus, modularization is a dynamic process with multi-dimensional consequences that affect: the relations between components within technological artifacts (→ technological trajectories); the knowledge relations and the form of knowledge exchange in design and production relations (→ socio-organizational trajectories).

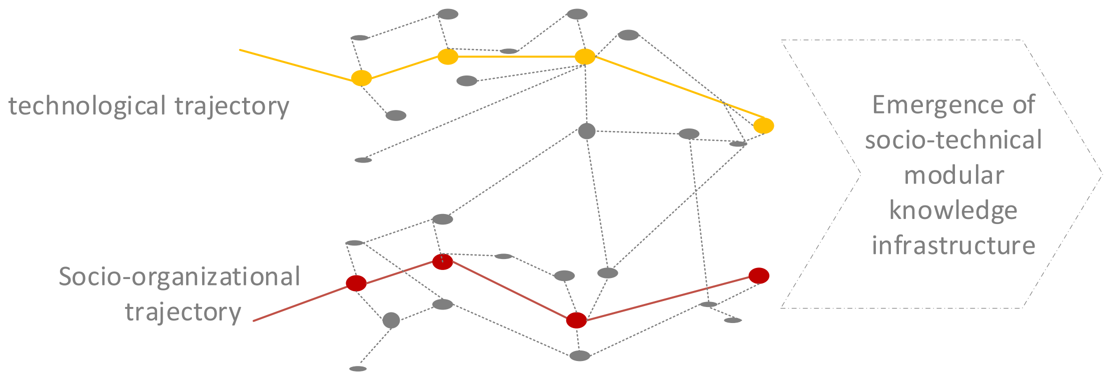


Figure 9: Emergence of knowledge infrastructures

The infrastructure for the transfer and diffusion of knowledge and information comprises digital as well as physical transmission channels. This means that interaction can be embedded in the artifact or the cyber-physical production system (i.e. digital interaction) and/or the relationships between individual actors. Socio-technical knowledge infrastructures in modular production systems emerge from the intertwining between technological and socio-organizational trajectories and the interactions between its elements and the surrounding environment (cf. Figure 9).

2.4.3 Phases of modularization

The aim of this chapter is to combine insights form the strategic and the evolutionary perspective on modularization and identify specific phases and their main characteristics.

From a **strategic and positivist point of view**, modularization can be separated into three main phases. During the **phase of development** knowledge on inner- and inter-systemic interdependencies needs to be codified into common standards on which the modular design relies. This phase is often characterized by competition of different standards and standard languages and the negotiation on consensus on what has to be fixed in a common document and where modular boundaries have to be drawn (cf. chapter 2.2.5). During the **implementation or diffusion phase**, codified knowledge and standard architectures need to be shared and diffuse within the production network (e.g., via coercive pressure by a lead firm and related conformity and compliance measures; via integrative common development etc.). The diffusion depends on the reach and scope of the production network and the configuration of its relations. Since, modularization also implies a reconfiguration of exchange relations within the production network this might lead to organizational discontinuities.

Finally, the new knowledge infrastructure including its technological and codification dimension needs to be enacted and "put in use". During the **enactment phase**, actors that are confronted with this new infrastructure and relational constellation are either adapting to it via learning and modifying, or rejecting it. There might arise conflicts due to different interpretations or the incompatibility with existing conventions and norms.

Table 3 summarizes the key actors and elements of the three phases and gives some examples for illustration.

Table 3: Phases of modularization (Key actors and elements)

Phase	**Key actors**	**Key elements/Outputs**
Development	International Standard setting organizations, industry consortia, lead firms involved in standard setting organizations	Interface and interoperability standards, standard product and process architectures, information infrastructures
Diffusion/Implementation	Regulatory Agencies, consultants, certifiers, lead firms	Certificates, accreditations, audits
Enactment	Lower tier suppliers, local actors	Modifications, adaptations of existing architectures, practices and routines

During each phase, technical, proprietary and organizational interfaces must be harmonized. The three phases might overlap in time (Millerand and Baker, 2010).

From an **evolutionary perspective** and on a more abstract and aggregated level, the literature on global value chains describes the transformation from a relational type of value chain (cf. chapter 2.1.2) to value chain modularity as a process that is enabled by codifying complex information (e.g., through computer-aided design/CAD, process automatization etc.). But it can be also undermined, disrupted or destroyed by what Gereffi et al. (2005) refer to as “de-codification.” “De-codification” is either driven by technological change (e.g., the emergence of optical circuit board assembly in the electronics industry) or the enhancement of supplier capabilities towards crossing the codified link and cooperate in product design and/or customer contact, which are considered to be highly proprietary activities that are intended to remain rather tacit (Gereffi et al. 2005, p. 95f.). Without explicitly mentioning it, Gereffi et al (2005) put the mirroring hypothesis into question. They consider the change of exchange relations in production as an evolutionary process. Phases of codification that enable modular linkages are followed by phases where these codes become obsolete due to technological change. Whereas the transition from integrated to modular architectures implies enormous changes on the relational and institutional dimension, once a modular architecture is established it fosters and enhances, flexibility, recombination and variety within the given system rather than “out of the box thinking” when it comes to the solution of technological problems. From an engineering perspective, these standards temporarily “freeze” solutions concerning interoperability and matching problems (Vries 1999, p. 213). Hence, the “lock-in” situation is created by the knowledge infrastructure, its standard base and its underlying organizational principles.

2.4.4 Summary and conclusions for the further analysis

A large body of literature has evolved throughout the last decades, in order to explain how knowledge and knowledge relations are organized in trans-national industries and how governance structures influence the development of firms and regions. Rather than conceptualizing modular linkages as one type of governance mechanism as in the GVC literature (chapter 2.1.2), it should be considered as a dynamic driver for industrial and economic change in propulsive industries.

Chapter 2.3 has shown that knowledge of product and system architectures is crucial in order to understand socio-technical interrelations within contemporary high technology industries. Modularity as an architectural paradigm and design principle shapes the configuration of global production systems and networks. Modular designs codify the architectural knowledge inherent in complex product and process architectures via interoperability and interface standards. The developed codification schemes are shared throughout the production network and enable more loosely coupled and flexible forms of organizing design/product development and production including decentralized forms of decision-making.

The last two chapters have argued that relational changes on the artifact level are reflected in changes of the knowledge exchange relations and network relations that tie actors together in a global production network, especially, when modularization is strategically implemented top-down. Chapter 2.3.2 has moreover pointed out that knowledge relations and vertical production relations (buyer-supplier, contracting and proprietary relations) are not in any case congruent, hence actors need to oscillate between openness (sharing knowledge) and disclosure (i.e. protecting intellectual property).

Existing literature, however, has not considered the temporal dimension of modularization as a process, which always implicates a change of the knowledge infrastructure. Drawing on literature that examines processes of standard formation, diffusion and enactment and the distribution of knowledge infrastructures (cf. chapter 2.2.5 and 2.3.2) three phases can be identified: development/formation, diffusion and enactment. Integrating the insights form the prior chapter on overall modularization processes, it can be conceptualized in a cyclical model that adapts the three already mentioned phases, which I refer to as modular transition, modular maturity and modular decline (cf. Figure 10). The phase of **modular transition** is characterized by knowledge codification and standard formation and the building of a knowledge infrastructure with far reaching implications for network relations and knowledge exchange relations and the organization of design and production. It is initiated by strategic (i.e.) purposeful decisions of designers and/or managers. This phase is not part of most of the empirical studies on modularization. **Modular maturity** is the phase, which is predominantly described in research in the field of organizational and economic studies. In an ideal setting, socio-technical modular architectures are characterized by loosely coupled relations and rely on a knowledge infrastructure that establishes a "governing through standards" pattern. The architectural knowledge diffuses due to network externalities and modularity emerges as a dominant logic for the organization of design (product architecture) and production (production system architecture). On the one hand, it diffuses due to network and crowd effects, on the other hand adaptation and diffusion can also by forced by coercive pressure of lead firms or private and other regulatory agencies. **Modular decline** describes the phase in which an existing modular architecture (design, industry structure, knowledge infrastructure) either declines and disappears or is transformed initiating another phase of modular transition. This phase might be entered once the limits of technological modularization are achieved[28] or due to technological change and radical innovations. It is characterized by decodification (new technological knowledge that needs to be codified first), but can also be initiated by the enhancement of supplier capabilities towards crossing the codified link and cooperate in product design. This also indicates how technological and organizational trajectories are intertwined and influenced by interactions and strategic decisions.

[28] E.g. when further partitioning and decomposition is not possible or not efficient.

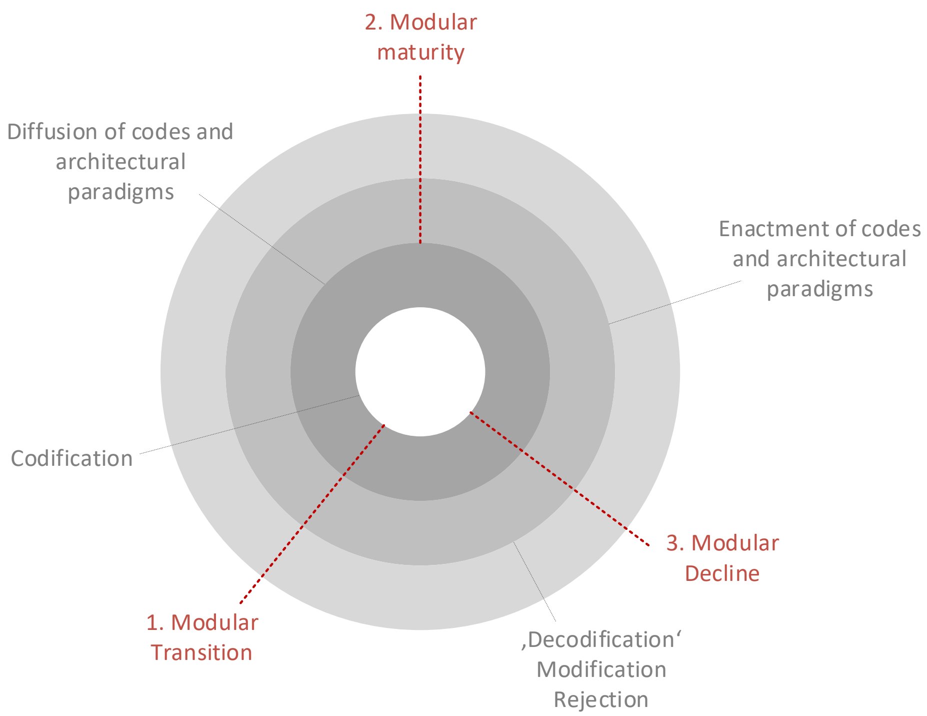


Figure 10: Phases of modularization

Hence, change is the outcome of the decisions of many actors in a production network that are following different strategic interests. This points to the duality of structure and agency and this is also where the strategic and the evolutionary perspective come together, and the interrelatedness between micro processes and macro structural transformations emerges. Product, system and process architectures and their related knowledge infrastructures are designed structures for coordinating and organizing social action (i.e. the design and manufacturing of complex cyber-physical artifacts). They are the outcome of intended design processes, but once established they become a structure or framework for organizing technological, process and network relations affecting the behavior of (economic) actors in turn. Research on modularity should account for this duality of structure and agency in industrial systems.

The focus of the following empirical analysis is on the phase of modular transition, because it is mostly a black box in existing research.

2.5 Modularization and territorial development and change

Based on the insights from the prior chapters (2.1, 2.2., 2.3, 2.4), this chapter collects the different dimensions into a coherent conceptual model that links global modular transition processes to territorial development. It starts with a brief literature review on how territorial development has been explained in the literature on global production networks so far. It is followed by a synthesis of the concepts developed throughout the previous theoretical chapters. The phases of modularization identified in chapter 2.4 are associated with the concept of embeddedness introduced in chapter 2.2.3 and put in relation to respective processes of disembedding and re-embedding. In doing so, territorial development is conceptualized as an emergent phenomenon that relies on phases of disembedding and re-embedding on the artifact/knowledge, the social and spatial dimensions. These processes of disembedding and re-embedding happen on different spatial scales and are, hence, able to display interrelations between global and local development dynamics.

2.5.1 Global production networks and territorial development

In order to explain interrelations between global and local development dynamics two intertwined perspectives dominate the analysis and perception of regional change and development in economic geography. The first one takes a strategic stance and considers economic change as a process of "industrial up-grading" and the second one considers regional economic development as an emergent path-dependent process. Both perspectives will be introduced and connected to the insights from the prior chapters.

Many empirical studies examine local industry clusters and their integration in the global organization of production in terms of **industrial upgrading.** Studies on the economic and social upgrading of regions make use of the value chain approach (cf. chapter 2.1.2), its conception of vertical production relations and typology of governance structures (Dannenberg, 2012; Gereffi and Lee, 2016). The term economic or industrial upgrading refers to "moving up the chain" (e.g., from contract manufacturer to system developers) via product upgrading or different ways of contributing to higher value-added production. It is "the process by which economic actors - firms and workers - move from low-value to relatively high-value activities in global production networks." (Gereffi 2005, p. 171). The term "social upgrading" is defined as "the process of improving the rights and entitlements of workers as social actors and enhancing of the quality of their employment (Barrientos et al., 2011; Gereffi and Lee, 2016), for instance through the adoption of social and social corporate responsibility standards. It also involves increasing rates and wage growth (Bernhardt and Milberg, 2011).

By using the concept of governance, this perspective views processes of upgrading as outcomes of strategic decisions and, hence, as more or less steerable processes. The interest of scholars in this field refers mostly to how functional vertical production relations (e.g., value chains) link places and industries and how knowledge diffuses therein. (Gereffi and Lee, 2016) combine, for instance, concepts of governance as linking and governance as normalizing (cf. chapter 2.2.2) in what they term synergistic governance. They describe processes of economic and social upgrading in GVC and industrial clusters and show how mechanisms of corporate social responsibility governance links global value chains and local industry clusters. (Turkina et al., 2016) also focus on interrelations between global and local dynamics in terms of the evolution of global cluster networks in the aerospace industry referring to value chains (i.e. vertical production relations) as an organizing principle. They find empirical support for their hypothesis that "the global aerospace network has been evolving from a geographically localized community structure toward a trans-local hierarchical community structure that is stratified along value chain stages." (Turkina et al., 2016, p. 1211). Trans-national inter-organizational relations bind together actors located in different places with different responsibilities along the value chain. A rather positivist than structuralist perspective underlies this conception, in which the connection between autonomous actors and processes causes upgrading and economic growth in regions (Henderson et al. 2002; Coe et al. 2008). More recent theoretical work emphasizes that the relational nature of regional economic development also indicates that it is a path-dependent process. This work combines insights from evolutionary economic geography frameworks with strength of the relational approach (Hassink et al., 2012; Hudson, 2007; Hudson, 2008; MacKinnon et al., 2009; MacKinnon, 2011b; Martin and Sunley, 2006; Martin and Sunley, 2015).

Territorial development on a sub-national, local scale is considered as the dynamic outcome of the complex interactions between region-specific networks and global production networks in the context of changing governance structures (Coe and Yeung 2015). Hence, the key to understand economic development is the sub-national region, since economic actors are situated in particular places with different institutional conditions forming development and firm practices (Coe and Yeung 2015, p. 18f). The articulation of regions is, on the hand, constituted by the horizontal and vertical relationships among actors located in the region, but on the other hand influenced by local territorial interfaces of global production networks in that region. Hence, within a global interconnected economy, regional development must be considered as an interdependent and relational process (Coe and Yeung 2015, p. 168). Regional territorial embeddedness and networks and their intersection with vertical network relations to GPN must be both taken into account, in order to be able to capture the multi-scalar nature of regional development (Yeung, 2005). Martin and Sunley (2006) argue that the place dependent nature of relations is an important aspect of path-dependence. Which means that regional development is a path-dependent process (MacKinnon et al., 2009; MacKinnon, 2011a; Martin and Sunley, 2006).

> *"Path dependence (…) can itself be viewed as an emergent property of the economic landscape, while at the same time acting as a key mechanism by which the spatial forms of that landscape themselves emerge. The*

> *issue, however, is how 'strong' that path dependence is, and what the relative roles are of low-level components (firms, institutions), and higher-level (regional) emergent forms and processes." (Martin and Sunley, 2015, p.723)*

Within the relational GPN analysis path dependence and regional development rely mainly on "strategic coupling" (MacKinnon, 2011a). **Strategic coupling** is understood as a process that occurs when complementary effects between regions and GPNs enfold over time. A firm (within a region) has, for instance, strategically coupled with a broader production system, when it has established stable exchange relationships with other actors in the GPN. From the perspective of the actors, it is an intentional process, which also indicates that resulting relations(hips) are time and place specific, instead of entirely generic or deterministic (Coe and Yeung 2015, p. 171). According to this argumentation, regional development and change relies on a process of coupling (and decoupling) to the rapidly changing strategic needs of GPN and the rather slow changes in regional economies. Regional institutions play a significant role in negotiating and promoting both regional assets and advantages as well as the region's coupling and integration into broader structures of GPN. These regional institutions must not be necessarily located there, they can also take the form of extra-local institutions that function as intermediaries between GPN and particular local spaces (e.g., standard setting institutions).

Thought of in evolutionary terms that means that regional development is "shaped by periods of strategic coupling in sequence with phases of decoupling and subsequent recoupling. " (Coe and Yeung 2015, p. 20). It is important to note that the fact that a region is coupled to a GPN does not mean that positive (regional) development is guaranteed, since strategic needs of GPN are subject to change and regional assets can sometimes not cope with these changes. Hence, there are "dark sides" of coupling and phases in which frictions and tensions between GPN actors and local firms and institutions are likely to occur, because GPN do not operate in isolation from broader social relations their national and macro-regional embedding (Coe and Yeung 2015, p. 170). MacKinnon emphasized in empirical studies on resource economies that the balanced process of strategic coupling depicted in the GPN literature does not account for more unbalanced forms of what he refers to as "**structural coupling"** (MacKinnon, 2013). Global production networks do not only connect firms functionally (i.e. integration into the value chain). Based on their territorial embedding they also connect to respective aspects of social norms and technical conventions and the values, priorities and expectations of actors and the communities they are embedded in.

> *"The ways in which the different agents establish and perform their connections to others and the specifics of embedding and disembedding processes are to a certain extent based upon the 'heritage' and origin of these agents." (Henderson et al., 2002, p.451)*

In summary, the notion of *strategic* coupling emphasizes, first of all, the intentional nature of actions and interventions of GPN actors as well as regional organizations. Secondly, it emphasizes the time-space contingency, since constellations between local and non-local actors are temporarily and subject to change; and third, the transitive nature of territorial development, because actors from different spatial scales interact (Coe and Yeung 2015, p.20).

In order to understand the dynamics of regional development, empirical research should focus on periods of change rather than periods of relative stability, meaning periods when existing ties and routines are disrupted and reconfigured and frictions and discontinuities are likely to occur (footnote 32, p. 30, cf. also Coe and Hess 2011). Moreover, the results of regions coupling with GPN require examination in particular industries and localities (Coe and Yeung 2015, p. 170).

2.5.2 Socio-spatial disembedding and re-embedding of knowledge and production relations

The processes initiated by the implementation of strategic modularization can be considered as such a period of change that is characterized by decoupling and recoupling or disembedding and re-embedding. Within this chapter the cyclical phases of modularization identified throughout chapter 2.5 are linked to the concept of embeddedness and processes of relational dis- and re-embedding on different dimensions and how they initiate and constitute territorial development.

Giddens (1990) considers the process of disembedding as one in which social relations are disconnected from their original localized context of interaction. He describes globalization as a process of socio-spatial disembedding of market transactions and interpersonal trust relations (cf. also Polanyi 1977). The basic mechanisms behind this process are the creation and establishment of symbolic tokens and expert systems or in other words the codification of expert knowledge into common code systems “on which actors rely and in which they put their trust.” (Hess 2004, p. 175). This makes systemic trust (cf. chapter 2.1.4) a key characteristic and indicator of a disembedded economy (Giddens 1990, p. 119). According to this view, in a disembedded economy interpersonal trust has become *de-localized* (Hess 2004, p. 175). Chapter 2.1.3 has shown that there are also non-local forms of embeddedness such as network embeddedness. Processes of disembedding on one dimension can simultaneously enact processes of re-embedding on another. Hess (2004) suggests that the three proposed dimensions of embeddedness need to be considered over time integrating changes in the socio-spatial configuration of networks on different scales (cf. also Amin 2002, p. 387; Yeung 2002, p. 5f.-6). Hence, the dynamic aspects of embedding and disembedding processes need to be considered. This requires for a relational concept of place and space (Dicken and Malmberg, 2001) that considers knowledge and production relations as “dynamic topologies of practice that link different places and territories.” (Hess 2004, p. 178, Amin 2002). Taking into account the multi-scalarity of embeddedness and its development over time, global production networks link places via relations of embedded actors and institutions that change in scope and shape over time (Hess 2004). In this sense, globalization also involves a process of re-embedding into or building trans-local networks at various multi-dimensional and interrelated scales (Henderson et al. 2002; p. 451). Hence GPN connect and integrate actors in various ways (Hess 2004), such as functionally (vertically and task-dependent), territorially, and socio-spatially, since they also connect to arrangements in which actors are embedded and that have an impact on their strategies and actions.

For instance, positive effects for value creation that arise from the co-location and anchoring of external firms in a specific location may create regional advantage through processes of embedding local actors, but they may involve a stronger disembedding of network relations of actors in other regions (Amin and Thrift, 2001; Grabher, 1994; Scott, 2000).

In order to support the formation of new nodes, national and local policy strategies can aim at embedding larger actor-networks in their region (through tax advantages, common trade standards etc.), this does however not guarantee the positive impact of embeddedness in regional development. A lead firm in a local network can cut its ties or, as in the case of modularization, change the network structure and, hence, network embeddedness of production and knowledge relations, which always involves processes of disembedding from former contexts and relational constellations and processes of re-embedding into new ones (Hess 2004). The interrelating proportions of different types of embeddedness produce, bridge and reduce distances among actors and regions and also require for different forms and levels of trust. These inter-dimensional links between processes of dis- and re-embedding provide valuable insights into the structures and dynamics of change that characterize contemporary industries.

2.5.3 Synthesis: Conceptual model and research question

This chapter integrates the concepts and dimensions developed in the precedent paragraphs into a coherent model displayed in Figure 11 and 12 and derives the research questions arising therefrom.

Modular network relations are enabled by codified architectural knowledge and rely on a specific knowledge infrastructure. The “infrastructure” for the transfer and diffusion of knowledge and information is increasingly realized via digital channels that are already inscribed in the cyber-physical artifact and the processes used to create it (e.g., computer-aided design software, RFID-chips in components, automated production processes).

Figure 11 illustrates the inter-dimensional embeddedness of modularization during different phases of modularization (cf. chapter 2.4.3). During the phase of **modular transition** knowledge is codified and architectural and process standards (i.e. interoperability and interface standards) are developed. Codes and architectural paradigms increasingly diffuse within the production network. Both processes and practices depend on the specific network, social and territorial embeddedness of knowledge and production relations. The codification of knowledge and its formation into standards are place-specific. The codification of routines and expert technological knowledge can take place locally or in trans-local networks etc. The diffusion of codes depends on the nature of relations as well as the structure of the network actors are embedded in.

During the phase of **modular maturity**, codes and architectural paradigms are enacted by actors that adopt them voluntarily or on which those expert rules/standards are enforced. This again directly depends on the embeddedness into the structure of the production network and the nature of its previous exchange relations. With regard to the enactment, the social or socio-spatial embeddedness plays a significant role. Enacted codes (or enacted artifacts) refer to how they are perceived, conceived and applied in particular contexts (cf. also chapter 2.2.6 on knowledge infrastructures). The way in which actors are engaged in standard development/knowledge codification and enact technological standards depends on the socio-cultural and institutional structures they are embedded in. These organizational arrangements of routines, conventions, standards and norms, mediate the development of standards on the one hand, and contribute to the reconfiguration of the socio-spatial organizational arrangement on the other hand. Accordingly, during the phase of **modular decline**, codes are modified and/or rejected or "decodification" takes place due to technological innovation or enhanced supplier capabilities (cf. chapter 2.4.4).

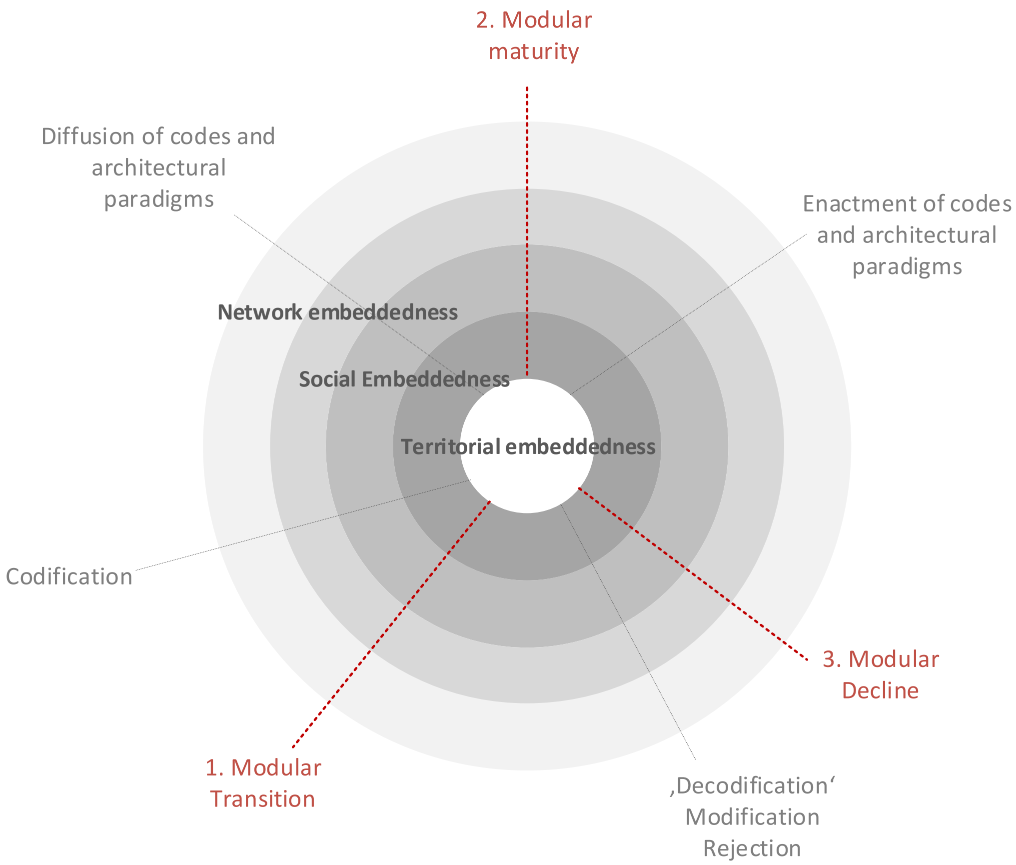


Figure 11: The inter-dimensional embeddedness of modularization processes

In conclusion, the previous chapters have conceptualized territorial development as being shaped by the complex interactions between region-specific networks and global production networks. Regional change and development rely on phases of dis- and re-embedding to GPN creating path-dependent trajectories that are, however, always to be viewed in their specific spatio-temporal context. This understanding has been associated with different types of embeddedness (territorial, social, network) and processes of dis- and re-embedding on the different dimensions that constitute a production system (cf. chapter 2.5.2). It is during **periods of change**, when existing ties and routines are disrupted and reconfigured and frictions and discontinuities are likely to occur. The processes initiated by the strategic implementation of modularization on the GPN level can be considered as such a period of change. By altering the socio-technical knowledge infrastructure, it also alters socio-organizational and place-dependent development trajectories (cf. chapter 2.4.2).
The following figure integrates the insights from the preceding chapters into the conceptual model around which the following empirical analysis is framed.

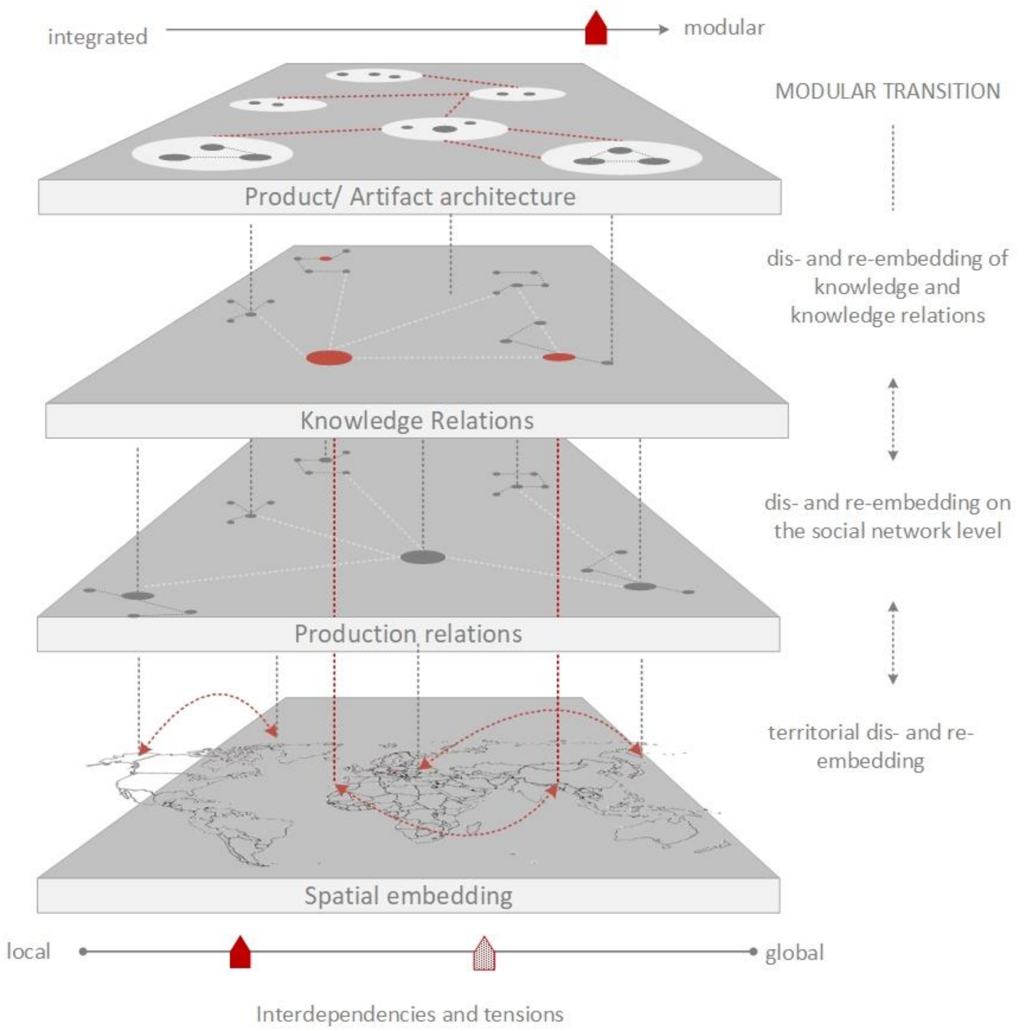


Figure 12: Multi-dimensional dynamical conceptual framework

Figure 11 and Figure 12 conceptualize modularization as a temporal multi-dimensional process that has different geographies (spatial manifestations). Modularization is enabled by a specific knowledge infrastructure. The dimension of the artifact (i.e. its architecture) and the dimension of knowledge and production relations of the production system are both affected by modularization via processes of dis- and re-embedding. What is unknown in this context is how these processes affect territorial development and are reflected in space. The following overall research question can be derived from that premises: How does the development of a global knowledge infrastructure during modular transition affects a local industry cluster?

3 Case study of the *Airbus* production network and the aerospace cluster in the Metropolitan Region of Hamburg

3.1 Introduction and methodological approach

The previous theoretical discussion demonstrated that processes that connect global and local development processes are multi-dimensional and highly complex. Modularization is a phenomenon that underlies socio-technological change. It is becoming increasingly important due to the increasing digitization of artifacts and production systems towards cyber-physical systems that rely on a specific modular knowledge infrastructure. Existing theoretical models and explanations do not fully capture the phenomena especially not regarding its temporal dimension and procedural character.

The interaction between different dimensions and the temporal dimension of the phenomenon of modularization cannot be explained within a hypothesis testing quantitative approach. Instead qualitative data are able to offer insights into complex social processes (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). "Process studies take time seriously, illuminate the role of tensions and contradictions in driving patterns of change, and show how interactions *across* levels contribute to change." (Langley et al., 2013, p.1) Setting the focus of interest on dynamic processes and relations demands for rich empirical data sets and case study narratives (Boggs and Rantisi 2003, p. 112). Moreover, a vast amount of literature on knowledge and knowledge processes neglects the content of what is actually known and learned. It operates with fuzzy distinctions of tacit and explicit knowledge without further grounding them in empirical phenomena. Social science, and anthropology in particular, offer a lot of qualitative methods that can meet the needs of a dynamic relational analysis in Economic Geography (Yeung 2002, Boggs and Rantisi 2003, p. 114f.) and build theories from cases that are grounded in empirical phenomena (Eisenhardt, 1989).

The methodological approach which has been applied here stands in the tradition of empirically grounded theory building (Corbin and Strauss, 2015). The grounded theory approach is based on an iterative, interpretative research methodology (Lincoln and Guba, 1985). This type of qualitative heuristic is characterized by four main principles specifying the relation between researcher and research object (Mey and Mruck, 2010): the researcher must be open and prepared to change his or her perceptions about the topic if necessary; the research topic may be subject to change during the exploratory research; the perspectives (collected) must vary structurally as much as possible during the phase(s) of data collection, so that the researcher can view the topic from different angles; the data are analyzed for common patterns.

The main feature of GT is that the representation of data analysis and theory building are considered to be practical, interactive tasks the researcher has to carry out. GT emphasizes the simultaneity and reciprocal functional interdependency between the processes of data collection, analysis and theorization (Strauss, 1991). None of these processes is considered ever to be entirely completed, since theory is considered not to be the final end of a research process, but is constantly produced and in flux (ibid.). Choosing a GT approach also means being able to cope with the insecurity of unforeseen results or the more appropriate German term of *Ergebnisoffenheit* (literally, “openness to results”). In his very enlightening article on “What grounded theory is not”, Suddaby (2006) recognizes that “grounded theory is often used as a rhetorical sleight of hand by authors who are unfamiliar with qualitative research and who wish to avoid close description or illumination of their methods.” (p. 633). There exist, indeed, some serious misconceptions about grounded theory, especially when applied in fields outside of its origins (Kruse, 2014; Suddaby, 2006).

One of the major challenges that researchers are facing when they choose to apply GT or building theories from empirical data drawn from case studies is that the empirical project cannot be – or only in an artificial way - sequentially presented in publications (Eisenhardt and Graebner, 2007; Kruse 2014; Suddaby, 2006; Strübing 2014). The iterative cycles of data collection, analysis and theorization are actually opposed to the tradition of linear presentation of research results in the dominant nomological-deductive approach that takes the form of a block format. The “block format” that is typical for classical research publications is conventionally organized in the following passages: 1) Introduction, 2) Problem/State of the Art/Research Question/Research Aim. Chapter 3) usually entails a detailed theoretical paragraph, followed by 4) Methodology/Research Design and 5) the Empirical Part containing the presentation and discussion of research results with regard to the theoretical claims formulated in the initial theoretical chapter. This “block format” linearizes the documentation of the research process and is based on an understanding of empirical research as a linear epistemological process. A lot of qualitative studies adapt that linear presentation of results and the research process, mostly in order to increase clarity and readability for its recipients (Kruse, 2014).

Although it might tell the story of the emergence of the theory and the research process in a more realistic way, I also decided to suspend the interpretative reporting hallmark here, which is characterized by exhausting and complex qualitative data representations, before it becomes clear to the reader what the core categories and theoretical dimensions actually are (Suddaby, 2006). This decision, however, inherently includes some implications that I would like the reader to keep in mind throughout the rest of the text. From the framing of the introduction to the theoretical and conceptual overviews, I already employed theoretical concepts and causal relations that actually evolved from the study itself including consultations of literature considered to be relevant in the course of the emerging thematic analysis (Suddaby 2006). The same counts for research questions and research design that evolved and have been concretized during analysis and the application of heuristics and methods that where most likely to provide results to generative questions and hypotheses. Hence, data collection has not been purely guided by prior (theoretical) knowledge; instead theoretical frameworks, data collection and analysis have been carried out in iterative interpretative cycles. This might be mistaken by readers not so familiar with qualitative interpretative research approaches as a weakness and lack of quality and reliability, but is in contrast one of the particularities and strength of explorative qualitative research and grounded theory building (cf. chapter 3.1.2). Nevertheless, for the sake of advancing clarity and readability, the results are presented in the conventional “block format” that roughly structures this document. Therefore, after this brief unconventional cut, I will continue in the format the reader is most likely to be accustomed to.

The present study is built around an explorative **single case study** of the *Metropolitan Region of Hamburg* and its wider embedding in the *Airbus* production network. Qualitative research and building theory from case studies (or the methodology of grounded theory building) is often accused to lack reliability and validity. In order to make clear, how I came to conclusions throughout the analysis I will first introduce the case and review the existing literature and insights on the civil European aerospace industry, the *Airbus* production network, as well as the local aerospace cluster in the *Metropolitan Region of Hamburg* (**chapter 3.1.1**). I will, secondly, clarify the main principles of GT building and how they have been combined with a case study design strategy (**chapter 3.1.2 and 3.1.3**) and define the selection and boundaries of the case example (**chapter 3.1.4.**)

Throughout **chapter 3.2** I will explain the main steps of my analysis, in order to strengthen intersubjective comprehensibility and plausibility of the results by explaining how the analysis and research questions have been operationalized and units of analysis have been defined referring to the different dimensions and categories that have been identified in the conceptual model. The analysis and research questions are operationalized in different methods and heuristics including semi-structured, narrative interviews, semi-overt as well as participant observation, the collection and analysis of documents, technical data and standards documents (chapter 3.2.1). In **chapter 3.2.2** I explain how the heterogeneous data have been analyzed combining the technique of artifact analysis, techniques used to display and spatially map production networks, as well as the coding and grounded theory building process using the Software ATLAS t.i. **Chapter 3** concludes with some remarks concerning the reliability, validity and scope of results.

3.1.1 The *Airbus* production network and the aerospace cluster in Hamburg as a heuristic single case study

The aerospace industry is a high technology industry and a key sector for technological and organizational innovation bearing a high strategic relevance although it is relatively small compared to other industries. High innovation dynamics are decisive for its international competitiveness and other sectors increasingly recognize its innovative potential and integrate successful approaches (Hinsch and Olthoff, 2013). Since the 1970s the European Aerospace Industry is organized around the lead firm *Airbus* that today coordinates an increasingly global network of production relations connecting firms and regions with one another. The creation of *Airbus* is the result of a consortium of the leading European Aerospace Nations (UK, France, Germany, Spain, Italy) and the intention of European politicians to establish a counterbalance to the strong US aerospace industry. All nations involved in the consortia tried to push participation of their firms, which resulted in a quite fragmented industry structure and a very high number of SMEs that formed regional and inter-regional supply bases around the supranational enterprise from the 1980s ongoing (Acha et al., 2007; Anderssen et al., 2008; Turkina et al., 2016; Wink, 2010). Hence, the *Airbus* production network is also the outcome of European economic development and integration policies.

The aerospace industry can be split up in three main sectors: air travel, military air travel and space travel. The aerospace industry covers the design and manufacture of air and spacecraft related machinery and systems. The given analysis focuses on the civil aerospace manufacturing industry as the largest segment of the overall sector. This part of the industry is dominated by two major players: *Airbus* in Europe and *Boeing* in the US. Within the last decade the powerful duo is, however, facing a growing competition from Canada (Bombardier), Brazil (*Embraer*), Japan (Mitsubishi Heavy Industries), China (Comac) and Russia (Sukhoi, Irkut) especially in the domain of short and medium haul aircrafts. Moreover, India and the UAE are forcing the development of their own independent aerospace industry including R&D and production sites.

The civil aviation industry is characterized by a high degree of complexity that is embodied in the final product and comprises a wide range of components (e.g., propulsion and navigation systems) that are each extremely complex and need to interact in the final product leaving an overall pervasive technological uncertainty that always remains in aircraft design (Acha et al., 2007).

From a technology and knowledge-based perspective, technological changes have mainly occurred in airframe and propulsion technology. The shift from piston to jet engines (initially developed for military use during WW II) in civil aircrafts in the 1960s can be considered as a major technological shift. This more complex technology also resulted in considerable changes that affected the entire sector including the establishment of an industry consortia for jet engines that served as a basis for the formation of a unique sector within the industry (Dosi, 1982; Frenken and Leydesdorff, 2000). This technology is still used today though several efficiency-oriented incremental innovations have been made reducing fuel consumption considerably. Other major technological changes have come along with the increasing integration of avionic (i.e. electronic) devices and embedded systems. In the absence of *radical* innovations, engineers continue to optimize and improve existing core technologies and processes for instance by using new materials and manufacturing technologies or integrating more and more electronic equipment in every domain of the aircraft. The aerospace industry is also an industry that relies highly on codified knowledge. In 1987 an extensive study carried out by Boeing contested that 39% of all engineering data and 38% of all manufacturing data in aircraft design, manufacturing and maintenance is derived from standards (AIA, 2005). Due to processes of globalization and an increasing modularization of the product and production system architectures, the number of standards has increased dramatically since then and it takes a couple of thousands of standards to define an aircraft and to monitor and control all the engineering and manufacturing processes involved in building and maintaining the product. Most of these standards are based on other standards, leading to the fact that a single standard rarely is a "stand-alone technical document". Instead each standard is part of a larger "web of technical information." (AIA, 2005, p.10). Against this background, there have been some major shifts and transformations in standard formation in the aviation industry in the last 10 to 20 years. Three major trends can be identified. First, there exist an increasing need for consistent global standards (creating new and harmonizing existing standards) and in the course of European economic development and integration policies, there is an increasing demand for common European standards. Second, the increasing modularization and integration of different technologies and knowledge bases into aircraft design and manufacturing (especially IT and new hybrid materials requires for new standards and cross-sectoral collaboration in standard setting activities. Third, one can observe and increasing privatization and profit orientation of standard setting activities and regulatory organizations.[29]

From an organizational perspective, firms in this sector rely strongly on inter-firm collaboration (vertically as well as horizontally) and the organizational structure is characterized by a high rate of sub-contracting along the supply chain due to the general complexity of aircrafts (Cagli et al., 2012; Niosi and Zhegu, 2005, 2010a, 2010b). Accordingly, at the top of the industry stand lead firms such as *Airbus* or *Boeing* that have specialized in system or so called architectural integration and the orchestration of the supplier network (Kechidi, 2013; Kechidi and Talbot, 2010). The (design) and production of major sub-systems such as propulsion systems (i.e. engines) and avionics has been outsourced to sub-contractors referred to as system or first tier suppliers (Ehret and Cooke, 2010). A more recent study from (Turkina et al., 2016) examined the evolution of global cluster networks in the aerospace industry identifying value chains as an organizing principle. They find empirical support for their hypothesis that "the global aerospace network has been evolving from a geographically localized community structure toward a trans-local hierarchical community structure that is stratified along value chain stages." (Turkina et al., 2016).

[29] Please note that the case study focuses on and is limited to standards that are involved in the design and manufacturing of aircrafts *not* including air traffic control or logistics standards.

The present case study focuses on the production network that has formed around *Airbus* (former *EADS*) as the focal company in design and manufacturing of aircrafts in Europe. The technological innovations as well as the scientific progress in various fields that have historically marked the evolution of the *Airbus* programs (from the A300 in the 1970s to the A380) have also, at each stage, provoked profound modifications in the product and system architecture that required for changes in the industrial organization and *Airbus*' relationships to its sub-contracting firms (Kechidi, 2013). This also affected the division, flow and governance of knowledge and information in the production network. In the „traditional" production process jet engines were basically the only segregated and specified parts (i.e. modules) outsourced to specialized „system suppliers" (Acha et al., 2007; Frenken and Leydesdorff, 2000). These firms (for instance Thales or Liebherr in Toulouse) have been also conceptualized as hub firms that take the role of knowledge intermediaries in terms of territorial innovation (Gilly et al., 2011). Thus, until the 1980s, the selection of suppliers has been mainly determined by geographical proximity as well as political pressure to source in a certain region or country of location (Benzler and Wink, 2010) due to the high political influence exercised by national governments. Initial patterns of modularization already took place in the period from 1987 (launch of the A330-340) to the mid1990s. It was during that time that *Airbus* carried out a "systemic rationalization" based on the decomposition of the aircraft technologies into subsystems (Kechidi and Talbot, 2010), which allowed *Airbus* to define a supplier network based on knowledge and expertise as an answer to the increasing heterogeneity of different technologies and scientific fields. In the following, the knowledge base/expertise became an important criteria of supplier selection marking a fundamental turn from a technical division of labor to a more cognitive division of knowledge (ibid., p. 92) and a more "knowledge-focused" globally oriented sourcing process that has a strong impact on the organization of the industry.

With regard to complex cyber-physical systems such as aircrafts knowledge from different scientific areas and technologies comes together. The integration of different technologies and areas of expertise (e.g., electronic, mechanical and software engineering) results in a growing integration of different markets (Hobday et al., 2005). Thus, the integration of different systems might also increase the demand for common standards and challenge standardization (Vries 1999, p. 214). And since standards diffuse geographically and temporarily, we might also observe a shift from national to regional (e.g., EU) and transnational/global standards addressing problems of spatial, economic and political integration and the increasing globalization of production (Vries 1999, p. 216).

From a **purchasing (though proprietary rather than organizational) perspective**, *Airbus* is the prime contractor (often referred to as *prime*), who directly contracts with the so-called first tier suppliers. They consist of large globally active engine and system suppliers (e.g., Rockwell Collins, Pratt& Whitney, Daimler etc.), with whom strong ties have to be developed and capital expenditures as well as development costs and risks have to be shared. They, in turn, contract with second tier and n-tier suppliers (i.e. component manufacturers, engineering service providers etc.) (Acha et al., 2007). In the management literature, this organizational model is referred to as the "Tier 1 Model". It has been pioneered by Bombardier in the aerospace industry during 1990s and is inspired by lean management approaches and organizational models developed within the automotive industry (Womack et al., 2007). Many firms in the aerospace industry employed executives from automotive supply chains in the 2000s who reduced the number of suppliers drastically (e.g., Rolls Royce, *Boeing*).

The aerospace industry can be characterized as a very technology and knowledge intense sector with high R&D intensity, technological complexity, long lead times and steep development costs, long product life cycles and very high market entry barriers. An additional particular feature of the industry is the high influence of governmental institutions which exercise regulation, hold ownership or act as customers (Alfonso Gil and Chronicas, 2007) as the development of the European sector illustrates. During the 1990s and 2000s, the industry has been altered by several crises, consolidation waves, integration processes and a still ongoing global reconfiguration process. The current industry structure can be characterized as spatially distributed hierarchically organized pyramids with lead firms and first tier suppliers at the top (Acha et al., 2007).They interact in the institutional frame of the EU zone, but are each also embedded within national and sub-national institutional structures. The direction of innovation within the industry can be restructured through radical changes in technology (e.g., from piston to jet engines), market structure or changes institutional design and organization (e.g., from integrated to modular organizational forms) (Hartley, 2015; Turkina et al., 2016).

Finally, from a spatial perspective, aerospace manufacturing is agglomerated in only a very limited number of countries and regions due to the fact that it implies a high degree of technology, engineering and innovation, highly qualified personnel, long product development and production times as well as capital intensive production facilities (Niosi and Zhegu, 2005). A recent study carried out by Turkina et al (2016) identified 52 aerospace clusters in Europe and Northern America based on data from the global cluster observatory for the periods of 2002-2005, 2006-2009 and 2010-2014. Nevertheless, the development of growing industry structures in Brazil, India, Russia, China and Japan also indicates an increasing global distribution.

The Metropolitan Region of Hamburg is today estimated to be third largest location of the civil aerospace industry in the world. It hosts the focal companies *Airbus* Deutschland GmbH and Lufthansa Technik AG, several associations, research institutes, as well as about 300 small and medium-sized companies (SMEs), which are linked both vertically and horizontally with one another. Although Hamburg gained its economic importance and popularity because of its harbor and the shipping industry, aircraft manufacturing has a long tradition in the region of Hamburg starting as early as 1933 with the production of seaplanes by a local shipyard company. Interrupted by World War II, Hamburg managed to regain its status as an important location for aeronautics with the beginning of the bi-lateral

Franco-German *Airbus* program in 1969, when *Airbus* installed a plant in Finkenwerder (Köpke, 2008; Kunkel, 2010). Due to political pressure of the German government in the 1980s the site managed to become the location for the second final assembly wharf followed by an increasing specialization in cabin interior that attracted new investments and suppliers in these areas (Benzler and Wink, 2010).

The firms and institutions agglomerated in the aerospace sector in the *Metropolitan Region of Hamburg* are supported by the City of Hamburg and promoted through several national cluster promotion strategies. One of the outcomes of these policy efforts is the establishment of the cluster management institution *Hamburg Aviation* e.V. [30], which aims at strengthening the common identity of local industry actors, raising (international) public awareness of the location and overcoming lacks in qualification and R&D (Benzler and Wink, 2010). The public-private partnership association has formed around the focal companies *Airbus* and Lufthansa Technik AG, several SME associations, research institutes and universities. According to estimated numbers of *Hamburg Aviation e.V.*, the regional aerospace industry employs between 36,000 and 40,000 people and can therefore be considered as the third largest cluster of the aerospace industry in the world after Seattle (*Boeing* Headquarters) and Toulouse (*Airbus* Headquarters) (Bräuninger et al., 2010).[31] The particularity of the Hamburg cluster is that it is closely connected to the cluster in Toulouse via the lead firm *Airbus*. A strong division of labor as well as strong cooperation relationships between the two sites have been established throughout the decades (Bräuninger et al., 2010). According to studies from the HWWI from 2010 and 2012 the aerospace industry in the *Metropolitan Region of Hamburg* is growing fast (Biermann et al., 2012; Bräuninger et al., 2010)

***Airbus* and its relations to the regional supply base in Hamburg**

The large base of small and medium sized firms in the *Hamburg Aviation* cluster is organized around a few large globally active companies (i.e. *Airbus* and LHT). This structure is typical for a lot of aerospace clusters in which the firms that take an integrating role (e.g., *Boeing*, *Embraer*) are surrounded by a high number of heterogeneous small and medium-sized so called tier 3 and tier 4 suppliers (Niosi and Zhegu, 2010b). These actors have only limited resources and potentials for research and development, internationalization strategies and the integration of partners and complementary knowledge bases (Pfähler et al., 2003). All the big system suppliers are in close geographical proximity to the *Airbus* headquarters in Toulouse (Benzler and Wink, 2010). Whereas *Airbus* holds various interactions with different firms in its role as a dominant integrator of knowledge, collaboration among other firms in the Hamburg cluster is relatively weak. Although actors of the production network complained about these

[30] http://www.hamburg-aviation.de/start.html

[31] Numbers differ however, and I estimate the number to be lower, since temporary work contracts among engineers are increasing, and moreover personnel service providers and secondary employment in the cleaning and overall logistics sector have been included in the estimations.

"weak knowledge competencies", suppliers at the local site in Hamburg mainly focused on establishing direct linkages to *Airbus* in the past (Benzler and Wink, 2010; Lublinski, 2003).

Even if a production network is basically dominated by the actors that take an integrating role (i.e. *Airbus*), the internal behavior is considered to be organic as the regional networks have evolved over time (Anderssen et al., 2008). Close, long-term personal relationships building on a high level of cognitive proximity, interpersonal trust and mutual dependence have been characteristic for the constellation in Hamburg (Benzler and Wink, 2010; Wink 2009). Orders came *directly* from *Airbus* to its diverse suppliers without passing through numerous sub-contractors. It was a "classical subcontracting situation where firms functioned as external workshops supplying components according to the detailed design provided by the manufacturer" (Kechidi, 2013, p. 12; cf. also Acha et al. 2007).

In terms of knowledge diffusion and the willingness to share knowledge, it is worth noticing that aeronautics and military use and research and development activities are historically strongly intertwined leading to a strong influence of the state, not only as a customer, but also as a shareholder (Benzler and Wink, 2010). Military use requires for restrictive rules for knowledge disclosure and secrecy. This particularity can be considered as a major motivation of producing companies to keep R&D activities in-house and establish personal idiosyncratic linkages with their suppliers (Alfonso Gil and Chronicas, 2007) until the mid-1990s. Consequently, R&D and production was characterized by a strong control of knowledge and knowledge flows, particularly on the system level, which has been realized strategically, for instance, by spatial concentration and co-location (Benzler and Wink 2010). Thus, creating geographical proximity has been a crucial mechanism in terms of knowledge governance.

In summary, the region is plugged into the increasingly global production network of aerospace manufacturing via the anchor company *Airbus*. The regional cluster is subject to promotion and subsidization from cluster policy strategies and public funds of the senate in Hamburg. Against the background of the results of the analysis these must eventually be reconsidered and put into question. From a pragmatic/practical perspective, the case study can thus contribute to a deeper understanding which circumstances, framing conditions and influences determine regional changes in the aerospace supplier industry in northern Germany (*Metropolitan Region of Hamburg*).

3.1.2 Grounded theory as an interpretative, explorative approach

Within the last four decades Grounded Theory (GT) building has evolved into one of the most wide spread procedures within qualitative-interpretative social research (Strübing, 2014). Grounded Theory is less a prescriptive procedure than a conceptually densified, methodologically grounded and consistent *collection of suggestions*. Thus, the notion of "theory" distinguishes vastly from other approaches. Theory is understood here as a permanent process of "theorizing" or as Glaser and Strauss put it: "The published word is not the final one, but only a pause in the never-ending process of generating theory." (Glaser and Strauss, 1967, p. 40) Hence, a theory is considered as a temporary fluent reification. The moment of its formulation constitutes at the same time the starting point for new theories to be developed (Strübing 2014, p. 5). The process of theorization and the epistemological foundation of GT is based on a permanent iteration of induction, abduction and deduction.

Thus, GT suggests a mediation between theory and empirical data. Geography is and always has been a deeply empirical science; the grounded theory methodology can be one way of bridging the gap or facing the dualism between theory and practice after the cultural turn (Geiselhart et al. 2012), although it until now it has failed to find its way into many curricula in the field of human geography. According to a pragmatic epistemology, GT develops theories and knowledge always with regard to a specific context, which renders them rationally and empirically grounded. They are contingent and path-dependent and therefore not at all arbitrary. Theories shall grow, be integrated or viewed from different angles, without losing its ground with regard to social problems and situations. Hence, the resulting theories must always be viewed in light of their specific socio-political context and shall ideally be a reference point for involved actors for enhancing understanding as well as problem solution (Geiselhart et al. 2012).

The main feature of GT is that the representation of data analysis and theory building are practical, interactive tasks the researcher has to carry out. None of these processes is considered ever to be entirely completed, since theory is not the final end of a research process, but is constantly produced (Strauss, 1991). This liberal understanding of methodology that underlies Strauss's understanding of GT does not provide the formulation of a rigid set of rules for analytical procedures, but instead provides suggestions from which researchers can develop their own practices with regard to their specific research context, individual work flows and personal experiences (Strauss 1991, p. 33). This liberal understanding should, however, not be misunderstood as a "carte blanche" for "anything goes" (Strübing 2014, p. 14).

The role of prior knowledge

Some disagreements and instances of misreading exist with regard to the integration of existing literature and theories in GT procedures among scholars and prevail until present day. Those who follow a very strict interpretation of GT argue that, in order to develop new concepts and explanations for (novel) phenomena one should not integrate views of existing theoretical explanations and literature on the topic or related topics. However, theoretical concepts do not simply "emerge" out of the data via induction as for instance Glaser suggests. In doing so phenomena can easily be mistaken as indicators for theoretical concepts (Strübing 2014, p. 53). Peirce's concept of abduction grounds on the assumption that new insights rely only partly on experience as a form of "qualitative induction" (Peirce, 1958), but more essentially on a sort of "abductive lightning" that brings a new quality into the research process (cf. also Strübing 2014, p. 54).

Within GT the *inductive* mode of gaining insights, which argues against the integration of prior theoretical and scientific knowledge, has been overemphasized for a long time. Strauss and Glaser, in their early writings, have advised researchers to ignore literature on the state of art and theory of the investigated field, in order to avoid bias and assure the creation of truly "novel" categories. Existing literature should be integrated only in later stages (Glaser and Strauss, 1998). This, however, is impossible since one is always more or less influenced by prior knowledge of the field of study or related fields, which automatically influences the researcher's view of the observed phenomena and the categories he or she uses, creates and relates to each other.

The concept of 'theoretical sensitivity' in GT building, indeed, presupposes the integration and critical analysis of prior theories, it just argues for a different way of integrating and treating that knowledge as compared to nomological-deductive methodologies. But only in later publications Strauss (as opposed to Glaser[32]) has explicitly valued the role of prior knowledge (scientific, theoretical as well as everyday knowledge) in GT as important and positive (Strauss and Corbin, 2010 [1996]), p. 25f.) and that analytical questions and field selection can actually only be formulated on the basis of prior existing knowledge and theories (cf. also Suddaby 2006). In this sense, prior knowledge should not be considered as undeniable valid statements/assumptions, but rather as a stimulation to think about the investigated phenomena from different angles – as a fundus of "sensitizing concepts" (ibid.; Strübing 2014, p. 60). Hence, the relation between empirics and theory (i.e. prior knowledge) in GT is a dialectical one.

A systematic approach to the iterative process of induction, abduction and deduction

GT representatives have developed a systematic approach to the parallel procedures of data collection, analysis and theorization during the last decades since its initial formulation. It is mainly based on the practice and processes of coding and sampling empirical as well as theoretical data. I will basically rely on the model of (Corbin and Strauss, 2015) here that suggest a three stages of coding which will be explained in the following paragraphs.

Several software tools are available currently that facilitate data organization and analysis. ATLAS t.i. has been programmed based on procedures of the GT in the late 1980s. A recent version has been used here for data analysis. Throughout the chapter I will explain and illustrate how GT has been operationalized in the present analysis using ATLAS t.i., in order to guide the reader through the iterative process of data collection, analysis and theorization, or in other words, how I developed and related categories and dimensions and came to theoretical conclusions based on empirical findings.

[32] Glaser took this position until late in his career.

The notion of category is understood here as a theoretical concept with specific structural characteristics that arises from the comparative analysis of the empirical phenomena that it represents (Strübing 2014, p. 15ff). Within other qualitative approaches such as qualitative content analysis categories are usually referred to as variables (cf. e.g., Gläser and Laudel 2004) - not in a one-dimensional and statistically-defined sense, but as being the basis for the definition of theoretical notions which describe complex circumstances, distinguishing between dependent, independent and intervening or mediating variables (Gläser and Laudel 2004, p. 76ff). This understanding of a variable in other qualitative approaches is similar to the notion of "category" as a theoretical concept in GT.

Coding

Coding is a constant comparative method in which divergent data are contrasted in a permanent comparison. It is an interpretative approach to empirical data such as texts, visual material etc. The coding process is the main source of grounded theory building (Glaser and Strauss 1998). Coding results in the identification and construction of categories, which are understood as theoretical concepts that are emerging from the structural features that can only be identified through the comparative analysis of the empirical phenomena they represent. Thus, coding is understood as the process in which concepts and categories are developed based on the empirical data (Glaser and Strauss 1998). As has been pointed out in the prior paragraph, prior knowledge and existing literature of course influences the reading and interpretation of the data.

Within the process of **open coding** phenomena and their characteristics and dimensions are extracted from the data. This initial phase is characterized by a broad and rather unstructured access to the data material in which a variety of related and unrelated concepts and categories are developed. The phase of open coding aims at creating analytical diversity instead of reduction via integration.

The following figure illustrates the open coding process in ATLAS t.i.

Example from the present case study (Open Coding in ATLAS t.i.)

Extract interview p. 34, Group SE, OEM

B: Das ist ja auch ein bisschen misleading. Weil ursprünglich wurde es mal für so Firmen wie Honeywell zum Beispiel verwendet. Original Equipment Manufacturer - das ist nämlich der Euquipment Manufacturer, der das zuliefert. Und man hat es dann zunehmend auf die Integratoren verwendet. Ist eigentlich irre führend. Ist eindeutig so. Man sollte wirklich mehr von dem OEM als Integrator reden. Der hat die Integrationsverantwortung auf höchster Ebene. Der integriert das Produkt, das ist der Produkthersteller. Die anderen sind Zulieferer, ob die jetzt Teilsysteme, Systeme, Komponenten oder was auch immer - das entscheidet im Endeffekt übrigens der Integrator in welchen Modulen er einkauft. Ist wie gesagt nichts dagegen einzuwenden, dass man immer mehr modularisiert. Aber man muss eben aufpassen, dass man die Module so schneidet, dass der der für ein Modul zuständig ist, nicht plötzlich den Konkurrenten mit einbinden muss. Das wird nichts funktionieren. Das ist das Thema Grenze. Wenn wir die Module so schneiden, dass man nur über Schnittstellen spricht, dass man wirklich die Anforderungen an den anderen über ganz einfache Schnittstellenanforderungen reduzieren kann, dann passiert gar nichts. Aber wenn ich sage: Du musst mir jetzt mal erklären, wie hast du das eigentlich gelöst oder so. Dann sagt der: sag ich nicht. Kommt nicht in Frage. Ich lege doch nicht mein Intellectual Property hier dir auf den Tisch. Kommt nicht in Frage. #01:07:12-4#

*Verhältnis OEM- First-tier, n-tier supplier

*Umstrukturierung Zuliefererbeziehungen

*OEM als Systemintegrator

*Definition Modulschnittstellen

*Angst vor Wissensabfluss

*Oszillieren zwischen Wettbewerb und Kooperation

On the left-hand side you see the notions with which the text passage has been coded (e.g., *definition of module boundaries, *fear of losing competitive knowledge etc.[33].). In that initial phase they can also take the form of reduced paraphrases of the quotation. It is important to note that within the phase of open coding one text passage can be coded with different concepts/notions, in order to create analytical diversity and stay open for unexpected inquiries.

Figure 13: Open Coding in ATLAS t.i. (illustrative example)

The comparison of single events towards a category permits the researcher to detect commonalities and differences, which can be further abstracted to features and dimensions of categories and sub-categories (Strübing 2014, p. 17). The dimensionalization of data is an important step. According to Strauss and Corbin (1996, p. 43) dimensionalization designates the process in which a characteristic/feature is broken down into its different dimensions. The dimensional continuum can be imagined as a bipolar space of possibilities within which the feature of a category takes the form of a concrete empirical expression. Each category has a specific dimensional profile. Profiles of more than one category can be grouped to a cluster or pattern. The dimensional profile represents the specific features of a phenomenon under a set of given conditions (Strauss and Corbin 1996, p. 51). If you have created the category (i.e. code) **innovation pressure*, it can be high or low; or the **product development cycle* can be short or long (cf. Figure 14). Of course the researcher has to clarify, at which point the innovation pressure can be determined as high or rather low, which is usually done relying to the empirical data and/or a comparison with existing literature.

[33] Please note that I started coding in German language and switched to English in a later stage.

Within the phase of **axial coding** codes (i.e. categories and properties) are related to each other through a combination of inductive and deductive thinking. The aim of the phase of axial coding is to develop a phenomenon-related connection model. That means that qualified relations between concepts and categories are developed based on the empirical data and the consultation of existing literature and theoretical explanations. Depending on the (developing) research question(s) and the advances during open and axial coding, there typically are one or more categories that result in taking a central role in the analysis and the emerging theory. The hypotheses that turn out to yield most fruitful tend to result in a few central concepts, which Strauss and Corbin designate as "core categories". Thus, axial coding involves a lot of decisions on what is considered to be relevant by the researcher(s) with regard to the research interest.

In order to provide more structure and guidance for the phase of axial coding, (Corbin and Strauss, 2015) suggest the use of a coding paradigm (cf. table 4 for an example).

Table 4: Illustration of the Coding Paradigm

Element	Description
Phenomenon (What has been considered as conceptually relevant within the data material?)	Modularization
Causal conditions (What causes/contributes to the existence/emergence of the phenomenon?)	Increasing complexity of technological artifacts, fragmentation and spatial distribution of technological knowledge and expertise; high innovation pressure; long product development cycles
Context (What are the peculiarities/characteristics for the present research questions/the conditions for further action?)	E.g., propulsive (high technology) industry; aerospace design and manufacturing; European aerospace industry
Intervening conditions (What are the overall (cultural, technical, geographical etc.) preconditions for strategies?	E.g., actors must adapt routines of exchange and exchange relations; actors must collaborate and share knowledge rather than entirely disclose it *Note:* Preconditions vary according to the specific local embedding of the actors in the production network.
Actions (strategies) and interactions (How do actors cope with the phenomenon?)	E.g., vertical disintegration, vertical reintegration; codification, distribution and sharing of interface specific knowledge
Consequences (What are the results of phenomenon-related actions/actions strategies?)	E.g., changing relations between components (artifact level); global integration and local disembedding of production and knowledge relations, multi-dimensional processes of re and disembedding

The attributions within the code paradigm are relational features, which cannot be exclusively attributed to a single entity, but only through the relations among entities. Thus, core categories are categories to which all the other categories or codes relate (directly or indirectly).

Within the software ATLAS t.i. the representation of the coding paradigm takes the form of a network view that demonstrates the code-to-code links for a specific phenomenon. The higher the network of relations a code is embedded in, the more likely it is to be considered as a core category with regard to the overall research interest. Within the software tool a core category can be built by saving the relational embedding of a central code via creating a so-called "super-code."[34]

The level of density of a code indicates to how many other codes it relates. Figure 14 illustrates only an extract of central code-to-code links and how the core categories "modularization" and "standardization" are related in the coding paradigm. The category "standardization" has its own network constellation which is not part of Figure 14. The colors of the bars refer to the elements of the coding paradigm, which has been also used to define whether and how a category (i.e. code) is related to others (e.g., *is part of*; *is cause of*; *is a*; is a precondition for; is property of)

[34] There are different possible procedures, one can also use the family editor to hierarchize and sort code categories into sub-categories. This is somehow up to the preferences, creativity and experience of the user. I used the family function to create code clusters and subcategories, dummy variables to dimensionalize categories (i.e. *high, *low*); and the relation editor, the query tool as well as the super-code function to identify 'core categories' and verify relational constellations through constant comparison.

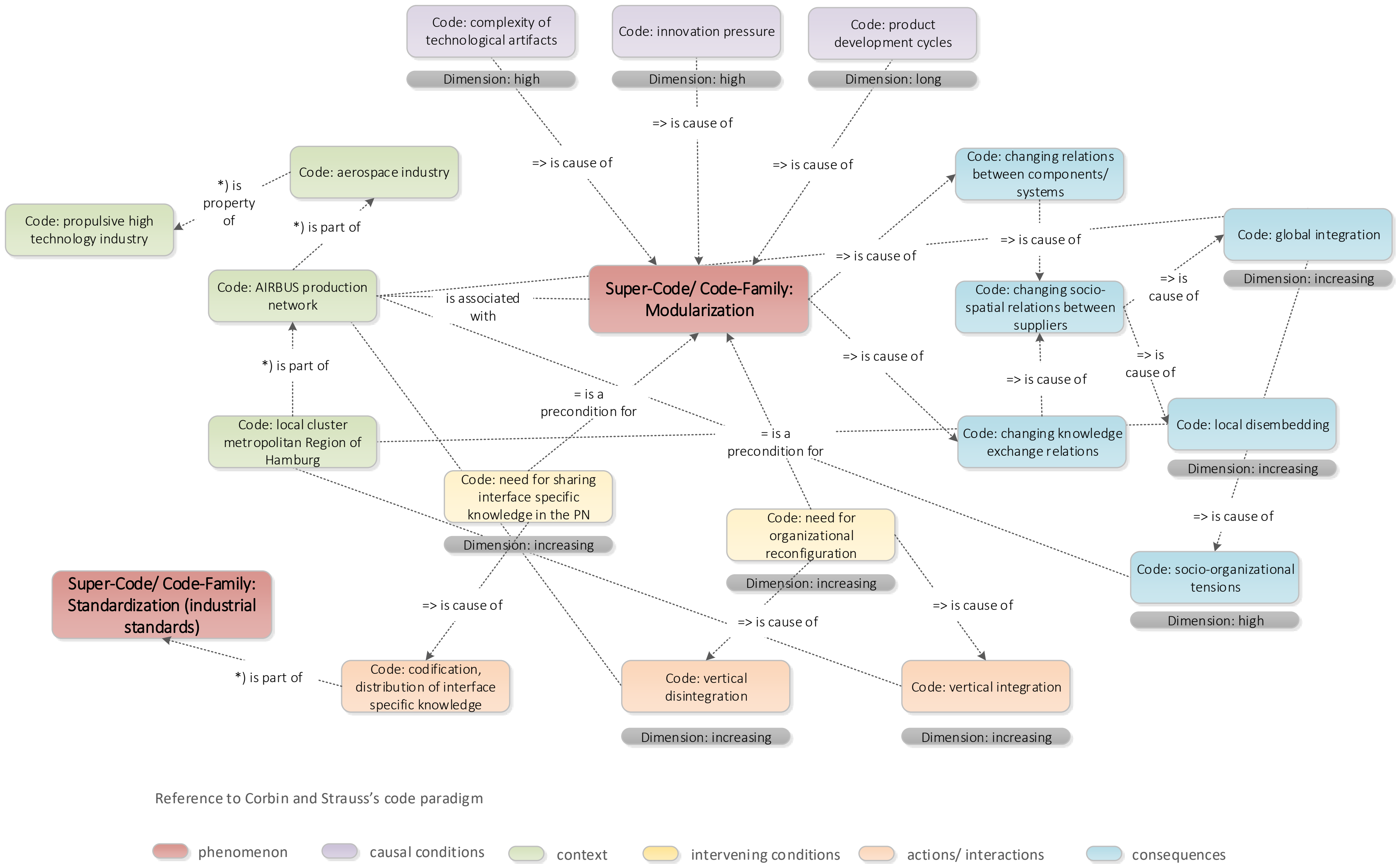


Figure 14: Network view: Code-to-Code Links (Advanced phase of axial coding)

The identification of core categories also helps to identify the "main story" that one wants to tell out of the rich and dense empirical data base. With regard to industrial change or drivers of industrial change and evolution, the core categories of the present study in its broadest sense are "modularization" and "standardization." Consequently, axial coding involves a lot of decision-making on what is considered to be relevant and what is not. Axial coding is similar to cuts through the overall data material. Only a thin layer of connections is extracted from a series of phenomena (Strübing 2014).

The final phase of **selective coding** aims at the integration of the hitherto developed concepts with regard to the identified core categories. That often involves the "recoding" of a vast amount of the material, in order to clarify the relations between the different empirical concepts to the core categories and in order to achieve theoretical closure. The following figure summarizes the iterative process of qualitative data analysis according to principles of grounded theory building suggested by Strauss and Corbin (2015).

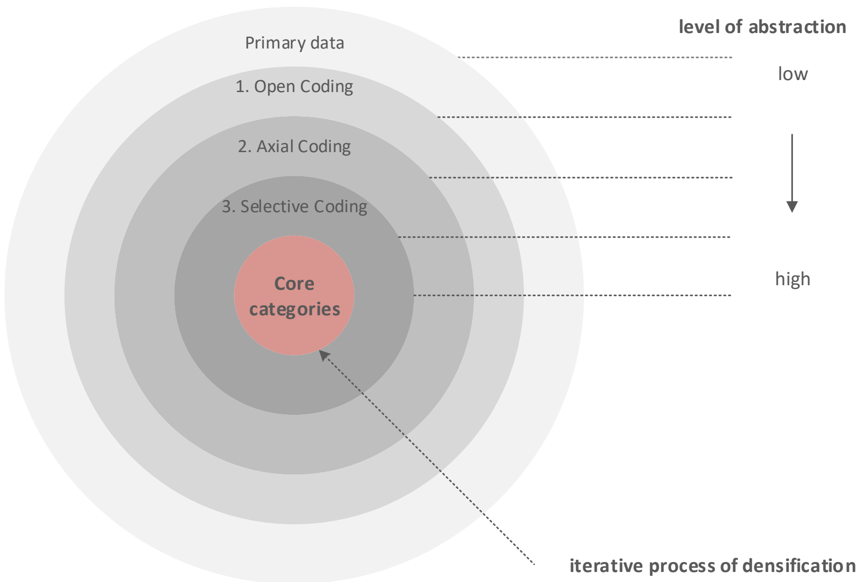


Figure 15: Phases of coding in qualitative data analysis

Theoretical Sampling and theoretical saturation

Features of the investigated phenomena, which are identified during comparison, indicate to the already existing data and might or might not cause the collection of additional data in the course of what is called *theoretical sampling*. Theoretical sampling is the central mode through which data collection, analysis and theorization are interconnected. The iterative cyclical process model of the GT with its temporal narrow intertwining between data collection, analysis and theory building has some consequences for the design of selection procedures. Compared to other procedures, the selection of cases cannot be restricted to a strict selection plan, which defines *a priori* which data to collect and how to analyze them. Instead of being determined by non-empirical (German: "gegenstandsunspezifischen") rules, data selection in GT has to be based on analytical questions that can be derived from the existing state of theorization with regard to the specific project (Strübing 2014, p. 29ff.). Thus, theoretical sampling is a process of collecting data that aims at the generation of theory. The researcher simultaneously collects, codes and analyzes data and decides, which data are to be collected next and where to find them. This process of data collection is "controlled" and guided by the emerging material of formal theory (Glaser and Strauss 1998, p. 53). If done well, theoretical sampling can lead to dense and differentiated concepts and causal explanations (Strübing 2014, p. 24).

From a practical point of view, theoretical sampling can be considered as a chain of incremental selection decisions during the research process, in which the selection criteria become increasingly specific and clear while passing the different phases of coding (Strübing 2014). **During open coding** one samples material that provides good chances to develop many relevant concepts (broad selection) and maximizes potential perspectives and interpretations (cf. also chapter 3.2.3 on data sources and collection methods). **During axial coding**, the selection of cases and data aims primarily at the previously identified tentative correlation/interrelation hypotheses and its verification. The creation of generative questions and hypotheses is crucial for the progress in iterative GT cycles. The following main generative hypotheses have been developed throughout the research and guided the analysis: (1) Changes in the (product) architecture of complex cyber-physical artifacts can lead to changes of the socio-spatial configuration of industries; (2) modularization of product and process architectures presupposes the codification of knowledge into common technological standards; (3) the strategic modularization of product and process architectures (can) lead to a spatial and institutional change of knowledge processes (codification and standard formation) and exchange relations within a given production network; (4) the spatial embedding of economic and non-economic actors that are participating in related knowledge codification and standard formation processes has an impact on territorial development and the global hierarchy of industrial regions (industrial sites), and (5) strategic modularization induces multi-scalar institutional changes in the long term. **During selective coding** prevailing gaps in the theory are closed and the theory is verified through revising the material and - only if necessary - adding new material (Strauss and Corbin 2010 [1996], p. 156ff.)[35]

During each phase, theoretical sampling is deeply intertwined with the criteria of **theoretical saturation**. It is important to note, that this type of sampling aims towards the genesis of theory and not testing a theory or theoretical explanation as in statistical sampling procedures. Statistical samples aim at achieving a predefined level of representativeness in relation to a population. The aim of theoretical sampling in GT is to achieve *conceptual* representativeness. Distinct from analytical induction, theoretical sampling does not follow a falsification rationale searching for negative cases (Glaser und Strauss 1998, p. 109 f.). Although within GT one also conscientiously searches for cases and incidents

[35] The problem that many researchers face in reality, however, is that they often cannot return to the field whenever they please. Field data collection is therefore often restricted to a certain period of time.

that do *not* fit with the initial hypotheses, they are integrated differently in the process of theorization (Strübing 2014, p. 31). Theoretical saturation is the criteria to assess at which point the sampling (per category) can be ended (Glaser and Strauss 1998, p. 69). Again the aim in GT is not to achieve a statistical representativeness, but a conceptual one. Consequently, theoretical saturation can be assumed, when examples for a concept or category repeat themselves within the material. This is of course a subjective and therefore risky decision to be carried out by the researcher(s). One needs to explain how far causations go and at which stage of the data basis a category can be claimed to be sufficiently saturated. The writing of so-called "theoretical memos" during the entire research process is therefore essential to produce valid results (Strübing 2014).

GT and the analysis of multi-dimensional changes

Finally, the question might come up why I decided to use the GT mode that is predominantly applied in investigating social interactions and perceptions often through methods of situational analysis. It is undeniable that GT has a strong affinity to (symbolic) interactionism and situational analysis (Strübing 2014). Further developments of GT and situational analysis account, however, for the integration of broader structural impacts (Clarke, 2012). Clarke (2012) argues that general cause-effect relationships in the plural world we are living in today are losing their legimatory and explanatory power. She argues for empirical social research that is able to capture the multi-dimensionality and multiple perspectives of experienced and "designed" sociality. The process character of social phenomena suggests a transition of micro- and macro phenomena up to a point where the analytical separation of these categories is being increasingly questioned (Clarke 2012, p. 14). This transition and intertwining of micro and macro phenomena can be better captured by GT procedures than other approaches.

3.1.3 Case study analysis and theory building

Case studies are dense, empirical descriptions of particular instances of a phenomenon that are based on a variety of data sources. (Yin, 2007) Hence, case studies rely on the "real-world" context in which phenomena occur. In order to build theory from case studies one or more case is used to create theoretical constructs derived from case-based empirical evidence (Eisenhardt, 1989). Each case is unique as an analytic unit (Eisenhardt and Graebner, 2007). As has been already pointed out in the prior chapter, the theory building process grounds on recursive cycling between empirical data of the case, the emerging theory and extant literature.

Whereas I consider GT a research methodology that reflects the epistemological process of generating knowledge via iterative cycles of induction, abduction and deduction, the case study itself is, first of all, a comprehensive research design *strategy* that can entail qualitative as well as quantitative data collection and analysis methods. To be clear, case studies are one way of framing the research questions (and their scope) and GT or the building of theory from case studies is a more general strategy for conducting qualitative research. It can serve as a basis for *how* to collect and analyze the data *from* the case study. It depends on the approach to the case study and the underlying research interest. A case study can indeed be based on rather nomological-deductive premises such as in explanatory case studies that intend to test a hypothesis that has been generated from prior literature and theories, or it can be descriptive such as for example in ethnographic approaches approaches (Yin, 2003).

Yin explicitly states that “[the] role of theory development, prior to the conduct of any data collection, is one point of difference between case studies and related methods such as ethnography […] and ‘grounded theory’ (Strauss & Corbin, 1998). Typically, these related methods deliberately avoid specifying any theoretical propositions at the outset of an inquiry” (Yin 2003, p. 28). Although citing Strauss and Corbin (1998), he actually refers to Glaser’s interpretation of GT, who denies the integration of prior knowledge at the beginning of the research process and assumes that the theory must emerge from the data. Whereas in the Straussian approach one should definitely have a general idea of where to begin, in order to “force” the theory with generative and structured questions.

Despite some differences in reception, I consider the case study design strategy a helpful tool to frame and define the field of investigation, especially with regard to real-time field research without contradicting the open-ended methodological approach of GT building, since as Yin (2003, p. 13) states: a “case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when, the boundaries between phenomenon and context are not clearly evident.” (Yin 2003, p. 13). He proceeds that case study inquiry copes with ‘situations’ in which there are many more variables of interest than data points and that relies on multiple sources of evidence, but which also “benefits from the prior development of theoretical propositions to guide data collection and analysis” (Yin 2003, pp. 13-14). Thus, the case study research strategy can help the researcher to frame the field of investigation without losing *Ergebnisoffenheit*.

3.2 Operationalization of the analysis

The operationalization of the analysis is oriented towards the conceptual model developed throughout the second chapter, which aims at answering the overall research question of how the development of a global knowledge infrastructure that evolves during modular transition affects the development of a local industry cluster.

3.2.1 Selection and definition of the case example

In the context of building theories from case studies, the selection of cases is determined by whether they are "particularly suitable for illuminating and extending relationships and logic among constructs." (Eisenhardt and Graebner, 2007, p.27)

Existing case studies on modularization have been mainly carried out in the computer, software and electronics industry and rely on cases where modular approaches have been assumed to have evolved bottom-up over a long period of time (cf. e.g., Sturgeon 2002, 2003) and extra-firm institutions have not played a particularly strong role (exception Hess 2006). The top-down implementation by the lead firms and its strategic partners in the given case might also result in different outcomes. It represents an extreme and temporal densified process of modularization. The selected case is, therefore, particularly suitable for the purposes of the heuristic analysis. One can expect that the relations that are of interest to the analysis occur here above average and will become particularly apparent (Flyvbjerg, 2006).

As has been pointed out in chapter 2.5.1, the key to understand economic development is the sub-national scale. The articulation of a region is on the one hand constituted by horizontal and vertical relationships among actors located there and on the other hand affected by local territorial interfaces to global production networks. Within a local industry cluster the interplay of local and global interfaces and relations become epitomized and the interrelations between global and local dynamics become inscribed in the trajectory of that region. This is why on the **spatial dimension**, I designed the case study around a local industry cluster in Hamburg. The firms in the *Metropolitan Region of Hamburg* serve as a starting point for tracking relations that go beyond national and continental borders.

The most common approach to spatially locate a(n) (industry) cluster is via the location quotient approach. In a recent quantitative study, Turkina et al. (2016) identified 52 aerospace clusters worldwide including the one in Hamburg using this method. The LQ computes the proportion of an industry sector relative to that industry's share of employment across a region (e.g., Europe, Germany or sub-national scales) as a whole. If the value of the LQ equals or is larger than 1 this indicates a potential industry cluster, because the agglomeration of sectoral employment is higher than the average in the region. In order to locate the cluster, they collected data from the Global Cluster Observatory and drew on a large body of prior work using a location quotient approach (Delgado et al., 2014). However, potential bias might occur, because one or two large firms with very high employment numbers might be mistaken for a cluster as a regional agglomeration of firms. The research interest and questions and the underlying understanding of what is considered to be a cluster determines whether the approach is suitable or not. Since I am interested in how far a region is plugged into wider structures of trans-regional production networks, I chose a different way here. Besides existing studies on the aerospace cluster in Hamburg I drew on *Airbus* supplier lists from the year 2014 (ca. 3986 entries[36]) to

[36] Please note that firms can have more than one entry, if they offer multiple products and/or services.

reconstruct and geographically map exchange relations in the production network. GPN analysis emphasizes the necessary presence of a global lead firm for the constitution of a GPN (Coe and Yeung 2015, p. 40) that means GPN can be analytically organized around a single or multiple lead firms. Since the GPN of the European Aerospace Industry is, indeed, organized around one lead firm, this is certainly a practical approach and basis for displaying the spatial configuration of production (i.e. buyer-supplier relations) in a production network. The supplier network orchestrated by and organized around the lead firm can give me information about the size, spatial distribution and level of vertical specialization of the actors. The supplier lists contain information on the geographical location (postal firm addresses) as well as information on the product or service provided by a firm. Suppliers within that database are classified according to 6 main technical groups that are sub-divided into several sub-classes indicating their specific vertigal integration (German: ”Wertschöpfungstiefe”) which gives us further information and evidence on the degree of vertical integration of the production as well as the global dispersion of the actors that form the production network. The main groups entail: airframe, material (hardware and fasteners), cabin and cargo, equipment and systems, engineering services and capital goods, and propulsion systems. The results of that analysis have been used to display the spatial agglomeration of different suppliers and *Airbus* sites in northern Germany and the *Metropolitan Region of Hamburg* as well as the specific expertise and level of vertical specialization indicated by the specific product group (cf. the following figure for a brief illustration).

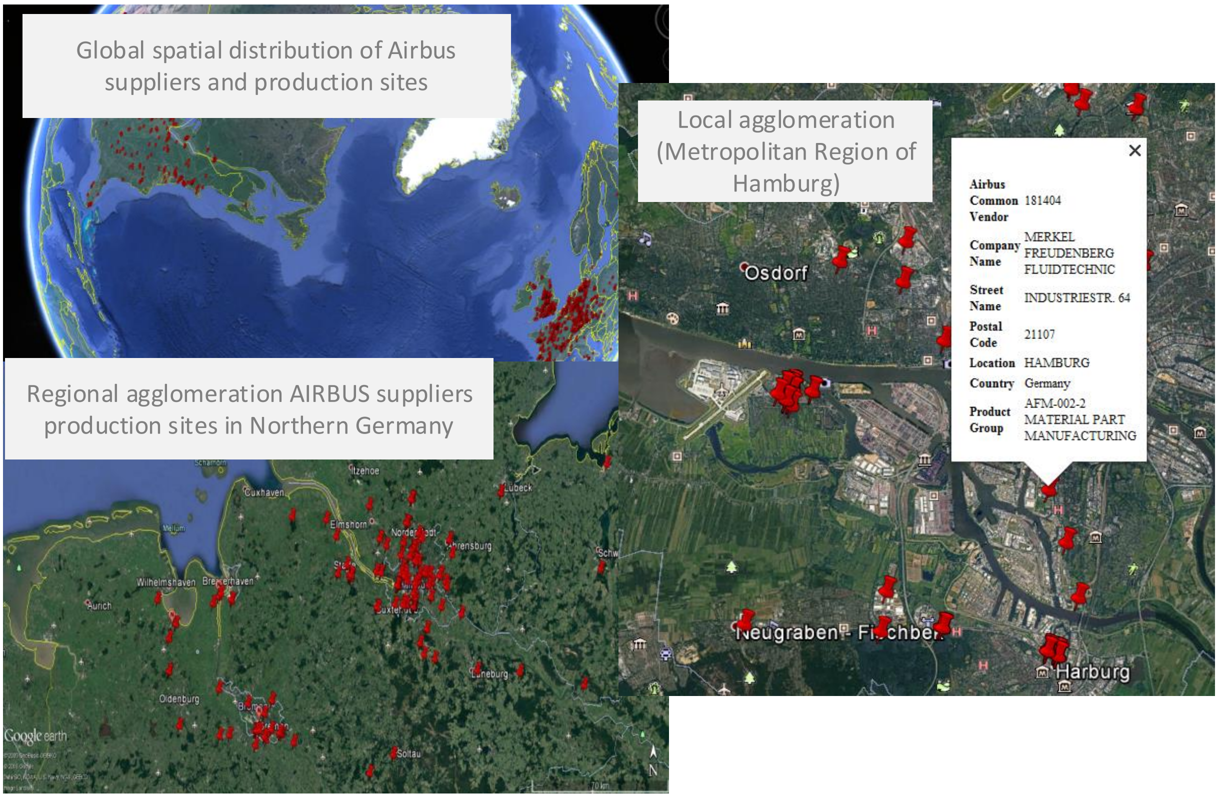


Figure 16: Extract of geographical mapping of the Airbus production network

According to this data set, a total number of 772 enterprises are located in Germany and a total number of 239 in the *Metropolitan Region of Hamburg* (including all postal codes starting with 19, 20, 21, 22, 23, 24, 25, 27).

The **boundaries of the knowledge dimension** of the production system (i.e. its underlying knowledge infrastructure) are determined by the artifact, in this case, the A380 aircraft. Within my analysis the artifact-as-designed as distinct from the artifact-as-used (Ramduny-Ellis et al., 2005) limits the boundary of what I consider to be part of the production system. This involves all the actors that are involved in the actual design and manufacturing of aircrafts excluding by definition airports, airlines, and passengers. This has three reasons. First of all, the artifact embodies the knowledge that is needed in order to design and produce it and, secondly, it enables me to identify the actors that are involved in its development (design) and production (manufacture) as well as in the development of the knowledge infrastructure. Since I assume that relational changes at the artifact level induce relational changes at the production network level (i.e. knowledge and production relations), choosing the entry of the study via the artifact is the only reasonable way, in order to address that interrelation. This means that beside vertical buyer-supplier relations in the production network additional data have to be integrated in order to get insights into more horizontal knowledge relations of non- or extra firm actors, such as standard setting organizations.

3.2.2 Operationalization of the temporal dimension and time frame of the analysis

Case studies often aim at investigating contemporary phenomena in “real-time” settings. The present thesis addresses, however, questions about how and why things emerge and develop over time and space, which is distinct from research that relies on the covariation of dependent and independent variables (Langley et al., 2013).

Studies on processes and change can focus either on how the qualities of an entity change (e.g., from integrated to modular forms of organization). Here processes are captured or represented in things and their changing qualities. Another way of approaching processes is to focus on how they themselves emerge, develop and decline. This perspective is more interested in how processes unfold over time (Langley et al., 2013). It tends to adopt a dynamic social constructivist view that explains change processes as the outcome of ongoing interactions between individuals and organizations acting on multiple levels and across contexts (Langley et al. 2013, p. 9). This perspective on change also corresponds to the definition of territorial development introduced in chapter 2.5.1 that considers territorial development as the dynamic outcome of the complex interactions between region-specific networks and global production networks in the context of changing governance structures, and as an essentially path-dependent process.

The given analysis tries to capture processes in changing qualities of entities as well as ongoing cross-dimensional interactions. The understanding of a production system that is suggested here contains several dimensions: the artifact, the production network (i.e. knowledge and exchange relations) and its spatial manifestation. The knowledge related to the design and production of the artifact is embodied in technological standards on which I will rely in order to reconstruct the artifact and the knowledge dimension. The boundaries of the production network are drawn based on vertical supplier relations and horizontal knowledge relations of non- and extra-firm actors involved in standard setting and diffusion related activities (cf. also prior chapter 3.1.4). Changes induced by modularization can be indicated by changing relations between components and modules on the artifact level as well as changing exchange relations on the organizational and network level and its specific spatiality. In order to capture these relational changes, the analysis needs to answer just what kind of relational changes occur due to the strategic modularization of product and process architectures in the European aerospace manufacturing industry on the dimensions of the artifact (changing relations between components and modules), the production network (knowledge and exchange relations) and how are changes on the different dimensions interrelated. Hence, the multi-dimensional model displayed in Figure 12 aims at indicating processes of change in changing relations in the production system. This serves as a basis to draw conclusions on more abstract and generalizable patterns of modularization processes that have been conceptualized in the phase model in Figure 11. Within this model, modular transition has been described as a phase that entails the development of standards and codes as well as its diffusion and enactment depending on the multi-scalar embeddedness of the actors involved. The spatial dimension of embeddedness can be displayed by: tracking the location/geographical groundedness of actors involved in standard setting and diffusion related activities and their organizational and network embeddedness; tracking the spatiality of standard diffusion and adoption of standards. Hence, in order to explain the spatiality of modular transition one needs first to know: How, where and by whom are new modularity-related standards developed (knowledge codification and standard formation related activities)? Secondly, one needs to know how these standards diffuse within the production network. This serves as a basis to analyze how they affect firms in the local cluster and their embeddedness in specific practices networks and organizations. Finally, via describing the multi-dimensional processes of dis- and re-embedding of knowledge and production relations the emergence and development of socio-technical and socio-spatial development trajectories can be explained. “[H]ow the past is drawn upon and made relevant to the present is not an atomistic or random exercise but crucially depends on the social practices in which actors are embedded.” (Langley et al., 2013, p. 5). Thus, this analytical part goes beyond capturing change in changing qualities of things. It also addresses the (far more difficult to operationalize) on-going cross-dimensional interactions between different entities.

Nonetheless, the empirical data and the timeframe of the case analyses address one particular temporal phase of modularization: the phase from modular transition to modular maturity. In doing so, the time frame of the present analysis starts with the formal beginning of the A380 program in the 1990s and ends in 2017. That means that data have been collected for an approximate 25-year period, 21 years of which were retrospective and almost four years of which were "real-time."

3.2.3 Triangulation of data sources and data collection methods

The multi-dimensional approach to the analysis that has been chosen here requires for different data (sources), in order to reconstruct a holistic picture of the industry and patterns of change that are related to modularization. Mixed methods combining documents, archival data, interviews and observations are particularly suitable for examining processes of change in contemporary phenomena (Rasche and Chia, 2009). It also prevents potential bias and post-hoc rationalization of the past. Hence, several methods for data collection and analysis have been employed here based on principles of triangulation.

Triangulation refers to the combination of different data sources and/or different kinds of data collection methods, which need to be analyzed against the background of their respective theoretical perspectives. Triangulation of different data sources and methods aims at *broadening insights generated on different dimensions* which cannot be gained using only one entry (Flick, 2011). According to (Denzin, 1970)one can distinguish between integrating different data sources and *applying* different methods for data collection, which is quite similar to the theoretical sampling procedure suggested by Glaser and Strauss (cf. chapter 3.1.2) in which the data is approached via multiple perspectives and with different hypotheses in mind (Denzin 1970, p. 303). Regarding the present analysis this means, in order to answer the research questions data collection needs to provide information on

- the artifact including product architecture and technologies before and after the A380 program (i.e. *technological/knowledge based perspective*),
- the supplier and knowledge exchange relations and their socio-spatial embedding in the local cluster in Hamburg (*i.e. social/organizational perspective*),
- the geographical groundedness of the GPN and its spatial distribution (*i.e. spatial perspective*)
- knowledge codification processes and standard formation that is related to the new technologies and organizational principles applied in the A380 program *(functional knowledge based perspective)*,
- the socio-spatial embedding of actors that are involved in standard formation and diffusion related activities/the spatiality of standard formation and diffusion (*spatial perspective*),
- spatiality of standard diffusion, and

- the adoption of/confrontation with new standards and knowledge on the local level (i.e. in Hamburg (*normative perspective*).

3.2.3.1 Semi-structured expert interviews

The main feature of qualitative interviews is to give the interviewees enough space to verbalize their subjective systems of relevance, perspectives and interpretations without being too much influenced by the theoretical presuppositions and prior structural thoughts of the interviewer (as far as this is possible). The interview rather takes the form of a guided conversation than a structured interview. The concrete questions are supposed to be oriented towards the listener and are supposed to stimulate narration (Kruse, 2014). It is important to emphasize, that narrative interviews are not a specific type of interview[37], but a specific communication strategy that aims at the generation of narration.

The **expert interview** is also not a separate interview type, but a "case specific variant" of a guided interview (Kruse 2014, p. 168), since it focuses on a specific target group not an interview method that is exclusively used interviewing so-called "experts" (ibid., p. 171). The expert can be considered as the representative for specific types of action, perspectives and knowledge systems with regard to a specific field of action (Gläser and Laudel, 2004). Consequently, the realization of this type of interview often takes the form of a dialogical expert discussion and is characterized by purposeful communication.

The main challenge in this context is determining what and who can be considered an expert. I draw on the sociology of knowledge perspective here. Within these approaches the expert is constituted via the specific structure of the knowledge he possesses, for instance context specific, practical or corporate knowledge. His or her self-reflective knowledge directly relates to the fields of action and processes for which the person stands as a representative (Kruse 2014, p. 176). Of course, these so-called experts are not context-free deliverers of objective information. Expert conversations also always have to be methodologically reflected and theoretically grounded (Bogner and Menz, 2005).

I combine the open structure of a narrative with the more structured form of an expert interview here and refer to the definition carried out by Bogner and Menz (2005), who distinguish between explorative expert interviews, systematizing expert interviews, and theory generating interviews. The **explorative expert interview** is applied at the beginning of research projects and during field exploration or in projects on knowledge dimensions, which are rarely or at all documented and examined. Within this phase, the interview is highly monological, listener-oriented and narrative (not in the sense of generating a specific text form, i.e. the "narration"), but as explicative in a more general sense (Kruse 2014, p. 169). Dialogue sequences occur only when specific dimensions are mentioned, but not explained. The **systematizing expert interview** aims at elaborating and deepening relations and finer

[37] There are different opinions with regard to that question.

structures with regard to dimensions that are already known and documented. The interviewer can take the role of a “co-expert” here and the focus and structuration of frames of relevance are negotiated between the interviewer and the interviewee during dialogical sequences. It is more structured and has less narrative elements. The **theory generating expert interview** aims not only at generating pertinent/relevant information, but more profoundly at examining the genesis of professional knowledge systems from a social-constructivist perspective. It can entail monological, dialogical as well as argumentative-discursive and narrative sequences alike. Dialogical sequences aim at detecting the more implicit dimensions of the professional knowledge systems that are of interest to the researcher (Bogner and Menz 2005; Kruse 2014, p. 170).

These different types of expert interviews can be also aligned to the different phases of coding in grounded theory building (cf. chapter 3.1.2). Within the phase of open coding, the field is explored; during axial coding, generated hypothesis and relations are refined, reviewed and verified; and during selective or theoretical coding core categories and their broader relations and implications are put in a coherent causal model. Hence, in the initial phase of data collection the interview strategy has been oriented along the explorative expert interview, followed by more systematizing and theorizing types in later stages of data collection with higher levels of theoretical saturation.

The **first selection of interview partners** aimed at catching a variety of different perspectives that were considered as promising for providing many relevant concepts, perspectives and interpretations regarding the relations, collaboration and knowledge transfer among the actors in the aerospace cluster corresponding to the requirements of the open coding phase (cf. chapter 3.1.2)[38]

Interview partners have been chosen in order to reflect the multiple relations and actors that are present at the local cluster in Hamburg and include: R&D department of the focal company *Airbus*, cabin supplier, contract manufacturer, engineering service providers, representative of local SME association, representatives of DLR and ZAL (applied research centers), public officials of the “Behörde für Verkehr und Innovation” that had been involved in establishing public-private partnerships, funding and location promotion, CEOs of cluster institution, external aerospace consultant (telephone interview), and project leaders of multi-lateral cross-cluster projects that existed due to the extensive funding at that time. Interestingly but not very surprising, a lot of interview partners had been “switching sides” over the

[38] Please note that the initial data collection and analysis has been carried out within an interdisciplinary team that, besides me, consisted of three other persons. The aim of the project was to identify under which circumstances and with which methods and tools cross-cluster projects and knowledge exchange (inter-organizational collaboration) could be achieved. This did serve as a basis for developing a concept for inter-organizational knowledge management in the cluster. The head of the team decided not to integrate two interviews that had been carried out with (former) suppliers of *Airbus*, since he considered them not valid for further analysis, because they basically contained criticism of the lead firm and complaints about the changing structure and conditions for suppliers in the region. I later reintegrated them in my analysis, since they contained very important perspectives and perceptions on the changes that had taken place. In the latter stage of my own PhD project, however, I only selected those interviews that were relevant for my personal research interest, recoded them accordingly and conducted additional interviews.

years working for different firms, research institutes or governmental institutions, which made them valuable informants also with regard to the development and the history of the location. For the purpose of data protection and privacy policy names of interview partners have been anonymized this also counts for the names of firms except for *Airbus* and public institutions.

After the initial cycle of data collection and analysis I was still lacking information and prove on if, and if yes, how technological and organizational changes are interrelated in the given case. I conducted additional interviews with partners I had already interviewed during the explorative phase and soon figured that interviewees working in management took the strategic and economic perspective on the events that is typically for their field of expertise (i.e. the supply base has been consolidated for rationalization purposes and in order to reduce transaction and communication costs) lacking however expertise on technological and design related changes. I therefore searched for interview partners in the field of system engineering that had been involved in the development of the A380 program in the past or informants that could provide helpful insights including some of the engineers at my institute (LaFT) that had been working a lot with *Airbus*. This ended up taking longer than expected, since only very few technical experts were aware of the technological innovations that altered the product architecture with the beginning of the A380 program and affected the reorganization of the production model, and the head of the respective department was not working for *Airbus* anymore. In the end I managed to identify him and convinced him to be interviewed and he provided me further information, documents and the missing links to my theory.

A limitation of the study (concerning theoretical sampling and saturation) is that due to a lack of time and resources, I was unable to interview standard setting actors or attend the organization's meetings in a standard setting (this is mostly due to the associated high travel costs, since those actors were not located at the Hamburg site). Thus, this part of the analysis relies predominantly on documents and interviews with people who adopted or where confronted with new industrial/technical standards at the local level.

3.2.3.2 Semi-overt participant observation/participant observation

Participant and semi-overt participant observations (Whyte and Whyte, 1984) have been also a very important data source for my analysis and for generating a deeper understanding of the world of aerospace engineering, supplier relations and practices in the local industry arena. Distinct from an artificial interview situation in which the interview always faces the social desirability of response bias, actors are interacting in a real situation. I have been participating at several regional industry meetings and workshops regularly organized by cluster institutions. Moreover, during the BMBF-funded multi-lateral industry project, I have been accompanying and (for some parts moderating) the inter-organizational task force *Aerospace Manufacturing* at the Centre for Applied Aeronautical Research for more than one year. During the multi-lateral business meetings (the members consisted of experts and university professors for robotics, production engineering, representatives of lead firm, SME etc.), tensions and constraints of inter-organizational relations and cooperation became particularly apparent. Last but not least, I attended several engineering conferences in different countries and carried out observations during my daily work as a research fellow at the Institute for Production Engineering and Manufacturing Technologies that has frequently collaborated with the local aerospace industry in bi- and multi-lateral R&D projects.

3.2.3.3 Collection of documents and technical data

The collection of documents focused on scholarly and non-scholarly secondary sources on the aerospace industry and the *Airbus* production network as well as the local/regional industry cluster in particular. Additionally, firm data including *Airbus* and DIEHL supplier lists, regional aviation cluster database and technological data on systems design, materials and assembly have been collected and integrated into the analysis.

For the second part of the analysis, I researched industrial standards documents, related standard setting organizations member lists and management boards and related compliance and regulatory agencies. Standard setting organizations and their members, related regulatory agencies as well as firms that have adopted specific modularity-related standards (*ARINC*[39], *NADCAP*[40]) have been added into the overall data base. These include headquarters and regional branches of standard setting organizations and regulatory agencies as well as their members (based on sponsoring and membership lists) Spatial diffusion and adoption of identified standards in the so-called *NadCap* program have been partly captured by referring to a publicly accessible database.[41] This database contains all companies that hold a Performance Review Institute (PRI) accreditation and/or registration. I filtered only those companies that have a registration/accreditation to the industry-managed *NadCap* program, which has been pushed by *Airbus* and other lead firms and which develops technological interoperability standards for special materials and processes for the aerospace industry.

3.2.3.4 Overview of empirical database

The empirical database created during the last five years contains documents, transcripts of semi-structured narrative interviews as well as field notes and protocols from participant and semi-overt participant observation.

[39] ARINC standards refer to standards in avionics and data communication protocols in the aerospace industry.
[40] NadCap standards codify knowledge on special materials and processes in the aerospace industry.
[41] https://www.eauditnet.com/eauditnet/ean/user/mainpage.htm

Table 5: Overview empirical data base

Documents	**Transcripts of semi-structured narrative interviews (23 in total, each 1-3h)**	**Field notes and protocols from semi overt participant observation**
scholarly secondary resources	Lead firm representatives	Regional industry meetings organized by several cluster institutions
non-scholarly secondary resources	Local SMEs (engineering service provider)	Multi-lateral business meetings (we accompanied the inter-organizational "Aerospace Manufacturing" task force at the Centre for Applied Aeronautical Research for at least 1 year)
firm data	Local SMEs (manufacturer)	Several engineering conferences
technological data (systems design, materials, assembly)	Representatives of regional sector specific SME association	Observations carried out during my daily work as a research fellow at the Institute for Production Engineering and Manufacturing Technologies that frequently collaborates with a lead firm in bi- and multi-lateral R&D projects
Airbus supplier lists	Aerospace consultants	
Regional aviation cluster data base	Public officials (regional economic promoters)	
Standard setting organization member lists	System engineers (one of whom has been involved in the development and implementation of Open IMA)	
Industrial standard documents (*ARINC*, *NadCap*, *SAE*)		

The interview data have been anonymized. Moreover, interviews, observations and documents have been assigned to a specific code that contains information on the type of data (cf. Appendix). With regard to interview data it also contains information on the background of the interviewee. Throughout the presentation of results references to empirical data are displayed only by the code.

3.2.4 Combination and aims of data analysis methods and different steps in the process of data analysis

The analysis is based on the principles of grounded theory development and is framed around a heuristic case study using different data sources and collection methods that relate to different perspectives and dimensions of the conceptual model developed in the second chapter.

The **dimension of the artifact** and hence analyzing changing relations between components in cyber-physical systems has been realized using artifact analysis. **Artifact analysis** is mostly used in anthropology, ethnography and archeology, but has been also applied in economic geography, since artifacts, whether historic or contemporary, offer significant insights into technological processes, economic development and underlying social structures. Artifact analysis has been used here as a parallel procedure in triangulation. The focus has not been on the artifact-as-used, but on the artifact-as-designed (Ramduny-Ellis et al., 2005), since artifacts embody knowledge, skills and assumptions of the original designer(s) (Houkes and Vermaas, 2010; Kroes, 2012). Reverse Engineering, as a form of technological artefact analysis, is increasingly used by engineers to analyze products of competitors or detect malware, is the process of deconstructing a man-made object, extracting missing knowledge and analyzing its structure, function and operation by going backwards through its development cycle[42]. Technical and design data have been collected in order to identify central innovations that led to significant changes in the product architecture (i.e. changing module boundaries) comprising of *Open IMA* which affects the logical and control structure of an aircraft, as well as material innovations (e.g., *GLARE* and *CFRP*) affecting the physical structure and assembly procedures. In this course new and newly combined technical standards on which those technologies rely have been identified (i.e. *ARINC* and *NadCap* as part of *SAE*) in a later step. The generated insights gave me first hints with regard to changing supplier relations and institutional changes at the network level.

Based on the results of the artifact analysis and accompanying document analysis, the actors that are involved in standard formation related activities in the course of modularization (private as well as public regulatory agencies and their subsidiaries) have been identified and added into the data base, in order to geographically map the standard formation and diffusion related extra-firm practices within the GPN. Furthermore, based on publicly available data from standard setting organizations those companies have been added that have gained certification concerning a specific standard (i.e. adopted it). This has been used as an indicator for standard diffusion in the GPN with a special emphasis on the regional cluster in the metropolitan area of Hamburg. This analysis and mapping techniques give us only insights on who has been involved in standard formation, where this actor is located and who has adopted the standard in which locations. It does neither tell us, how standard formation processes take place, which modes of standard diffusion are prevalent, neither does it give us insights on how this affects local industrial dynamics. Thus, additional qualitative data (i.e. documents, interview transcripts and field note protocols) have been added to the analysis and again coded and analyzed with the software *ATLAS t.i.*

As has been pointed out throughout chapter 3.1, grounded theory development relies on a comparative method in which divergent data are contrasted in a permanent comparison. It is an interpretative approach to the qualitative analysis of empirical data such as texts, visual material etc. A recent version of ATLAS t.i. has been used to create and integrate the overall database. All the data, have been successively integrated in the different phases of coding (open axial, selective).

[42] Cf. also https://en.wikipedia.org/wiki/Reverse_engineering

To sum up, the analysis of the collected data has been operationalized by combining artifact analysis, text coding procedures and content analysis according to the GT procedure (cf. chapter 3.1.2), and several mapping techniques that have been used to display the GPN and its spatial distribution as well as the spatiality of standard formation and diffusion. The following table summarizes the different steps of analysis and its aims.

Table 6: Overview combination and aims of different steps in the process of data analysis

	Analysis of changing relations between components and transformation of knowledge infrastructure	**Analysis of changing socio-spatial relations (production relations)**	**Analysis of changing knowledge relations and transformation of knowledge infrastructure**
Perspective	Socio-technological	Socio-spatial	Socio-spatial
Data sources and data analysis methods	Technical documents, standards documents, qualitative interviews with system designers/engineers; Artifact analysis (focus on artifact-as-designed), qualitative coding	Supplier and cluster data bases, documents, qualitative interviews Document analysis, qualitative coding; geographical mapping and frequency tables	Qualitative Interviews, field notes, documents Qualitative coding, geographical mapping of standard diffusion
Main aim	*To identify* Central architectural and or technological innovations that alter the relation between components, modules, assemblies New module boundaries and relations New technology-related interoperability standards	*To identify* Central actors and roles in the PN Embeddedness of actors and relations Spatial and social configuration and structure of the *Airbus* production network before and after modularization	*To identify* Specific standards that codify the respective (interface related) knowledge Central knowledge processes and exchange relations before and after modularization and their specific embeddedness in organizational practice

In a last step, interrelations between the dimensions and perspectives and the dynamics of change have been analyzed in the phase of theoretical coding.

3.3 Some concluding remarks on the reliability, validity and scope of results

Similar to other qualitative methodologies GT is often accused of lacking quality criteria to assess procedures and research results. It is, therefore, important to reemphasize that GT stems from a very different epistemological paradigm than nomological-deductive methodologies. Representatives of the latter are among the sharpest critics since the quality criteria they developed cannot be easily transferred to (any) qualitative research methodology.

Theoretical sampling is a quality securing and controlling procedure in many respects. On the one hand, it fosters the conceptual density of the emerging theory through systematically developing and integrating variants in overall categories. On the other hand, due to the successive and process-driven selection and collection of data the appropriateness as well as the methods used to get the data can be optimized at all times (Strübing 2014, p. 32). Quality within that process is assured through the permanent comparison during coding, the development of generative questions during axial and selective coding, theoretical sampling, the writing of theoretical memos (Strübing 2014) as well as "peer debriefing" (cf. also Lincoln and Guba 1985). Within the first phase reliability has, for instance, been increased by using four independent coders (including me) followed by workshops in which the coders discussed varying readings/interpretations and agreed upon common coding schemes[43]. In later stages, I developed my own focus generative questions and core categories and regularly presented and discussed it with the members of this earlier research group, who also had profound knowledge of the initial data base that focused on knowledge processes within the local aerospace industry cluster.

The results of the case study do not claim to be representative in a statistical sense. GT aims at creating conceptual representativeness. Heuristic single case studies create first of all an internal validity. The external validity (i.e. the transferability to other cases) is difficult to assess, since the case of *Airbus* and the regional aerospace cluster is very specific. However, modular architectures and IuC technologies are diffusing into ever increasing areas and the role of interoperability standards increases in a lot of technology related industries and changes established governance patterns. The impact of technological industrial standard formation and its implications for institutional and regional change are increasing against the background of a growing deregulation and liberalization of markets and trade relations. Nevertheless, in the focus stands the theoretical reflection. The value of a heuristic single case study lies not in the generalizability of the causal mechanisms detected, but to comprehend and assess whether the chosen categories and relations of the conceptual model are appropriate.

[43] This has been only possible in the course of the BMBF-sponsored project and could not be carried out in later stages.

4 Case study results

The empirical part presents the results of the case study and is based on the insights and conceptual model developed in the second chapter.

Chapter 4.1. introduces the production network around *Airbus* and its history and agglomeration in Hamburg and northern Germany and describes the modular transition and increasing globalization from the mid 1990s until today. The analysis of the modular transition of the production network is split into two major parts. The first part (**4.1.2**) describes the modularization of product and process architectures (architectural innovations) and the accompanying reconfiguration of production relations and its structural disembedding from its former context, which results in profound technological and organizational tensions.

The second part (**4.1.4**), focuses specifically on knowledge relations and describes how the knowledge infrastructure for governing knowledge in modular global production networks is build and transformed during modularization. It analyzes how, where and by whom new technological knowledge is codified into common standards and how this infrastructure is established and diffuses in the production network.

The second part of the **chapter (4.2)**, examines the impact of the processes that take place during modular transition on the global scale on the aerospace cluster and the local *Airbus* supply base in the *Metropolitan Region of Hamburg*. After a brief classification and description of the former embedding of suppliers in vertical production and knowledge relations (4.2.1), chapter 4.2.2 describes processes of dis- and re-embedding of production and knowledge relations as well as tensions and new challenges for local suppliers. It examines how the institutional embedding of the actors and the trust relations change during modular transition (4.2.3). Chapter 4.2.4 outlines the horizontal exchange relations and the embedding in local institutions and analyzes how actors in the cluster are trying to cope with their situation.

4.1 Modular transition and globalization of the *Airbus* production network

4.1.1 The *Airbus* production network and the European aerospace industry

In the 1970s, the landscape of the European aerospace industry changed with the first multi-national programs trying to establish a European aerospace program. This resulted in the creation of *Airbus*, a consortium of the leading European aerospace nations[44] that had been founded as a response to the

[44] In 1970 the *Airbus* consortium has been founded out of the *French Aérospatiale* and the Deutsche *Airbus* (MBB, Dornier und Focker-VFW). Shortly after, the Spanish *CASA* and the *British Aerospace* joined the consortia.

increasing project volumes and the perceived need to establish a counterbalance to the dominating US aerospace industry around *Boeing* resulting in a strong competition among *Airbus* and *Boeing* in the following decades. In the late 1980s, all nations involved in the project tried to promote and protect the participation of their firms in the *Airbus* enterprise. The outcome has been an extremely fragmented industry structure with a very high number of very heterogeneous SMEs contributing to the supranational enterprise. In 1998/1999 not only the aircraft manufacturer *Airbus*, but also the defense and space segments[45] have been centralized under the European Holding Company *EADS* (European Aeronautic Defence and Space Company), a consortium of the firms *Aérospatiale-Matra*, *DASA* and *CASA*. Whereas 80% of *Airbus* had been integrated into *EADS*, 20% remained with *BAE Systems*. The new distribution of shares aimed primarily at lowering the political influence on the enterprise. Throughout the year 2013, the corporation announced changes that entailed the renaming of *EADS* into *Airbus* Group and the reorganization of the organizational model accompanied by the reduction of jobs especially in the defense and space travel sectors throughout the following 3 years starting in 2014.

Structure and spatial distribution of exchange relations

The fragmentation of knowledge bases and the division of labor can be divided into 7 main classes including airframe, material (hardware and fastener), cabin and cargo, equipment and systems, engineering services and propulsion systems and corporate jet (MRO and customization).

Whereas the majority of the 3,986 firms[46] listed in the *Airbus* supplier data base remains in European countries (74.4 %) and Northern America (19.25 %), the global distribution of the *Airbus* production network and the number of trans-local connections in remote yet cheaper locations increases (4.79% in Asia and 1.28% in Africa).

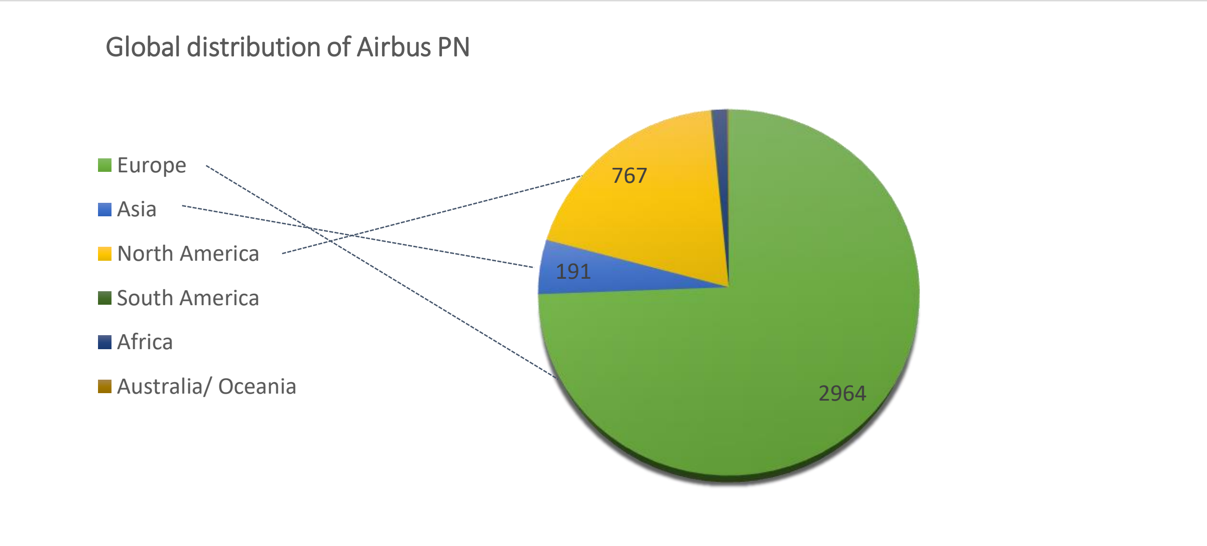


Figure 17: Global distribution of Airbus production network (author's elaboration based on Airbus supplier data from 2014)

[45] i.e. Astrium, Cassidian, Eurocopter.
[46] Please note that the database contains some duplicates, which could not be removed entirely.

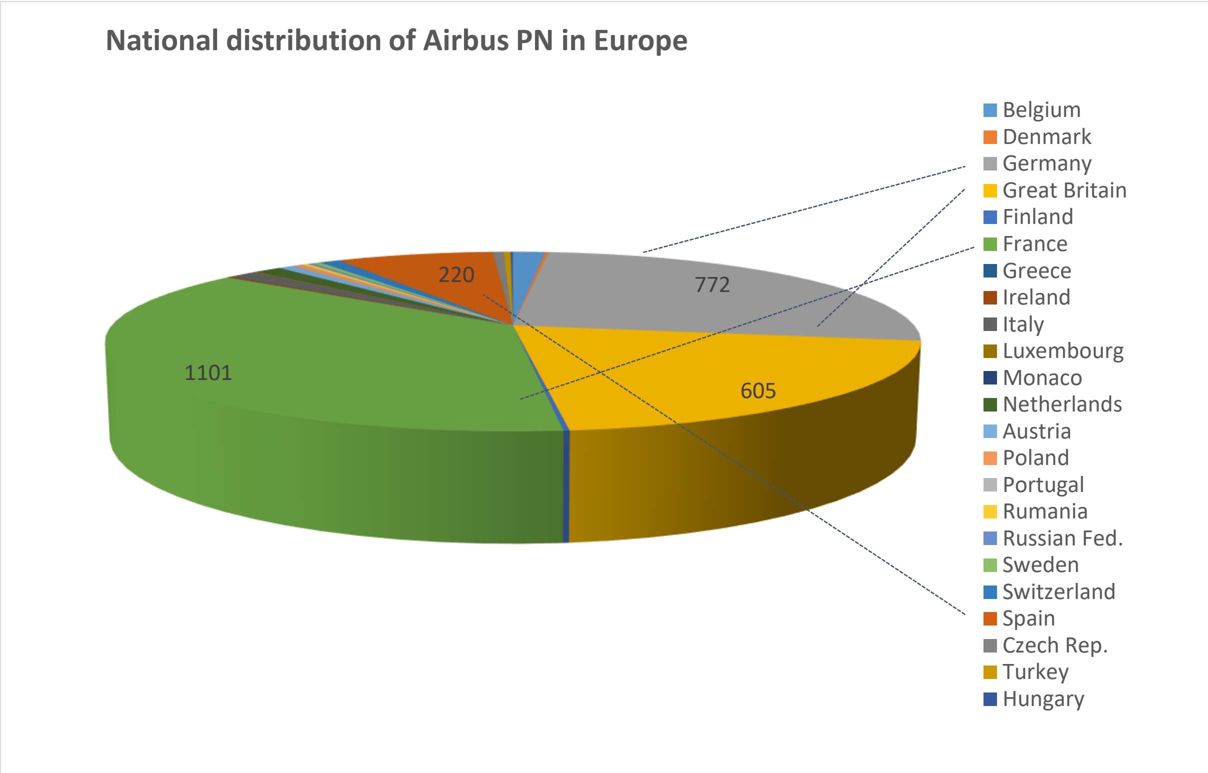


Figure 18: National distribution of Airbus production network (EU) (author's elaboration based on supplier data from 2014)

2964 firms listed in the data base are located in geographical Europe. Among them more than 80% are located in France (37,15%), Germany (26.05%), Great Britain (26,05%) and Spain (,.42%).

The division of labor and knowledge in the *Airbus* production network can be displayed roughly according to the following table. Only 1% of the firms active in the industry are specialized in propulsion systems (i.e. jet engines), followed by 7% that specialized in cabin and cargo, and 10% in equipment and systems (i.e. avionics). The vast majority of the firms in the production network consist of SMEs that are specialized in airframe manufacturing (18%), supplying hardware and fasteners (46%) and providing engineering and other services (18%).

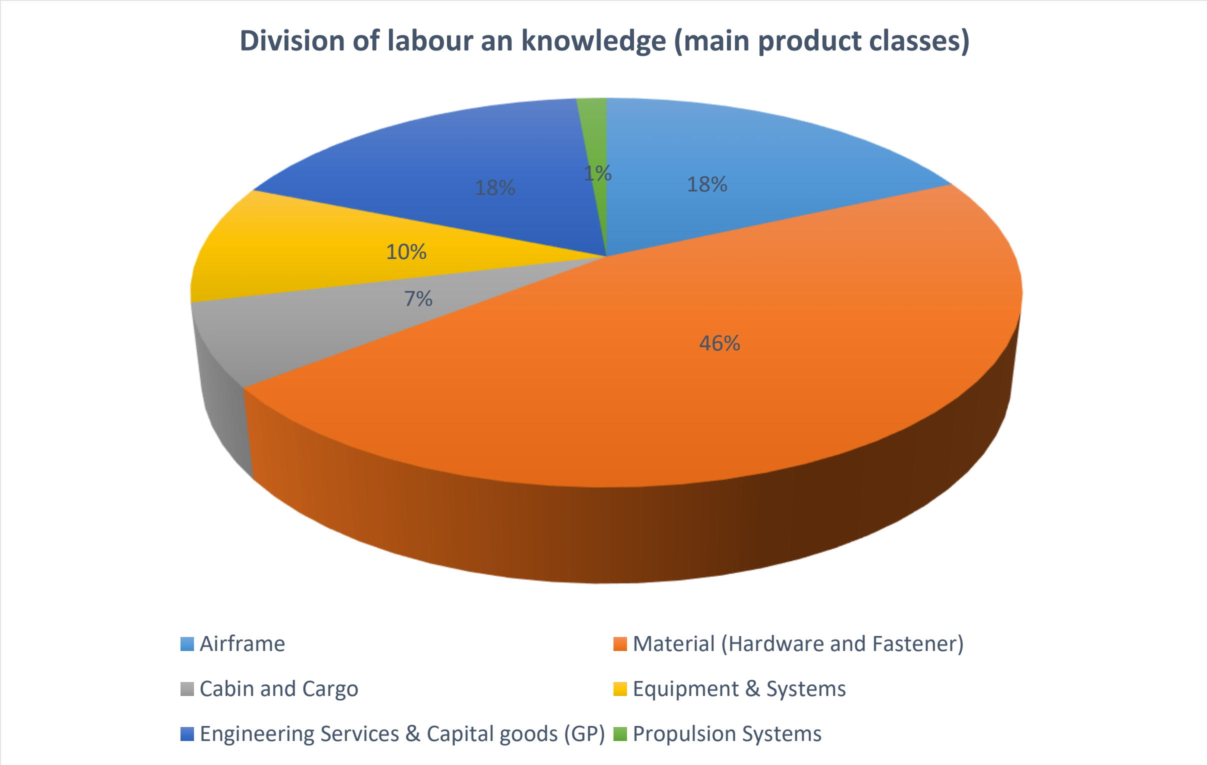


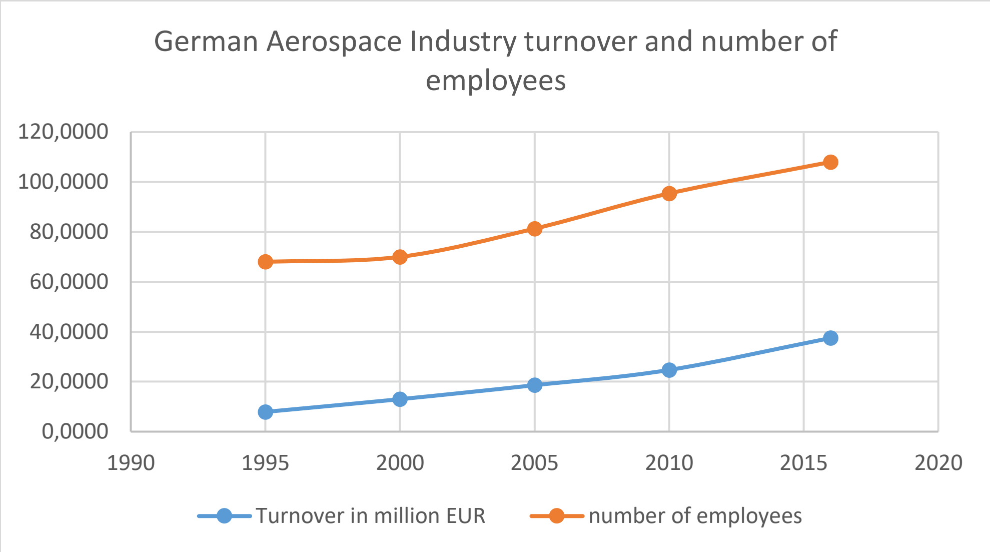
Figure 19: Division of labor and knowledge in the Airbus production network (author's elaboration based on Airbus supplier data from 2014)

According to *Airbus* data from 2010, aerostructures (airframe) and materials are "among the most offshorable commodities," the "offshore potential for these areas is considered to be high since these domains contain high labor inputs, whereas complexity can be partially limited. Strategic goals aim at increasing offshore production in aerostructures from less than 10% in 2006 to almost 40% in 2020 and in materials from less than 5% to almost 30% (PD24-DOC-OPENIMA).

4.1.2 *Airbus* and the aerospace industry in Hamburg and Northern Germany

According to data from the BDLI the aerospace sector in Germany has enjoyed unprecedented success and growth rates throughout the last decades. Since the mid 1990s industry revenues have more than quadrupled (cf. table 7). Out of the 37.5 billion annual turnover for the entire sector (including defense and military as well as space travel) in 2016, the civil aerospace industry comprises an amount of 27.1 billion. The export share in proportion to the turnover of the entire sector is 72%. An average of 75,000 people are working in the German civil aerospace sector. In spending around 11% of its turnover on R&D, it is also considered as one of the most innovative industries (BDLI, 2016).

Table 7: Development of turnover and employment from 1995 -2016 (Source: BDLI report 2016)



Data from the “Statistisches Bundesamt” indicate, however, that 60% of the firms involved in the sector are SMEs with less than 250 employees, which altogether realize less than 3% of the turnover of the overall sector, whereas 20% of the firms with more than 1,000 employees attain 87% of the total turnover (Homann and Wilke, 2013). Hence, the employment and turnover shares fall predominantly to big corporate and global players such as *Airbus*.

Within Germany, the major spatial agglomerations of the industry can be found in the *Metropolitan Region of Hamburg* (northern Germany) with a specialization in civil aviation, as well as in Bavaria, where several sites of the *Airbus* Military and Defense segment are located.

Airbus in Hamburg and Northern Germany

The development, management and manufacturing of the different *Airbus* aircraft programs is carried out in a manufacturing alliance within an international division of labor between the sites of the major countries Germany, France, Great Britain and Spain. Whereas central functions and the program management of the A330/340, A380 and A350XWB are located in France, the program management for the A320 and the A320 neo product families is situated in Germany. Core competencies of the German sites are in the domains of cabin, fuselage and tail units. The main site in **Hamburg-Finkenwerder** includes an airport end employs approximately 12,500 people. Hamburg hosts the final assembly line of the A320 family as well as manufacturing of structural components (for A318, A319, A320, A321), coating (paint shops) and several rear fuselage sections for the A330 and A350 XWB that are manufactured and equipped here. With regard to the A380 Hamburg also plays a key role, although the program management is located in Toulouse. The Hamburg site hosts the structural assembly and the equipping for the forward and rear fuselage sections including the paint shops (coating) and spare center. Hamburg is also the place where final acceptance and delivery of the A380 to the customers in Europe and the Middle East are carried out.

The focus at the second largest site in Bremen (approximately 3,000 employees) lies in the area of high-lift systems for the wings of all *Airbus* programs. And includes design, manufacturing, integration and testing. The site in Stade (Niedersachsen) employs approximately 1,600 people and produces vertical tail planes for all *Airbus* programs. Stade is known for its CFRP (carbon fiber reinforced plastics) technologies (i.e. composite materials and processes) a specialization that dates back to the 1980s. These new light-weight materials have increasingly been integrated on aircrafts (e.g., the A380, the A400M, A350 XWB). At the Stade factory major CFRP components for the fuselage and the wings of the A350 XWB are manufactured. The early specialization has helped the region of Stade to become more independent from *Airbus* and create the largest manufacturing site and innovation hub for lightweight materials in Europe. The small site in Buxtehude with approximately 350 employees develops cabin communication systems and cabin systems for crew and passengers. There are two more factories for component manufacturing in Varel and Nordenham that are operated by Premium Aerotec GmbH. The company is the outcome of a merger of the *EADS* plant in Augsburg with the *Airbus* plants in Nordenham and Varel in 2009. *Airbus* Group is today the sole shareholder of Premium Aerotec. The following figure illustrates an overview of the *Airbus* and *Airbus* owned production sites in Northern Germany. [47]

[47] http://company.airbus.com/company/worldwide-presence/germany.html
http://company.airbus.com/careers/apprentices-and-pupils/In-Germany/In-Germany-training-locations/schuler-ausbildungstandorte.html

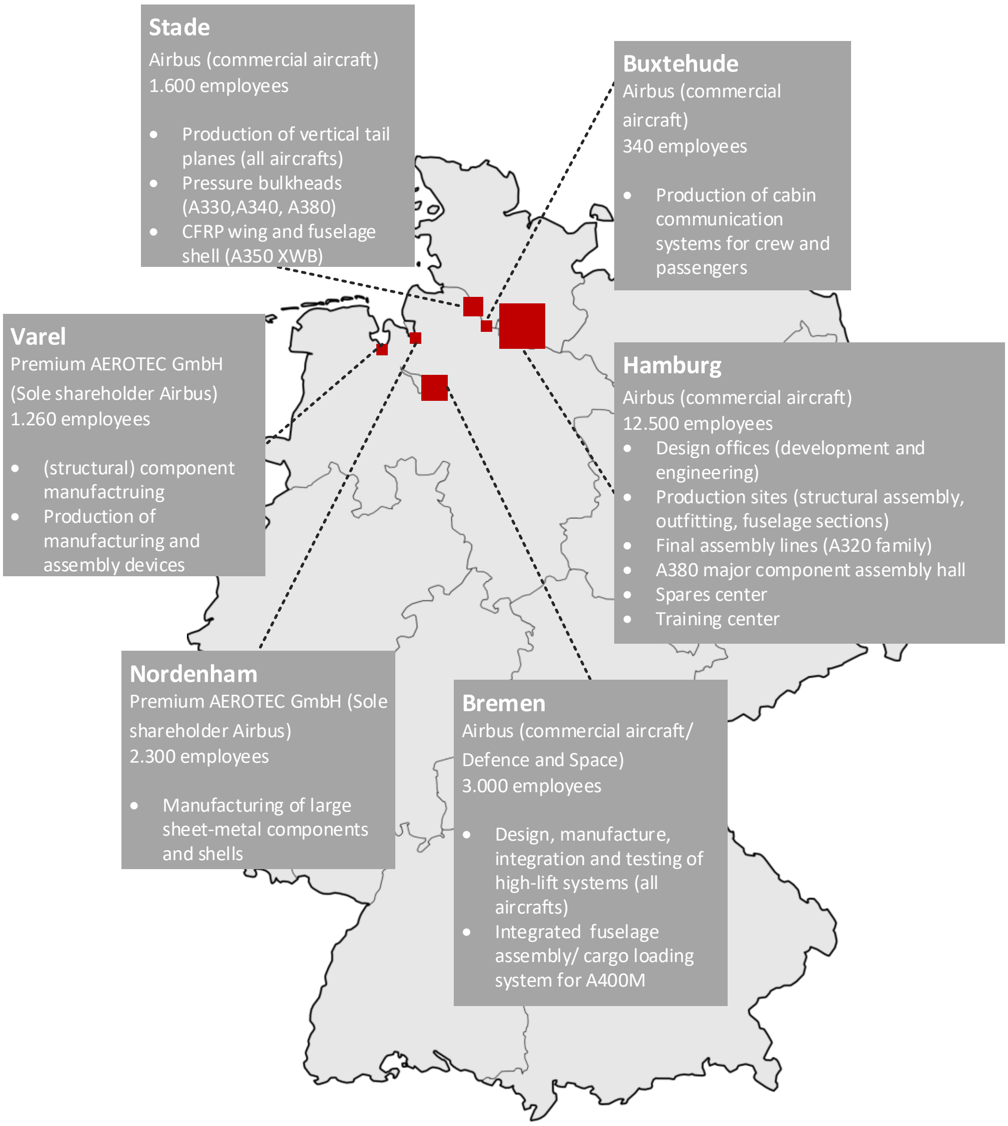


Figure 20: Overview Airbus commercial aircraft production sites in northern Germany (author's elaboration)

Compared to Toulouse (Headquarters of *Airbus*) the economic structure in Hamburg is dominated by very small and only medium-sized companies in business-related service industries (mainly engineering service providers). The rest of the suppliers are active in material and part manufacturing for aero structure (e.g., airframe) and cabin systems (cf. Figure 21). Major competencies in the domain of service engineering, aero structure and material and parts manufacturing entail: surface protection, material processing/treatment; equipment and model construction, measurement and control technology, services in cabin systems, software integration and documentation. In 2008, 8,000 people have been estimated to work in the SMEs related to the aerospace industry (cf. also Köpke 2008). According to HAV an estimated amount of 40.000 people are working in the local aerospace industry.[48] Hence, the majority of labor is created by Airbus, Lufthansa Technik and the Airport Hamburg.

[48] http://www.hamburg-aviation.de/netzwerk/standort.html

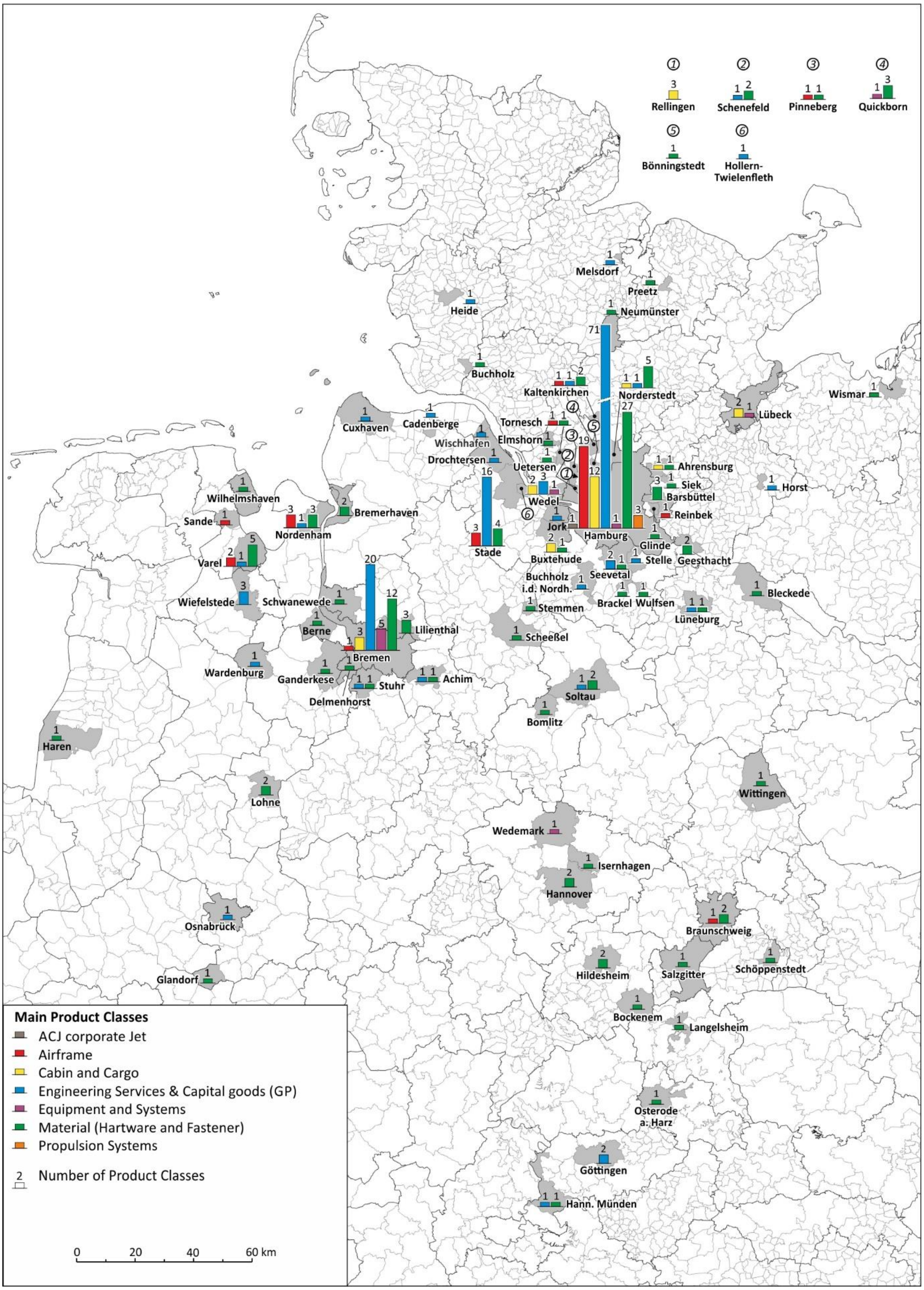


Figure 21: Agglomeration and Specialization of local supply base (author's elaboration based on Airbus supplier list 2014)

Although the medium-sized business structure bears high potentials for flexibility and innovative solutions most of the SMEs lack financial strength in that capital intensive market and compared to the software and electronic industries there is very few venture capital in that sector. The low amount of business founding activities can be additionally explained by the high market entry barriers and high barriers to enter the *Airbus* production network/supply chain. Moreover, engineering and business service providers are crucial for operative production processes, but lack R&D capabilities as the following quotation indicates:

> *"Engineering service providers and engineering offices are application-oriented, constructively acting people. Whatever the matter is, do I need to deliver a CAD graph, do I need to develop code for some kind of software, or do I need support in project management…. these things are necessary and reasonable in the operative production process. When it comes to innovation, they play, however, an inferior role, that means the innovation potential of these small and medium sized companies is very, very limited and that is the Achilles heel, which I see here in Hamburg." (PD7-INT-DLR)*

So the large base of small and medium sized firms in the *Hamburg Aviation* cluster is organized around a few large globally active companies (i.e. *Airbus* and LHT). This structure is typical for a lot of aerospace clusters in which the firms that take an integrating role (e.g., *Boeing*, *Embraer*) are surrounded by a high number of heterogeneous small and medium-sized so called tier 3 and tier 4 suppliers. The particularity of the Hamburg cluster is that it is closely connected to the cluster in Toulouse via the lead firm *Airbus*. A strong division of labor as well as strong cooperation relationships between the two sites has been established throughout the decades.

4.1.3 Changing product architectures and reconfiguration of production relations

As has been already pointed out, the technological innovations as well as the scientific progress in various fields that have historically marked the evolution of the *Airbus* programs (from the A300 in the 1970s to the A380) have also, at each stage, provoked profound modifications in the product and system architecture. This required for changes in the industrial organization and *Airbus*' relationships to its sub-contracting firms. This also affected the division, flow and governance of knowledge and information in the production network.

Architectural innovations and the introduction of modular avionics in the A380 program

70 years ago radios for communication and navigation were the first avionic (i.e. electronic) devices that have been integrated on an aircraft. Another 40 years later with the introduction of the fly-by-wire control on the A320 in the early 1980s, mechanical aircraft functions and equipment began to be increasingly replaced by analog and digital electronic controllers following an almost exponential growth of electronic equipment and embedded systems within aircrafts. This already led to the standardization of the cockpit equipment for several product families in the late 1980s. However, at that time the phenomenon was designated as "variety management" or a "commonality approach" serving as a basis

for the development of product families. It is mainly a company-internal diversification of the product portfolio that is based on the internal reuse of modules inspired by similar strategies in the automotive industry. It can be considered as an initial/first phase of modularization.

In the following decades, innovations in electronic equipment and embedded systems further increased until the concept of a federated (tightly integrated) product architecture (meaning “one function = one computer”) – that had been carried out up to the mid 1990s - could no longer be maintained. The increasing demand for data communication raised the number of signal interfaces between the different systems operating within an aircraft “into quantities which were beyond imagination some years ago.” (PD19-INT-SE-LF).

The first response to this increasing complexity has been developed by airframe assemblers and system suppliers and relied on a concept in which multiple software functions have been integrated on a single avionic computing device. This new concept – *Integrated Modular Avionics* (IMA) – was first presented for cockpit functions on the *Boeing* 777 in 1995. It soon became an open standard (*ARINC* 651)[49] on many new aircraft and helicopter programs (PD36-DOC-STAN-AR; cf. also (Fuchs, 2012)). However, the integration of multiple functions on a single processor lead to a lack of transparency in terms of fault propagation, significantly affecting the reliability of the controllers and increasing maintenance costs, which made modifications and upgrades a very costly and complicated procedure (PD19-INT-SE-LF).

Airbus and its former partners had also conducted research on IMA since the mid 1980s. As a European response to the shortcomings of the existing IMA approach, *Airbus* in collaboration with Thales-Diehl developed a so-called “Open-IMA” technology concept for the A380 program (PD19-INT-SE-LF; PD24DOC-OPENIMA). The idea of Open IMA relies basically on a combination of independent and interdependent modules with some of the resources being shared (including the common high-speed multiplexed avionics communications network (i.e. AFDX) as well as core processing and input and output modules). The concept of open IMA for the A380 has been selected as the foundation for systems design on cockpit (e.g., Flight control, Air Traffic Communication etc.), utility (e.g., fuel management, braking, steering etc.), energy (e.g., Circuit Breaker Monitoring) and cabin domains (e.g., Air conditioning, cabin pressure and ventilation control etc.) and then extended (globally) on all the domains (PD24DOC-OPENIMA). Open IMA shifts the avionics integration activities from the physical to the logical domain by segregating the avionics systems from much of the physical integration (Watkins, 2006). Figure 22 schematically illustrates the architecture of this approach and the combination of independent and interdependent modules such as the AFDX network based on *ARINC* standard 664.

[49] This counts for the entire ARINC 600 standards series.

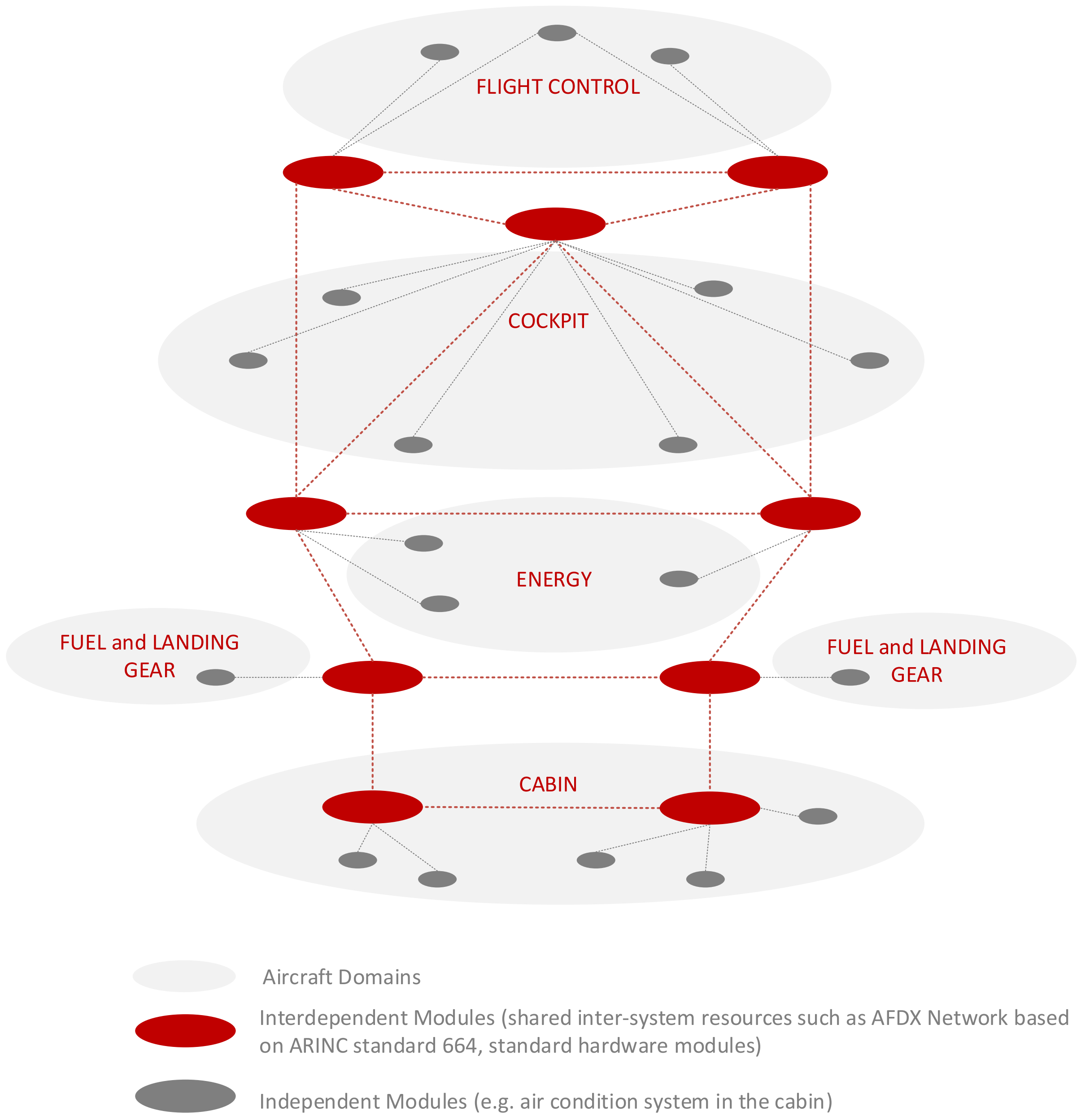


Figure 22: Open Integrated Modular Avionics (author's elaboration based on data from the Dpmt of Systems Architecture & Integration, Airbus SAS, Hamburg, Germany)

This modular partitioning of systems enables a greater system independence as well as incremental qualification and system certification. However, the challenge coming along with this new approach is mainly the management of the allocation of "open" shared intersystem resources, because it creates new dependencies between the different actors from a technical as well as from a process and organizational point of view, as the following quote illustrates:

> *"We have always been thinking and working in modules, the whole ATA chapters[50] are building on modules. But today, we have more and more systems that go beyond a single specified module. Modular avionics is a perfect example. In the past, it truly was segregated modules: I order an air condition system and all the hardware that belongs to the system will be delivered. Now, the module gets ripped open and the OEM says: you are delivering the function and your turbines etc., meaning the hardware, but the computer networks, which are necessary for sequencing and carrying out the functions, are delivered by someone else. That means I tear open the existing modules and create systems that affect multiple other modules. The same thing happened with hydraulics responsible for landing gear and flight control – that also was one 'system' affecting a lot of other systems and accordingly it was in need of information on requirements of a lot of different systems. The overall art is to reduce this (required) information to interface specifications." (PD19-INT-SE-LF).*

From a more strategic perspective, the question for single firms here is, as another interviewee puts it: "What is the minimum requirement to an information in order to be *use*ful. How far can I go without revealing my core competency?" (PD1-INT-CM). The logical (i.e. informational) and the physical architecture can often not be entirely segregated into separate modules and assemblies, due to a high level of coupling between assemblies, components, units and subassemblies in aircrafts of this size (PD19-INT-SE-LF). Hence, this also poses challenges in terms of the structure and coordination of the production network and the question of how design information and associated knowledge diffuses and needs to be shared among the dispersed actors in the complex production network.

Material and process innovations in the A380 program

Innovation in the aerospace industry is driven by the main goal of reducing weight. The lighter an aircraft is, the less fuel it consumes and the more aerodynamic it will be. Reducing weight of the overall aircraft has also been a major challenge with the A380 as the biggest passenger aircraft so far. In this regard, Open IMA also reduces the overall weight since less hardware is needed for processors, if the overall system is realized in a shared network and the premise of one system = one computer is abandoned.

Another way of achieving weight reduction is to apply lighter materials for structural components, cabin and fuselage. These materials require for different ways of manufacturing and they may behave differently once integrated into components and assemblies and also once they are in the air (PD-13-INT-PE). Compared to 1990 where 10% of the components (e.g., in the A320) where made of CFRP, the volume of CFRP raised to 22% for the A380 and 52% for the A350 WX. GLARE (Glass Laminate Aluminium Reinforced Epoxy)[51] is a composite material that combines thin layers of aluminum with CFRP. It has

[50] The ATA (Air transport association) chapters refer to a classification system that categorizes the technical domains of an aircraft into groups and sub-groups. This classification systems serves as a basis for the certification/approval of EASA CS-25 and FAR 25. http://www.ataebiz.org/Pages/default.aspx The ATA develops standards for the global commercial aviation industry for information exchange, engineering support, maintenance, material management and flight operations.

[51] GLARE has been meanwhile replaced by the approved version High Static Strength (HSS) GLARE. https://de.wikipedia.org/wiki/Glasfaserverst%C3%A4rktes_Aluminium

been developed specifically for the aerospace industry and has been extensively applied for the first time at the A380. The material has several advantages as compared to aluminum. The disadvantage is that it is more difficult to process and assemble and cost six times as much as conventional aluminum (Wiedemann, 2009).

As counts for modularity in design in the avionic systems, modularity in the design of physical components also requires for standardized information with regard to “interface properties” (e.g., how will the material behave once integrated/assembled into larger parts etc.). Consequently, if development, design and production is separated into modules and carried out by different actors along the value chain, actors must collaborate, codify and share interface specific information.

To sum up, modularity in design has been mainly carried out with regard to the avionic systems, whereas modularity in organizing vertical exchange relations in the overall production network have been realized by bundling tasks into modules that could be outsourced to suppliers as the following paragraph illustrates.

Airbus’ new modular systems policy and its top-down implementation

The new challenges imposed by the open IMA approach should be met strategically by a concentration on *Airbus*’ core competency as an architectural integrator[52], the redefinition and arrangement of systems and modules accompanied by the outsourcing of considerable working packages and a new globally oriented and “knowledge-focused” sourcing strategy (cf. chapter 3.1.1).

Airbus meanwhile outsourced 60% of its value on the A380 program and approximately 80% in the A350XWB program[53]. Whereas in 1990 *Airbus* spent 50% of their budget for external purchase, procurement expenses increased to 80% in 2009. Whereas the size of the “working packages” that are outsourced increases, the number of suppliers is constantly reduced PD22-DOC-LF; PD26-DOC-PRO1). Until today, the direct supply base has been reduced from 650 in 1987 to 200 in 1993 to less than a hundred in 2010 and is constantly being reduced. In the domain of service engineering the number of direct suppliers has also been drastically reduced from approximately 450 to 61 in 2008 to 26 in 2011 with the final aim of 20 (PD35-DOC-E2S). Additionally, the supplier relations have been (hierarchically) cascaded and the so-called first tier supplier model inspired by the automotive industry has been introduced (cf. chapter 3.1.1.). Since the new Open IMA affects almost all domains of the aircraft (from cockpit; flight control; to energy and cabin), only *system* suppliers have been chosen to be on the first tier having a *direct* linkage to *Airbus*. Focal companies are focusing on developing direct long-term supplier relationships only with “system suppliers” (first tier) which are able to deliver big working packages including financial development and production risks. They in turn support the restructuration

[52] This means that *Airbus* is mainly involved in system integration on the highest level.
[53] Very recent estimations of sectoral experts forecast an opposite so-called ‘Post Tier 1 trend’ in the northern American industry around Bombardier and *Boeing*, this counts, however, not for the European sector so far Michaels (2017).

of the supplier industry on the second and third tier. Table 8 presents the primary actors on the firm level their role and scope of value added-activity in the industry. It basically displays the structure of vertical exchange relations (i.e. buyer-supplier structure) as suggested by Gereffi et al. 2005 and Coe and Yeung (2015).

Table 8: First Tier Structure of the production network

Primary actors in the production network (firm-level)		Role	Scope of value-added activity	Civil European Aerospace industry (examples)
Lead firm		Coordination and control	Product and market definition, architectural integration, platform assembly	*Airbus (former EADS)*
first tier	System Suppliers (prime contractors)	Partial or complete (system) solutions to lead firms, strategic partnership, risk-sharing	Co-Design and development in manufacturing and advanced services, large scale system integration	***Aerospace Avionics Suppliers****, e.g., Honeywell, BAE systems, Rockwell Collins*
second tier	Specialized components suppliers (industry specific)	Dedicated supplies to support lead firms and/or their strategic partners	High value modules, components, products, component system integration	*Diehl Aerosystems (Service Modules)*
	Specialized suppliers (multi-industrial)	Critical supplies to lead firms and partners	Cross-industrial intermediate goods and services, value-added parts and assemblies	***e.g., engine and propulsion systems, integrated global service providers*** *Daimler-Benz, Rolls-Royce, Lockheed Martin, Safran Group*
n-tier	Generic suppliers	Arms' length providers of suppliers, contract manufacturing, engineering service providers	Standardized and low-value products and services, design-to-print parts and assemblies	*e.g., plastic parts in cabin interior (Krüger Aviation GmbH)*

The new purchasing strategy is realized according to the *Airbus* Guidelines General Conditions of Purchase 2000 (GCP 2000), GRAMS General Requirements for Aerostructure and Materials Suppliers (GRAMS), General Requirements for Equipment and System Suppliers (GRESS). This has also severely changed the qualification process and the requirements for suppliers to enter the production network (PD23-DOC-LF; PD25-DOC-PRO; PD26-DOC-PRO1).

Figure 23 illustrates the increasing modularization of value chain activities over time that is accompanied by considerable outsourcing of production and design activities, a changing structure of exchange relations and the emerging new industry roles of system integrators and (knowledge) intermediaries as well as an increasing vertical specialization. The y-axis displays the level of vertical specialization from component manufacturing to architectural integration and platform assembly. The x-axis shows the temporal development from the 1970s until today. The hatched part illustrates the increasing outsourcing of design and manufacturing activities. Whereas until the 1990s most of those activities had been carried out in-house, today the company focuses on architectural integration and platform assembly and has outsourced most of the component manufacturing to its suppliers.

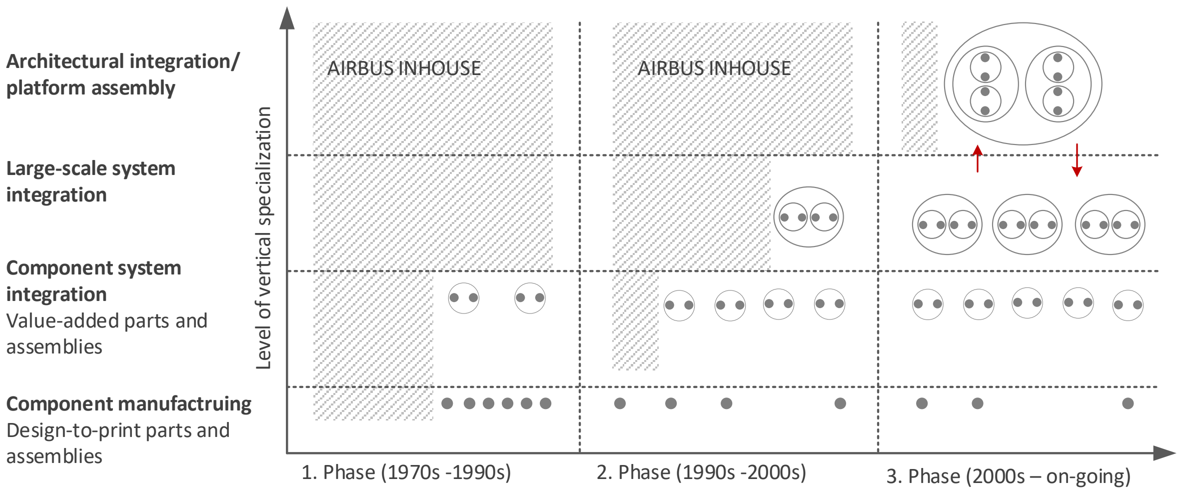


Figure 23: Main phases of modularization of Airbus industrial organizational model (author's elaboration partly based on Airbus presentation at a regional industry meeting)

Hence, in the given case technological changes (cf. Figure 22), and changes in the organizational model of exchange relations have been developed and implemented at the same time.

This lead to several **organizational tensions and technological difficulties**. For example, in the manufacture of the *Airbus* A380, engineers in Germany and Spain were working with a previous version of Dassault Systems SA's Catia design software, resulting in interoperability problems and difficulties with the installation of wires causing significant delays and massive additional costs (PD29-DOC-PRESS; PD-30-DOC-PRESS; PD19-INT-SE-LF). It also illustrates the cyber-physical dependencies in producing complex artifacts.

Modularization disembeds existing architectural knowledge and related exchange relations from their original context. In the given case, the accompanying vertical disintegration based on the outsourcing of considerable working packages disrupted existing exchange relations and routines. While at the same time, the interdependent modules required for new relational ties, close collaboration and sharing of interface-specific knowledge and information.

4.1.4 Building a new knowledge infrastructure

The prior chapter has demonstrated how exchange relations and the configuration of the structure of production relations has been changing in the first phase of strategic modularization and how technological and organizational trajectories are interwoven.

With the introduction of Open IMA and CFRP, new technologies have been introduced that also changed the technological dimension of the knowledge infrastructure. This second part focuses on the transformation of the knowledge infrastructure and especially how, where and by whom new technological and interface specific knowledge got codified and how these new standards diffused and have been enacted in the new constellation of the production network. Hence, the aim of this chapter is to show how a global infrastructure for governing technological knowledge is build and transformed during modular transition and how knowledge relations are re-embedded into that structure.

4.1.4.1 Technological and codification infrastructure

Within a highly fragmented, modularized and spatially dispersed industry, codification processes cannot simply rely on idiosyncratic firm specific practices, but must be themselves standardized. An attempt to face these challenges in the aerospace industry can be found in the ***AECMA SPEC 1000D*** standard, which is an international specification for technical documentation that uses a common source data base. The S1000D is a documentation standard that creates and provides information on the already existing web of standards in technical, product, process and materials. The initial aim of the US military was to develop a consistent documentation standard for multi-national defense projects, which allows a modular distributed documentation of technical data[54]. The S1000D structures technical documentation of systems according to their system architecture into subsystems, modules and components. Hence, the codification and integration of technical information its documentation and specification mirrors the architecture of the artifact and its decomposition into modules and sub-systems. The S1000D standard has meanwhile reached the civil aviation industry and is today also employed in other industries than aviation.

The increasing modularity in design architectures and the integration of complementary knowledge bases requires predominantly for common IT as well as compatibility and interoperability standards, because they enable interoperability and cross-organizational reliability of components and subsystems (AIA, 2005). Simultaneously, on a temporal scale, the business strategy of product life cycle management has extended the enterprise over the entire life cycle spectrum from design and development to ramp-up, maintenance and "retirement" of a product. Especially data exchange

[54] AECMA SPEC 1000D is based on US military specification standards (US MIL-SPEC), which shows again the deep intertwining of military and civilian aviation.

standards are crucial for spatially and temporally distributed design, manufacturing and maintenance practices along the life cycle (PD31-DOC-*NadCap*1). The following quotation describes how standards (i.e. design rules) become inscribed in the artifact and the processes used to create it.

> *"The rules are made by the avionics suppliers who also build the computers […] and they rely by principle on a standard, which is implemented as a "layer" within the processors. This layer functions as a contract. The layer within the processors makes sure that the rules are enforced. In other words, this is a standard, an aerospace standard, which has been jointly developed by Airbus and Boeing, but which is implemented by the avionics suppliers. That means it [i.e. the avionics supplier] publishes a rulebook that specifies this processor or this network needs to be designed and treated like that, meaning these rules need to be followed. And this guideline is part of the certification. It is a contract that says the following: dear user, those are the rules, follow them and we can guarantee you that your function will run perfectly. That also means that, we do not have to carry out any testing procedures anymore, we just need to formally proof that the rules have been followed. It is a huge advance that saves ten thousands of tests, thus, it saves a lot of money. Well, for once you need to put a lot of effort to certify that specific layer, which is a control layer in fact, but afterwards it gets far more easy." (PD19-INT-SE-LF).*

Nowadays, this type of modular avionics has become a global standard in aircrafts (cf. also (Fuchs, 2012). The basis for this technology is some of the already existing ***ARINC* standards**. A considerable amount of the *Open Integrated Modular Avionics* approach that has been first employed on the A380 is based on these standards. *ARINC* standards are open, yet proprietary.

The underlying codification practice is based on an emerging paradigm for the design of complex (embedded) systems referred to as contract-based design (CBD). This design practice particularly illustrates how expert knowledge gets codified into standard design rules that become inscribed into the artifact (i.e. the cyber-physical system). In CBD each module (or component) is associated with a "contract". The term "contract" refers to a detailed description of the expected system behavior (including all the possible system states) by specifying input-/output behavior (Cimatti and Tonetta, 2012). This approach has been, meanwhile, also adopted by *Airbus* and its system suppliers. It is an attempt to ensure a minimum of transparency and codify interface specific information and knowledge in order to ensure architectural integrity and optimal system performance in distributed value creation. Here, CBD can be considered as an operationalization of the modular avionics approach.

> *"Modular Avionics is Contract-Based Design. Why? Because this rule book says: dear user, those are the rules! Those are the assumptions or requirements and if you fulfill them, then we can guarantee that the whole network [i.e. AFDX network] will behave so and so. And in the end you only have to monitor, if the rules have been followed by everyone. That is the contract. There is a legal adviser [GER: Justiziar] who checks whether all the rules have been fulfilled and then the system will work. Modular Avionics is one of the most complex systems in the world, but this complexity does not become visible, because it is encapsulated within this contract. It reduces the whole inner quantum mechanics to approximately 100*

rules: follow them and the world will be okay. How do you do that – I don't care – as long as you follow the rules." (PD19-INT-SE-LF).

So in the case of system behavior and performance one can indeed conclude that design rules are "inscribed" within the artifact and the processes used to create them and that only interface specific design knowledge is exchanged. In this sense CBD can be considered as part of the emerging codification infrastructure and new knowledge governance patterns. This practice particularly indicates that technological standards are expert knowledge stored in the form of rules.

Finally, the physical components in cyber-physical systems are often ignored in studies of modularization. However, especially with regard to aircrafts they play a crucial role. The amount of new and "smart" materials (e.g., composite and hybrid materials cf. chapter 4.1.2) in aircrafts increases, thus, aircraft design and manufacturing involves a high amount of hitherto non-standardized special products and processes. Listing all of the standards developed in this domain would be exhausting. According to *NadCap*, from 1990 until 2010, 1,265 special processes had been defined by the standard developing organization (PD31-DOC-NadCap1; PD32-DOC-NadCap2).

Within cyber-physical systems such as modular avionics, interface specific knowledge gets embodied and stored in machines, systems and computational codes and makes inter-personal communication between different actors (i.e. firms, organizations) obsolete once the standard is established and has diffused within and beyond the production network. The codification infrastructure becomes embodied into the artifact.

4.1.4.2 Social infrastructure and diffusion of standards in the Airbus production network

Against the background that knowledge of design and development of modules is shared between specialized suppliers (often competitors), the development of complex embedded systems such as the avionic systems of an aircraft has undergone a paradigm shift in many industries (Cimatti and Tonetta, 2012), as the open IMA approach reveals for the aviation industry. This also indicates that in order to develop such a technological and codification infrastructure inter-organizational cooperation and inter-firm knowledge exchange apart from market competition and vertical exchange relations is crucial. This chapter describes who develops the standards and how it is done.

In 2004 the *Association Européenne des Constructeurs de Matériel Aérospatial* (AECMA) merged with the *European Defence Industries Group* (EDIG) and *EUROSPACE* (an association of 555 European companies involved in space activities) to become the *Aerospace and Defence Industries Association of Europe* (ASD), who are now the editors of the S1000D documentation standard. In 2005, the US American Air Transport Association (ATA) also joined their committees. The emerging codification infrastructure for technical documentation enables actors to operate in an environment that is characterized by geographically distributed and socio-culturally diverse actors. Today, the ASD also participates in standard setting through their affiliate organization ASD-STAN and simultaneously carries out conformity assessment and qualification via ASD-CERT. *Airbus*, *Boeing*, *Bombardier* and all the big system suppliers are members of the ASD[55].

According to the Working Group on the Future of Aerospace Standardization, the fastest growing domain in standardization work in the aerospace sector is participation in IT-standard setting, in order to ensure compatibility, interoperability and interconnectivity. *ARINC* (Aeronautical Radio Incorporated) is a firm founded in 1929 in Annapolis/Maryland[56]. It today develops standards for communication protocols between different systems in avionics. A considerable amount of the *Open Integrated Modular Avionics* is based on these standards, which are open, yet proprietary, meaning they must be bought. This brings me to an increasing trend in aerospace standardization, which can be found in an increasing privatization of standard setting and conformity assessment activities. *ARINC* Inc. as the leading developer and provider of standards in avionics has been bought by Rockwell Collins, as a major global player in the aerospace and defense sector, in 2013, indicating that IT standard setting, provision and distribution are growing business field in aeronautics.[57] In this course, *ARINC*'s Industries Standards Organization has been sold to *SAE* International (Society of Automotive Engineers) as a "neutral" actor and the global leader in VC-based standard setting through industry consortia. The *ARINC* aviation industry activities that are organized under the auspices of *SAE* "cooperatively establish consensus-based, voluntary aviation technical standards that no one organization could develop independently.[58]" Through the Airline Electronic Engineering Committee (AEEC) engineering standards and technical solutions for avionics, network and cabin systems are developed. According to numbers from *SAE*, over 4,000 engineers and scientists that represent approximately 250 sponsoring organizations participate in the development of *ARINC* standards, defining the equipment and systems installed in more than 10,000 aircrafts around the world.[59]

The *SAE* portfolio covers standards development, publication, conferences as well as certification. Founded in 1905 for the emerging automobile market, *SAE* expanded in 1916 to incorporate aeronautics. Until today it developed more than 8,000 aerospace related standards and in 2007 an *SAE* Aerospace Standards Europe office opened in London in geographical proximity to leading system developers in the aircraft and defense sector. Although *SAE* International is a not-for-profit-organization it has various for-profit subsidiaries such as the Performance Review Institute (PRI) and the ITC Industry Technology Consortia (ITC), which are separate legal entities that are, yet, managed through the CEO of

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[55] http://www.asd-europe.org/about-us/asd-at-a-glance
[56] https://de.wikipedia.org/wiki/ARINC
[57] https://www.rockwellcollins.com/Data/News/2013_Cal_Yr/RC/FY14RCNR13-ARINC-close.aspx
[58] http://aviation-ia.com/standards/index.html
[59] http://www.aviation-ia.com/aeec/

SAE International. In 2012 the two mentioned subsidiaries achieved an annual revenue of 57 million US dollars. [60]

As has been pointed out in the prior chapter, aircraft design and manufacturing involves a high amount of hitherto non-standardized special products and processes. These are, however, not developed and processed by *Airbus* as the architectural integrator who modularized and outsourced a considerable amount of development and manufacturing (cf. chapter 4.1.2), but by its specialized suppliers. Consequently, the lead firm lacks knowledge and capabilities to set standards in these domains or assess the reliability and quality of these special products, materials and processes. Against this background, in 1990 the *National Aerospace and Defense Contractors Accreditation Program* (*NadCap*) has been founded as well as, in collaboration with several governments, the *Performance Review Institute* (PRI) as a for-profit subsidiary of *SAE*. *NadCap* is a global industry-controlled program designed to manage a cost-effective consensus approach to special products and processes for the aeronautics sector by providing special product and process assessments and accreditation services. In these terms, the PRI administers *NadCap* and executes conformity assessments.

As has been argued in Chapter 2, knowledge and production relations are not in any case congruent in a production network. Hence, the network relations of actors involved in standard setting as well as the nature of these relations, in the given case, essentially differs from the vertical buyer-supplier relations. This raises the question as to how both come together or, in other words, just how does the new codification infrastructure diffuses among suppliers in the *Airbus* production network?

Within a document from 2010 where *Airbus* announces it's new material procurement strategy and the general requirements for aerostructure and materials suppliers (GRAMS) as well as for equipment and system suppliers emphasizing that "they need to set up a control to *minimize new standards and to replace the very few consumptions by alternatives.*" (PD26-DOC-PRO1, p. 5, emphasis added). This strategy aims at "building up international standards on special processes that include *Airbus* requirements and to implement a robust oversight of suppliers' special processes (rigorous and systematic)." (ibid.) A major underlying interest of the firm behind this strategy is to purchase material parts and aerostructure components outside of the western European hemisphere. This presupposes the codification of respective knowledge into standards as well as the enablement and qualification of suppliers to fulfill these standards. Hence, *NadCap* committees are not only codifying knowledge into common standards, it is also used as a tool for supplier qualification. A *NadCap* accreditation/certification is now mandatory for respective suppliers to enter the *Airbus* network.

Whereas major first tier and system suppliers in aeronautics such as Honeywell and Northorp already became members of *NadCap* in the early and mid-1990s, *Airbus* itself became an active member in 2002. *Airbus* now tries to control standard-setting activities at *NadCap* through participating in

[60] http://itc.sae.org/

management and oversight activities. “[*Airbus*] recognizes certificates granted by *NadCap*, mandates its suppliers to gain and maintain *NadCap* accreditation and flow down this mandate to their sub-tiers as applicable.” (PD31-DOC-*NadCap*1). Thus, they are directing the formulation of and conformity to standards to their suppliers on lower tiers through coercive and normative pressure. Until 2005, all the relevant system suppliers and prime contractors had gained *NadCap* accreditation in order to participate in common standard setting and “outsource” the conformity assessment measures (i.e. auditing, qualification, certification) to the PRI (subsidiary of *NadCap*). Before the establishment of *NadCap* as an overarching epistemic community, firms in the air- and space travel either carried out their own supplier audits according to their own specific procedural requirements, in order to achieve conformity. This is, however, only possible if procedures are similar or at least comparable to those of the focal companies, or in other words, if they share the same knowledge bases. The former procedure could no longer be maintained simply because of a lack of expertise. Thus, *NadCap* and the PRI are now being used by *Airbus* for controlling and coordinating widely distributed design and manufacturing activities within its global production network. Referring to data from 2012, *Airbus* (including subsidies) was involved in 3 of 4 management boards of *NadCap*. They held 20 employees (each) in eight out of ten existing technological task groups, thus, actively participating in standard formation related activities (EADS, 2012).

Standards are the basis for certification and approval of any aircraft related product and manufacturing process. Hence, there is also a need for common and consistent *de jure* standards and their institutional integration. In this regard, the formation of the European Aviation Safety Agency (EASA) illustrates the increasing trend from national to international standards. Before the establishment of the EASA in 2003 each nation state had its own agency and its own rules and certification procedures. In order to cope with the challenges of globalizing production networks the EASA has been founded as a response to the powerful Federal Aviation Administration (FAA) in the US and the growing need for consistent common standards and rules within the European economic zone. Ratified in 2002 and established in 2003, the EASA is now the regulatory agency of the EU for civilian aviation safety. The EASA sets and monitors common security and environmental standards (certification, approval, standards, languages etc.). Their first and simultaneously most prominent project has been the type certification of the highly modularized A380 (PD33-DOC-EASA). Whereas EASA sets *de jure* safety and environmental standards, it is the national agencies such as the Luftfahrtbundesamt (LBA) in Germany that are responsible for their execution in terms of approval and certification. Major challenges are imposed through the harmonization of existing standards. With regard to *de jure* standards, formation-related activities have been spatially as well as institutionally centralized in the EU. The headquarters of the EASA are now located in Cologne (western Germany).[61]

[61] https://www.easa.europa.eu/the-agency/the-agency

The EASA - as the legally binding regulatory agency in Europe - acknowledges the industry standards and conformity assessments developed and carried out by *NadCap*. The *NadCap* Program has been recognized by the EASA in 2010 (cf. EASA Decision 2010/016/R)[62] Thus, *SAE* standards development and EASA regulations and certification practices are deeply intertwined, since EASA certifications are largely based on *SAE* standards and documents. The difference lies simply in different taxonomies and nomenclatures. This is how so-called voluntary-consensus based standards set by industry consortia are finding their way into the *de jure* (and thus legally binding) rules of the EASA that any firm involved in the aerospace industry needs to comply to and gain certification. Standards development organizations assess their impact by counting the number of standards (developed under the auspices of their organization) that are referenced within EASA or FAA documents that are necessary in order to get a product or process legally approved and certified. According to data from *SAE* and ASD, almost 75% of the standards referenced in EASA and FAA documents have been developed by three private organizations and their subsidiaries: *SAE* (*ARINC*, *NadCap*), followed by ASD-Stan and ASTM.

4.1.4.3 Socio-spatial embedding

In chapter 2.1.3, different dimensions of embeddedness have been defined. Socio-cultural or institutional embeddedness, network embeddedness and the overall territorial embedding of actors and relations.

Considering the dimension of **network embeddedness**, what becomes particular evident is that actors in the *Airbus* case are at the same time embedded into vertical production relations as well as more horizontal knowledge relations. A closer look on the membership lists of supervisory councils and management boards of organizations that are engaged in standard development and regulation such as the *SAE* (including *NadCap* and *ARINC*) reveals that they are constituted of 4 groups of actors: representatives of lead firms (i.e. *Airbus*, *Boeing*, Bombardier, *Embraer*), representatives of system/first tier suppliers (e.g., Honeywell Aerospace, BAE Systems, Lockheed Martin, Lufthansa Technik, Northrop Grumann, Rolls Royce etc.), representatives of governmental agencies (e.g., FAA, EASA, NASA, U.S. Department of Defense etc.), representatives of other associations (e.g., ATA/A4A) as well as representatives of commercial airlines.

These organizations create spaces within which the boundaries between market competitors and state actors become increasingly blurry and the different interest groups are able to negotiate common standards and rules. In the given case, the actors that set the standards are deeply intertwined with the actors that assess conformity (e.g., certifiers as regulatory authorities) to these standards forming what I call powerful ***networks of compliance***. The codification of technological knowledge takes place within these international networks. It is embedded into two major **institutional settings**: voluntary-consensus

[62] http://cdn.p-r-i.org/wp-content/uploads/2012/11/EADS.pdf

based standard setting in industry consortia as well as de jure standard setting in public regulatory agencies. Here, the prior chapter has also shown that boundaries between private and public institutions become increasingly blurry. A standard that is formulated by an industry consortia constituted of firms with different strategic interests becomes a *de jure* directive to gain EASA certification and approval. Hence, standards developed by private industry consortia can become directives that are mandatory for any suppliers that want to participate in the *Airbus* production network.

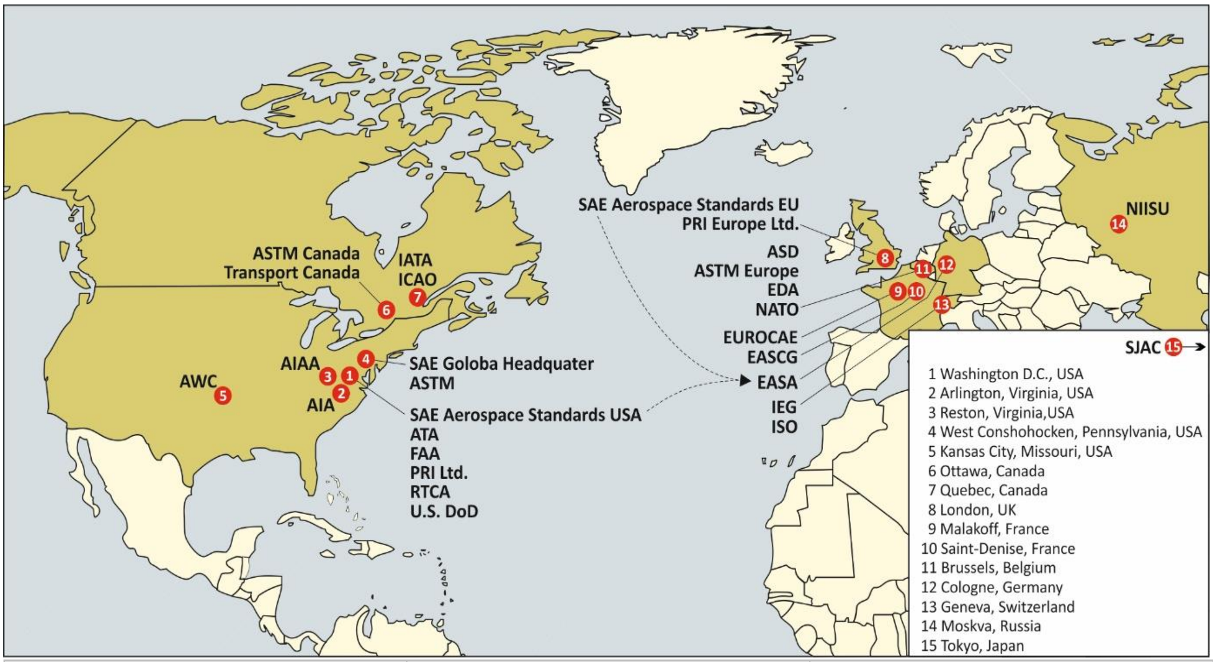
Against the background of an increasing deregulation and liberalization, in order to create a free market zone in the EU, standard setting has been increasingly centralized and privatized. The landscape and practices of standard setting actors and regulatory agencies in the European economic zone has severely changed over the last decades. From an organizational point of view, de jure standard setting became centralized and integrated into a single organization (i.e. the EASA) creating common standards for the EU. Hence, actors needed to connect to these new procedures and international conventions mostly through gaining EASA certification instead of prior national ones. This re-embedding of knowledge relations and connecting to new codes has also strongly affected local suppliers (cf. chapter 4.2).

Regarding voluntary-consensus based standard setting, codification practices diversified and now take place in global networks or epistemic communities of practice that meet only temporarily in space. The lead firms are at the same time intermediaries and gatekeepers of knowledge and formal codes. The epistemic communities and networks of compliance evolving from that governing through standards pattern are extremely exclusive, since accreditation, for instance to *NadCap*, is very costly and time-consuming. Moreover, although the annual conferences of *NadCap* or *ARINC* are free of charge, smaller companies often lack resources to get involved in standard-formation activities. Lead firms, systems/first tier suppliers and public regulatory agencies together set the codes for getting engaged in the given case example. Against this background, a whole new industry service sector has evolved consisting of consultants, certifiers, accreditors who extract value from creating, interpreting and applying standards or carrying out conformity assessments.

There are however locations where standard organizations offices are agglomerated or strategically located in spatial proximity to leading system suppliers and hubs of the aerospace industry taking advantage of the existing local networks and vice versa.

The following figure displays the geographical location and landscape of standard developing organizations and regulatory bodies that demonstrates that, despite of the emergence of the EASA, standard formation is in most of the cases dominated by US-based organizations, which is not surprising since the US has been dominating the industry for decades.

Figure 24 shows the geographical distribution of global standard developing organizations. The arrows illustrate which organizations develop standards that are later referenced in EASA certifications and where they are located. The legend below classifies the major organizations involved in standard setting for the Airbus production network into public regulatory agencies, industry based development organizations as well as private regulatory agencies indicating their institutional embedding.



Public regulatory agencies (certification/ approval)	Industry-based standards development organizations	Private regulatory agencies (certification/ approval)
ASTM (American Society for Testing and Materials) EASA (European Aviation Safety Agency) EASCG (European ATM Standards Coordination Group) EDA (European Defence Agency) FAA (Federal Aviation Administration)	AIA (Aerospace Industries Association Inc.) AIAA (The American Institute of Aeronautics and Astronautics) ASD-STAN (Aerospace and Defence Industries Association of Europe (formerly AECMA)) EUROCAE (European Organisation for Civil Aviation Electronics) *SAE* (Society of Automotive Engineers)	PRI Performance Review Institute ASD-Cert (Aerospace and Defence Industries Association of Europe (formerly AECMA))

Figure 24: Location and institutional background of standard setting organizations and regulatory agencies

4.1.5 Synthesis and conclusion

The modularization of product and process architectures always implicates a change of the existing exchange relations in a production network. Chapter 4.1.2 has described the interrelations between changing relations of components (system elements on the level of the architecture of the artifact) and structural and relational changes on the network level. On the level of production relations, modular transition in the given case is mainly characterized by:

- vertical disintegration,
- vertical specialization,
- the reconfiguration of exchange relations based on the First-Tier-Model,
- the disembedding of prior production and knowledge relations from their former context,
- and resulting organizational and technological difficulties and tensions.

The shifting in hierarchies and the increasing vertical specialization and decomposition of existing knowledge bases is also known from other modularizing industries such as electronics and automotive (Herrigel and Wittke, 2006; Jacobides, 2005; Sturgeon, 2003) (cf. chapter 2.1.2 and 2.4). It requires for the development of collective coordination systems that enable the architectural integrators (i.e. *Airbus*) to keep control over the distribution of knowledge and design information throughout the design and production processes and on a broader time horizon throughout the entire life cycle of an airplane.

The second part (4.2) has described and analyzed how knowledge relations have been altered and how the knowledge infrastructure has changed during modular transition and growing technological and organizational modular maturity. An infrastructure has been build that re-embeds knowledge relations that are necessary to develop common codes and to share knowledge and design information apart from the vertical and competitive buyer-supplier relations that give structure to (conventional) value chain configurations and relations in production systems. Figure 25 summarizes the knowledge infrastructure that underlies the modular transition.

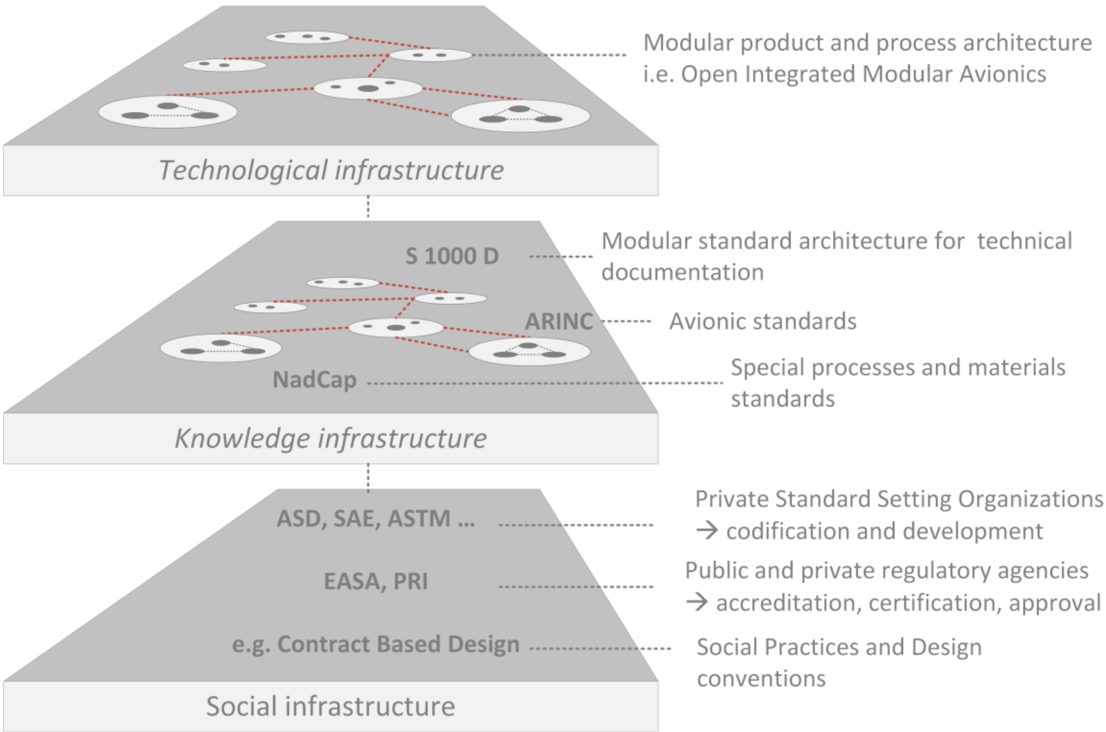


Figure 25: Dimensions of a knowledge infrastructure in the Aerospace Industry

From a dynamic perspective, socio-organizational and technological trajectories increasingly intertwine as displayed in the timeline (cf. Figure 26) that links central events of technological change to central events of socio-organizational change of knowledge and production relations during modular transition. After a phase of trial and error in terms of technological systems as well as organizational models – the understanding of technological as well as organizational interdependencies increases. This increasing understanding leads towards the growing **modular maturity of design and organization**. Knowledge on technological interdependencies and interactions gets codified within common standards and the diffusion of these standards within the production network increases as also shown in the timeline below.

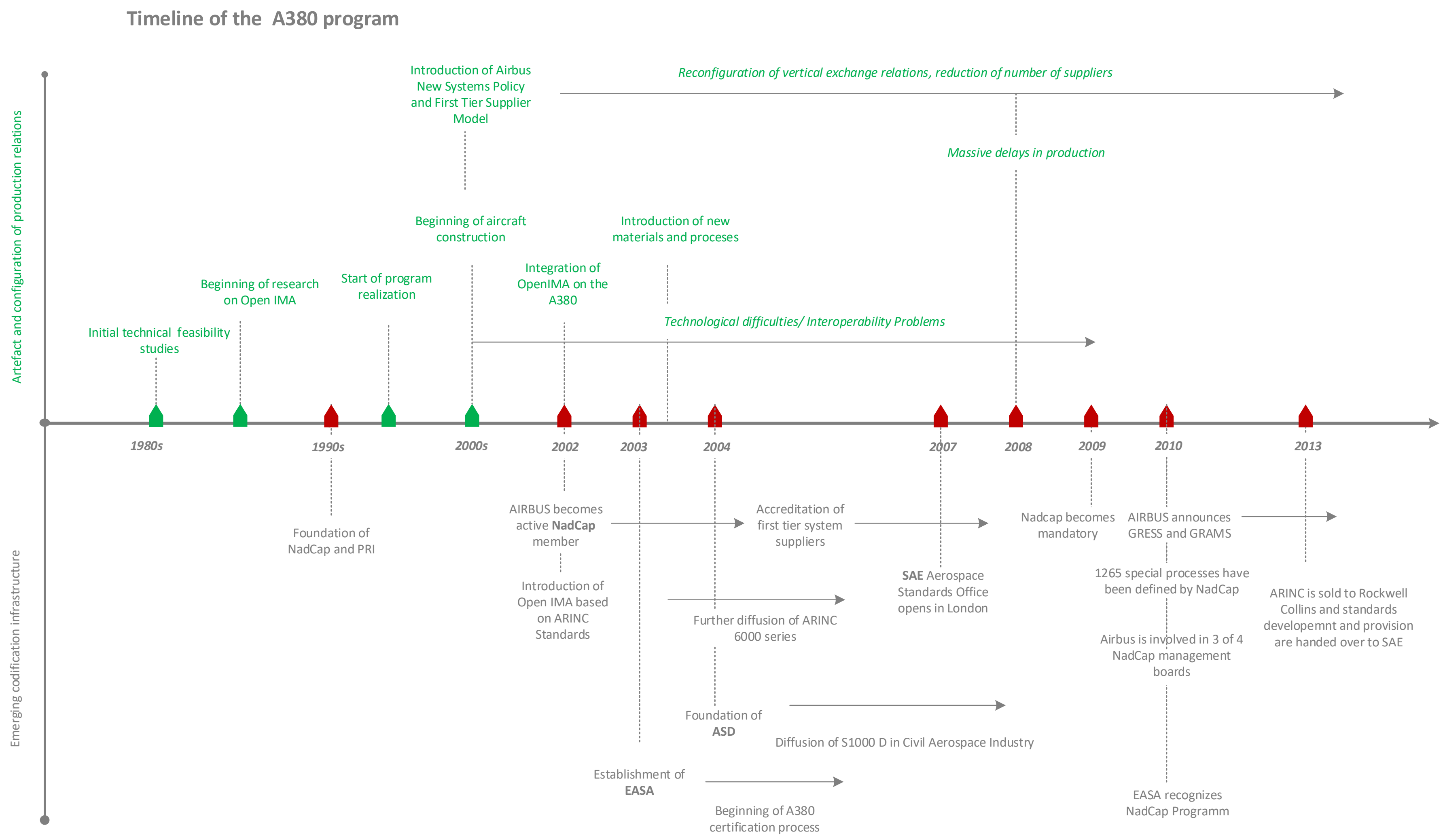


Figure 26: Socio-technological trajectory of the A380 program

4.2 The impact of modular transition on the aerospace cluster in the metropolitan region of Hamburg

4.2.1 Former embedding of suppliers in vertical production and knowledge relations

Even if a production network is basically dominated by the actors that take an integrating role (i.e. *Airbus*), the internal behavior is considered to be organic as the regional networks have evolved over time. Close, long-term personal relationships building on a high level of cognitive proximity, interpersonal trust and mutual dependence have been characteristic for the constellation in Hamburg. Orders came *directly* from *Airbus* to its diverse suppliers without passing through numerous sub-contractors. Suppliers took the role of "external workshops" providing components based on exact specifications of the designer (cf. also chapter 3.1.1).

> *"When it started with Airbus there were numerous suppliers, one for each service … or multiple suppliers competing for one service. […] back then I was at a company – that doesn't exist anymore today, they were producing bulkheads, flaps and other things. I asked them, what is your specific product? […] They answered that it is Airbus No so and so… This is significant, you know. Orders came directly from Airbus to them, no one defined the specific product or service he provided, no one had to carry out acquisitions, suppliers were the extended work bench and it was a relatively stable business for them." (PD9-INT-PO)*

The specification of products and services or in other words the codification of component and interface specific knowledge was at a very low level at that time. This somehow prevails until today on the local level. According to data from a strategy workshop with members and the management board of HAV in 2014, there is still a lack of standardized and process optimized workflows and processes in the SME domain and the amount of so-called (not specified) "individual engineering" is very high (PD28-DOC-CLUSTER-STRAT).

Thus, compared to today, direct face-to-face communication and a rather low level of standardization and formalization marked the interaction between the heterogeneous actors at the location for many decades. R&D and production was characterized by a strong control of knowledge flows, particularly on the system level, which has been realized strategically by spatial concentration and co-location (cf. also chapter 3.1.1). This strong dependence and control exercised by the lead firm is an indicator for a captive value chain configuration in which exchange relations are vertically integrated. The complexity of product specifications is very high, but available capabilities in the supply base to codify are relatively low. This is why *Airbus* established captive links, making suppliers extremely dependent. Knowledge transfer within this form of governing exchange relations is limited to the tasks and operations of the respective manufacturer or engineering service provider.

Nevertheless, besides what is referred to as "local buzz", there has been another indirect/informal form of knowledge diffusion within the production network. One interviewee described it as a principle analogously to the "Chinese whispers [GER: Stille Post]". *Airbus* formulates a so-called top-level purchase technical specification (PTS) containing the major technical requirements that must be met. From an engineering perspective, this PTS gives an initial frame of the problems that need to be addressed. This document serves as a basis for suppliers to respond with appropriate offers (i.e. solution/synthesis). These offers contain technical solutions and serve as a basis for the modification and reformulation of the PTS. Within an iterative process knowledge then diffused indirectly among the different suppliers and technological developments became increasingly homogenized over time, as the following quote illustrates:

> *"Airbus reformulates the solution given by one supplier and adds additional specifications, then sends it to the next, who is like 'Ah interesting, that is probably based on solution XY …' and that is how knowledge has been circulating – in a very very indirect manner. […] This also explains the similarity of technological developments over time. Because of these tenderings [i.e. PTS] knowledge flows back and forth, gets condensed at the OEM and over time it all becomes a homogenous mass." (PD19-INT-SE-LF)*

This prior pattern of knowledge diffusion can be compared to a wheel structure and illustrates the strong control of knowledge flows by the lead firm. *Airbus* directly exchanged information/knowledge with a very high number of different suppliers, whereas the suppliers did not exchange knowledge and information directly amongst each other, however, it indirectly diffused via *Airbus*.

As a result, one can speak of a rather "hermetic mentality" that has been characteristic for the aeronautical sector with regard to knowledge sharing and collaboration with other firms. This procedure also indicates that *Airbus* was still capable of formulating meaningful specifications for almost any of its components and systems at that time, because development and design activities had predominantly been carried out "in-house." Due to the strong consolidation of the market and the outsourcing of considerable working packages (often referred to as integrated service bundles) including design and development as well as rapid innovation in avionics and embedded systems, the workshare among the actors in the production network has been changing (cf. chapter 4.1.3). This also disrupted knowledge, competencies and routines that had been developed (internally) in these fields.

4.2.2 Disembedding and re-embedding of production and knowledge exchange relations

The strategic modularization of product architectures initiated the reorganization of the production network into segregated "working packages" and the diffusion of the so-called Tier 1 Model (cf. chapter 4.1.3).

If one takes a closer look at the competencies and structure present in the Hamburg region (cf. chapter 4.1.2), most of the local SMEs in the Hamburg Metropolitan area are lacking the capabilities (knowledge, expertise, financial resources) required for becoming a first tier *system* supplier. A major shortcoming of smaller firms is their lacking competencies in information technologies. There are no relevant system suppliers in the area, thus, participation in standard formation activities and access to the *Airbus* production system are in other regions such as the UK, US and France.

Hence, new system suppliers (i.e. system integrators) have to be formed on the regional level, if local actors want to stay in the *Airbus* production network. Many SMEs felt threatened and have meanwhile disappeared or oriented their activities towards neighboring sectors. A statement of the representative of a local SME Association shall illustrate the perception of the new economic environment after the consolidation of the production relations:

> *"How can we manage to survive as medium-sized companies [GER: Mittelstand] in this region in an environment that only deals with first tier companies? Everybody here lost their status as a direct supplier to Airbus. This is only reserved to the first tiers […] Access points to the value chain are not here anymore, but somewhere else in the world, namely, where the first tier companies are located." (PD12-INT-SME-ASSO)*

In the field of service engineering[63] where the majority of firms in the cluster are to be located, the further modularization of the supply chain can be understood as minimizing *task* interdependencies in order to define self-contained work packages. This has been operationalized in an overall consolidation and rationalization of the supplier network based on sub-contracting, which has been increasing since the late 1990s (cf. chapter 4.1.3). Especially in Germany, sub-contracting had a rather bad reputation before in this sector. The few big internationally active companies that still have direct linkages to *Airbus* (i.e. act on the first tier) are mostly French or have been taken over by French companies (PD14-INT-ESP). Out of the 12 engineering service providers that are located in Hamburg and are members of HECAS (cf. chapter 4.2.4) only four have been "awarded" the status of *Airbus* E2S[64] preferred suppliers for engineering services; among them the big international corporations or their subsidies such as SogiTech (Cap Gemini) (PD35-DOC-E2S). Moreover, many engineering service providers carried out testing services. Open IMA and *NadCap* make some of these tests obsolete. The introduction of the Open IMA and related standards also means that there is no need for carrying out testing procedures in this domain anymore, it just needs to be formally proofed, if the rules implemented in the architecture of the system have been followed. This saves up to 10,000 tests and the associated costs (cf. chapter 4.1.3). Combined with the consolidation of the supply base this has led to the disappearing of many small and medium sized engineering offices.

A lot of indirect, informal knowledge diffusion in this sector now takes place through temporary employment of engineers in different contexts, enticing of employees and temporary sub-contracting.

[63] E.g., testing, simulating, modeling, numerical controlling, manufacturing build-to-print parts etc.
[64] E2S is the abbreviation for the new service engineering purchase strategy.

That, in turn, also means that long established experiential knowledge that has been accumulated over years and decades is destroyed or becomes obsolete due to this new more flexible and “lean” engineering service sourcing strategy. A small engineering service provider illustrates the current situation he is finding himself in as follows:

> *“With Airbus I’m a sub-sub-sub-sub-sub-supplier, who can only be engaged via five nodes, which takes a lot of effort […] and I don’t know, who else profits from my hourly rate. It is an outrageous situation not suitable for cooperation at all […]. The whole ‘Airbus mentality’ is not helpful with their ‘I’m gonna go buy some work packages’. I’m an engineer, I look for solutions, I’m gonna make that thing fly, but they are just like ‘how much does that piece of engineer costs?’ […] I know a lot of engineering offices here, who say ‘Why should I get involved in aeronautics, that is not interesting to me, you are only a working package, you get payed extremely late and then there are a lot of misunderstandings and adhesion contracts on top.’” (PD4-INT-ESP)*

Figure 27 illustrates this kind of structural disembedding and cutting of ties of the spatially close former supply base of *Airbus* Hamburg as well as the global integration of the latter. By creating a structural proximity to distant first tier companies in other regions in order to tap out their knowledge and skills, simultaneously, a structural distance to the actual spatially proximate actors in the regional cluster has been produced. Hence, the communication path and network distance to the geographically proximate prime contractor *Airbus* for suppliers on lower tiers in the region increases.

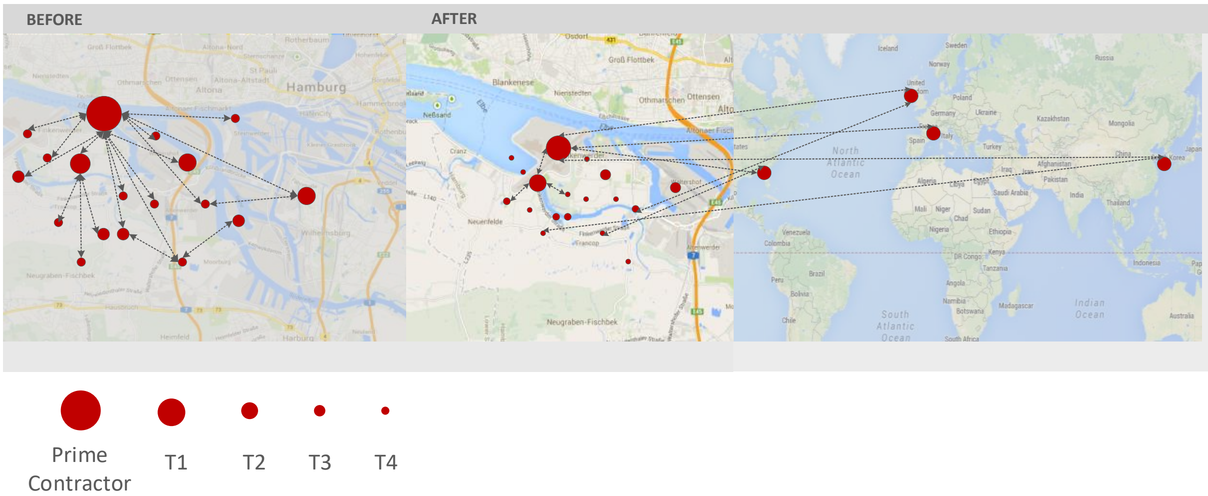


Figure 27: Local disembedding and global integration of the supply base in Hamburg

Hence, a lot of small engineering offices orient their activities more to neighboring industries such as the wind energy (Markus Adrian, 2015), the shipping industry or the light weight material construction industry (PD4-INT-ESP; PD18-INT-PO). Especially, the light weight industry that has its origins in the aerospace sector and came to the region due to *Airbus* in the 1980s, follows a strategy of emancipation and differentiation. As a result, a spin-off cluster, the CFK Valley e.V., has emerged throughout the last decade with increasing international recognition (PD18-INT-PO).

Comparable to the development in the automotive or electronics industry, aerospace suppliers are now trying to cope with these changes by acquiring and merging with other suppliers leading to the emergence of globally active and financially strong company groups mainly in France, the US and the UK (e.g., BE Aerospace, Thales, GKN). SMEs on the local level have not positioned themselves in the market with regard to a product oriented innovation strategy, they have been directing there activities mainly according to the demands of the focal company (i.e. *Airbus*) (PD1-INT-CM).

Consequently, within the *Hamburg Aviation* cluster this development has, until now, only very limited taken place leaving the intermediary markets of systems supply business to other predominantly French and US company groups. Only one merger has been successful so far, that is the case of Diehl buying two other aircraft interior companies to form a system supplier and could, thus, gain a first tier position. However, the new system supplier for air cabins has been formed as a reaction to *Airbus* new systems policy, therefore, well designed organizational and technical interfaces, standardization as well as system and management capabilities have not already been given, but have to be incrementally established. The new formed DIEHL Service and Comfort Modules, in order to cope with the new challenges and to reduce uncertainty, vertically re-embedded suppliers on lower tiers as a reaction to the new environment. Hence, processes of disembedding (i.e. vertical disintegration) initiated by *Airbus* new systems policy, resulted in processes of re-embedding (i.e. integration) on different tiers of the production network.

Actors in the production network are partly still in a phase of trial and error. The tearing up of existing modules and the emergence of new interdependent modules that affect multiple other modules also fragmented the existing knowledge and competencies which need to be re-integrated and build-up piece by piece in some contexts. Organizational experimenting and discontinuities mark this phase of modular transition on the local level. DIEHL tried for instance also to modularize and decentralize design and construction of cabin components, so that it is only involved in system integration. However, the cost for codification of respective knowledge are too high for small contract manufacturers, they lack resources and capabilities to engage in higher value-added activities, as the following citation from a contract manufacturer shall illustrate:

> *"They [i.e. DIEHL] wanted to outsource the design sovereignty and decentralize the construction so that each single firm designs and constructs their part and then harmonizes it with the others, but that did not work. There need to be a central authority making the decisions. […] That means that DIEHL has the authority and defines, which requirements the parts have to fulfill so that everything fits together in the end. (…) DIEHL intended to outsource the construction, because it is very costly. If they had done so, our company would have had to engage external construction engineering offices, since we do not have this competency,*

> *we are a manufacturer and we do not have the financial resources. […] we had a request for a plastic mirror for the A350. Manufacturing this mirror [according to existing specifications and standards] costs around 60 to 70 €. Anyhow, including the construction, technical documentation, installation and reconstruction measures costs rise up to € 800,000." (PD11b-INT-CM-1)*

To conclude, design, construction and production now takes place *across* companies and institutional contexts, which has not been the case before in most domains of the industry with its rather hermetic mentality. Thus, in order to ensure a smooth design and production process exchange relations have to be re-embedded and new routines and mechanisms have to be developed, in order to facilitate knowledge exchange and coordination (at least form the point of view of the actors in the production network that take an integrating role).

Throughout chapter 4.1.3, I have described how a new knowledge infrastructure for governing knowledge across contexts and places in a global, modular production network has been developed by the lead firm, relevant system suppliers, as well as public and private-public institutions. Depending on the reach and scope of the production network (global –local scale) it links different places and conventions of practice. In any case, it is learned of as part of membership (cf. chapter 2.3.5). Hence, the embeddedness of the creators and users of this knowledge infrastructure plays a crucial role in terms of the enactment of technologies, standards and, in the case of modularization, architectural paradigms (cf. chapter 2.5.2 and 2.5.3).

In the given case, the knowledge infrastructure is imposed on actors on lower tiers of the production network via coercive and normative pressure (cf. chapter 4.1.3.1). A large amount of them has not been included in the development of codes and standards. Competencies on the local scale are mostly in materials and parts manufacturing as well as service engineering (cf. chapter 4.2.1). According to data from the eAudit platform[65], until today only firms in northern Germany have gained *NadCap* accreditation, all of them belong however to the *Airbus* (formerly EADS) division[66]. Whereas *NadCap* events take place three times a year in changing locations and are free of charge, certification and accreditation are very costly and time-consuming procedures discouraging SMEs with less resources and internationalization intentions. According to data from a strategy workshop with members and the management board of HAV in 2014, there is an overall lack of standardized and process optimized workflows and processes in the SME domain and the amount of so-called (not specified) "individual engineering" is very high (PD28-DOC-CLUSTER-STRAT). This also explains why they are excluded from the production network. They cannot connect to the new codification schemes. They are (suddenly) confronted with formal codes that are developed by very distant epistemic communities and enforced by prime contractors as the dominant demanders of this formalized knowledge. SMEs/Suppliers in the

[65] https://www.eauditnet.com/eauditnet/ean/user/mainpage.htm

[66] Airbus, Aibus military, Eurocopter, Premium Aerotech, Aerolia, Cassidian.

Hamburg Aviation cluster are mostly cut-off these communities and networks and, therefore, also cut-off of knowledge flows and access to the global production network. The increasing use of formal industry-specific standards/norms by *Airbus* profoundly affects the interaction with its suppliers especially those on lower tiers having no direct linkages to *Airbus*.

Formal technology standards codify knowledge (technical data) within a specific language developed in the epistemic communities of standard setters. They are learnt of as part of membership. From the knowledge integrators point of view, standardization practices that accompany an industry during modularization foster global collaboration and enable the control and distribution of design and process specific information and its architectural integrity. But at the same time, tensions between this very formal technocratic information infrastructure tend to evolve when confronted with local realities. Those tensions mainly arise in terms of translation (i.e. understanding/decoding that information), trust, as well as related processes of inclusion, exclusion and marginalization.

Interviewees reported that they had to engage additional employees who are able to "decode" that specific formal language and web of rules (PD11a-INT-CM-1; PD11b-INT-CM-1). In the given case and the given state of analysis, rules and norms did not reduce cognitive complexity for these actors. Instead, the opposite is the case. In order to give the reader an idea of the formalization and codification of knowledge, norms and processes in terms of qualifying as an *Airbus* supplier, the following chart displays changes and requirements for supplier approval. It has been presented at a regional industry meeting throughout the time of my research:

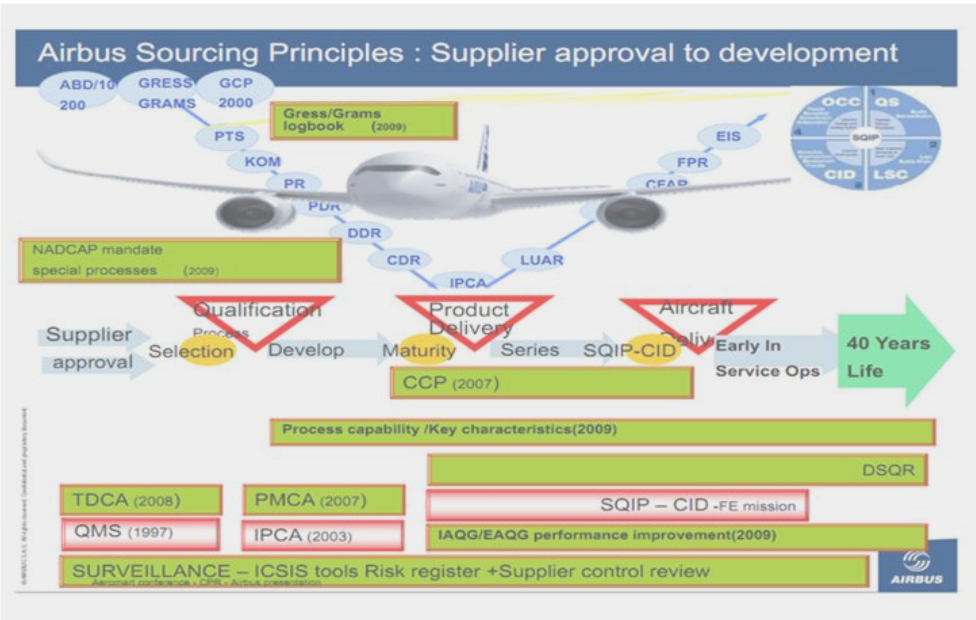


Figure 28: Airbus sourcing principles (Source: PD25-DOC-PRO-1).

The chart illustrates the changing requirements for qualification and contains numerous abbreviations. I asked several *Airbus* employees later to explain that jungle of abbreviations for me, but they were not able to entirely decode its exact meaning. The point I want to make here is that a small company may have an innovative idea or develop specific experiential knowledge, but they fail to link it to the web of existing codified technological norms and meet the challenges of regulation and bureaucracy as well as the financial power to cover the costs for approval.

4.2.3 Changing relations of trust

Trust is of fundamental importance when it comes to establishing and maintaining exchange relations and spatial proximity certainly facilitates building inter-personal long-term trust-based relationships (cf. chapter 2.1.4).

A lack of trust has been one of the core categories detected during the analysis of the interview data and field notes. This became evident in a pervasive distrust and what I refer to as “bitterness” towards the lead firm that spread among local suppliers.

> *“If I look over my shoulder there are not many companies left. I'm the only one left...it has been a complete disaster. So they put all this money into the Excellence Cluster and all that but there's only, you know, it's like watering you garden. You know the lawn is gone, there is only sand left and there's only a little weed there in a corner, you know and why invest there? It, it, it's toxic, it's-, they've been, you know, poisoning enough, they've been stealing enough staff, takin' our money and takin' our ideas. (laughs)” (PD14-INT-ESP).*

Those actors that could not cope with the changing conditions were suspicious and not willing to share or cooperate anymore. Interview partners complained about the lack of trust and the destruction of trust relations and have considered this as the main barrier to developing new horizontal exchange and knowledge relations within the cluster (PD7-INT-DLR; PD14-INT-ESP, PD12-INT-SME-ASSO; PD2-INT-LF). The fear of losing competitive knowledge and, hence, the strong need to protect “intellectual property” constrained many efforts to bring actors back together.

Paradoxically, the need to cooperate and share knowledge increased at the same time. As described throughout chapter 4.1.3 the formal supplier network has been cascaded into hierarchical tiers (first, second, third, n-tier), that means that:

> *“[…] there is one OEM [i.e. Airbus] who roughly specifies the system architecture, outsources it to the first tier supplier, who in turn needs to bundle and integrate all the suppliers on lower tiers and deliver the whole ‘product.’ […] What happens then is the following: The other suppliers complain: why should I share any of my knowledge? Those guys are my competitors!” (PD19-INT-SE-LF)*

It has never been a problem to give this information directly to *Airbus*, because *Airbus* had no intention to build and sell, for instance, its own fire smoke detection systems as opposed to Honeywell.

Figure 29 illustrates the above described changes.

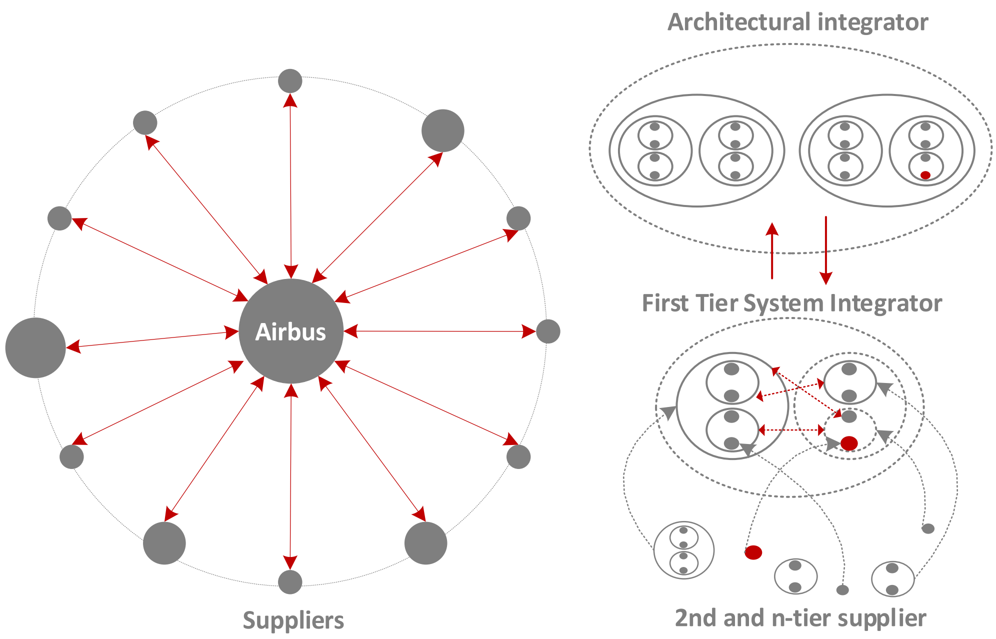


Figure 29: Knowledge exchange relations before (left side) and after modularization and cascadation of the supplier network (right side)

As a result, **tensions and conflicts increase** in terms of the coordination and sharing of knowledge and design information that affect the compatibility and interoperability of parts (e.g. plastic mirrors for the cabin) and systems (PD11b-INT-CM-1).

The destruction of existing trust-based relations is to a considerable extent the outcome of the top-down implemented modularization. Technological, proprietary and organizational interfaces have not been harmonized and hence conflicts and tensions are likely to occur.

Moreover, modular industry structures and related patterns of knowledge governance in a more mature state establish a governing through standards pattern. In doing so they disembed and anonymize or "de-personalize" interactions and transactions between actors through regulating and normalizing interaction via technocratic norms and standards. This requires for another type of trust than inter-personal trust in economic inter-firm relations. That is namely: to have trust in the functionality of a system of norms. The necessary transition from interpersonal to a more systemic form of trust in the regional supply base has not been taken place so far. Hence, relational bonds between economic actors in regional agglomerations are losing their importance in the favor of globally dispersed virtual epistemic communities and networks of compliance.

4.2.4 Horizontal exchange relations and embedding in local institutions

The prior section has described the regional industry structure and the vertical embedding and disembedding of local suppliers into the *Airbus* production network during modular transition. These actors are, however, also embedded in local horizontal exchange relations and institutional settings. The aim of this chapter is to introduce the local and regional network of firms and extra-firm organizations and institutions and to show, which strategies have been employed, in order to cope with the given circumstances. It is important to note, that not all of the people I interviewed and had informal conversations with have been entirely aware of the reconfiguration of the *Airbus* production network, its underlying causes and implications for local firms. Hence, the organizations and institutions that have formed throughout the last decade should not be considered as a direct response to modularization processes. The umbrella organization *Hamburg Aviation* is, first and foremost the result of the trend in regional development policies towards establishing cluster institutions and developing public-private partnership networks on a local scale.

The firms and organizations agglomerated in the aerospace sector in the *Metropolitan Region of Hamburg* are supported by the City of Hamburg as well as promoted within several national cluster promotion strategies, which resulted in the establishment of the cluster management institution ***Hamburg Aviation*** **e.V** (HAV)[67]. It aims at strengthening the common identity of local industry actors, raising (international) public awareness of the location and overcoming lacks in qualification and R&D. The public-private partnership association has formed around the focal companies *Airbus* and Lufthansa Technik AG, several associations, research institutes and universities, as well as about 300 small and medium-sized companies (SMEs), which are linked vertically and horizontally with one another. According to estimated numbers of *Hamburg Aviation e.V.*, the regional aerospace industry employs between 36,000 and 40,000 people and can, therefore, be considered as the third largest cluster of the aerospace industry in the world after Seattle (*Boeing* Headquarters) and Toulouse (*Airbus* Headquarters).[68] The association has been founded as an initiative of *Airbus*, Lufthansa Technik, the Airport Hamburg, the associations Hanse Aerospace e.V., HECAS and BDLI, the research institutes DLR, HCAT, ZAL as well as the four universities HAW, TU-HH, HSU and the University of Hamburg.

The HWF (Hamburgische Gesellschaft für Wirtschaftsförderung mbH) as well as the city of Hamburg and the BWVI (Behörde für Wirtschaft, Verkehr und Innovation) played a key role in founding the public private partnership initiative. All the members send representatives to the Management Board where strategies for the development of the aerospace industry in the region are developed and discussed. The administrative office (*Hamburg Aviation* Services) is the executive arm of the management board. They organize network events and provide online platforms and promote a common corporate identity of the location. The common overall strategy for the region is to render flying more economical, ecological comfortable, flexible, reliable and connected. In order to achieve this the management board identified four central product areas: the development and construction of aircrafts and aircraft systems, the development and construction of cabins and cabin systems, the optimization of aviation

[67] Former Luftfahrtcluster Metropolregion Hamburg e.V.

[68] Numbers differ however, and I estimate the number to be lower, since temporary work contracts among engineers are increasing, and moreover personnel service providers and secondary employment in the cleaning and overall logistics sector have been included in the estimations.

services, improving the efficiency of the air transportation system and aviation-related IT and communication systems. The cluster is decorated with several awards (Leading Edge-Cluster Germany/BMBF, Gold Label for Cluster Management Excellence/European Commission). Awards are a central tool for creating a common identity. Hamburg is, for instance, home to the Crystal Cabin Award. HAV mainly focuses on developing horizontal exchange relations and foster common R&D projects. Throughout the last 4 years, all of the multi-lateral cooperation and R&D projects that have been carried out have been realized due to the 80 million in funding[69] that they received in the course of the Leading Edge competition of the BMBF (PD1-INT-CM; PD9-INT-PO). Now that the massive funding has ended and sponsored multi-lateral projects are mostly finished, there have been fewer activities in this regard. After winning the Excellence Award, the euphoria within the community has declined amongst the many members. According to my observation, fewer and fewer members are visiting the regular network events (PD38-FN3; PD39-FN4).

Whereas *Hamburg Aviation* represents the entire sector including the focal companies, **Hanse Aerospace e.V**. is a local SME association founded in 1996 that represents the interests of small and medium-sized companies and suppliers of the aerospace industry. It offers its members advice, the coordination of regional activities (e.g., coordination and developing communication and relations with local government bodies), in order to address region-specific infrastructural issues. There are ad hoc and permanent working groups that address for instance problems associated with certification, standards, strategic orientation, etc. The subsidy of the association, the Hanse Aerospace Wirtschaftsdienst GmbH, organizes and advises the presence of its members on national and international trade fairs and exhibitions[70]. The initiative also applied for the leadership and management of *Hamburg Aviation*, but it was not considered as being neutral enough and was hence rejected by the community. They are now represented in the Management Board of *Hamburg Aviation* with one seat. Whereas they perceive themselves as "the voice of local enterprises and a counterbalance to the strong *Airbus* lobby", they consider *Hamburg Aviation* as the umbrella organization and the "political arm" of any activities in the aerospace industry in the Metropolitan region and the state of Hamburg (PD12-INT-SME-ASSO). They are aware of their threatened status and feel as a victim of recent consolidation processes and the reconfiguration of the supplier network. They also have an ambivalent position towards HAV. At the beginning, they felt kind of threatened when HAV has been founded and gained so much publicity and public subsidies, whereas they rely entirely on fees of their members. According to interview and field data, the association is perceived quite ambivalent by different actors in the cluster, because it competes with the more holistic *Hamburg Aviation* association in quite some points

[69] 40 million public funding and 40 million have to be provided by the industry (usually big corporate players).
[70] http://www.hanse-aerospace.net/en/association.html

(organization and representations on national and international trade fairs; advice and coordination of regional activities and networks).

HECAS (Hanseatic Engineering & Consulting Association e.V.) is an association that represents the engineering and business consultant service providers located in the region that are active in the aerospace sector. They also consider themselves as the interface between the aerospace industry and the local government and aim at keeping labor and jobs in the region. The competencies of its 12 members[71] lie in aerodynamics, consulting, EASA certification, construction and development, computing and testing, software engineering and technical documentation. HECAS is also member of HAV, HCAT and ZAL, which indicates the deep interweaving of local economic, political and scientific actors in the region[72].

The **ZAL** (Zentrum for Angewandte Luftfahrtforschung GmbH/Centre for Applied Aeronautical Research) aims to represent the technological research and development network of the civil aviation industry in the Hamburg Metropolitan Region. It presents itself as being the interface between research institutions, the aerospace sector and the City of Hamburg. In close collaboration with *Hamburg Aviation*, it aims to bundle the technological competence present in the region under the roof of the ZALTech Center which opened in 2016. The Tech Center is a huge facility located in HH-Finkenwerder in close proximity to the *Airbus* site with a working area of more than 26,000 sqm, 600 workplaces in offices, laboratories and hangars and a sophisticated research and testing infrastructure. The vision of the ZAL is to establish a "new form of cooperation" between the engineering and the academic sector. In collaboration with 8 partners the Free and Hanseatic City of Hamburg established the ZAL as a public-private partnership in 2009 one year after the region had been awarded as Germany's Leading-Edge Cluster. These partners also reflect the current shareholder structure. Whereas the universities (Uni HH, HAW, HSU, TUHH) hold 3% each, the DLR holds 10%, the Verein zur Förderung der Angewandten Luftfahrtforschung 18%, *Airbus*, Lufthansa Technik and the City of Hamburg hold each 20%.

Competencies are bundled in six different technological fields/technical domains: fuel cell lab; cabin innovation & technology; air and power systems; aerospace production and fuselage engineering; testing, safety & acoustics; and general processes & support topics. They develop a sophisticated physical infrastructure for testing and research for each domain. Within the technical domains the main subjects are negotiated with the partners *Airbus* and LHT. The aim is to bundle competencies and use synergistic potential. "These competencies will be further developed and then offered to interested partners as R&D services."[73] More skeptical voices emphasize, that big corporate players further outsource their R&D activities and profit from public investments at the same time. Operating since

[71] ALTRAN, Arts, Assystem, Manthey Aerrospace Consulting, MAXKON, Orange Engineering, phi, Sogeclair Aerospace, Sogeti High Tech, SPLU Engineers.

[72] http://www.hecas-ev.de/ziele/

[73] http://www.zal.aero/en/research-development/

2009, the ZAL GmbH has been mainly occupied with construction works of the huge facilities in the last years. Until 2016, only one multi-lateral research project has been realized, the Auto-Pro project (2014-2016) in the field of production and fuselage engineering (formerly named aerospace manufacturing). During my last visit the halls were still quite empty, though this might change in the future, if the ZAL manages to acquire multi-lateral research projects, attract financially stronger companies and reduce the prevailing distrust towards the lead firm (PD36-FN1)[74].

ZAL presents itself as a neutral partner that provides a neutral platform where partners can meet at eye-level. According to interview and field data, they are nevertheless not perceived by all actors as being "neutral," not only because they follow commercial interests themselves. The power asymmetries among them become apparent in the working groups/technical domains. The suspicion towards *Airbus* (who holds 20%) has been quite high due to its restrictive non-disclosure agreements and the perception that, if *Airbus* participates in multilateral R&D projects they claim intellectual property, which also hinders smaller players to participate, because they fear sharing expertise and ideas be "absorbed" afterwards by the more powerful actors of the network. Additionally, some representatives of universities complain that with the establishment of the ZAL their facilities and its specialized institutes (who are amongst each other already competing for private and public funds) now have to compete with another actor for qualified personal as well as funding. In summary, the ZAL acts between the poles of cooperation and competition, hence of knowledge sharing/exchange and disclosure (PD36-FN1; PD37-FN2).

In terms of the qualification of personnel for the aerospace industry, actors are organized in the Hamburg Centre for Aviation Training (HCAT e.V.). The HCAT sees itself as a coordinator and moderator in terms of qualifying personnel for the aerospace site in Hamburg. Via common projects the organization aims to foster capabilities especially of SMES in terms of a sustainable human resource development. They are cooperating with HECAS, Hanse Aerospace, *Airbus*, Nordmetall, Lufthansa Technik, TUHH, HSU, HAW, HIBB (Hamburger Institut für berufliche Weiterbildung) and the BWVI (City of Hamburg)[75]. Germanischer Llyod as well as TÜV Nord are located in Hamburg and carry out qualification/certification and approval of certain aerospace specific standards or provide information and qualification management seminars. HECAS and Hanse Aerospace also provide support with regard to gain EASA certifications. There are, however, no branches of *SAE* or other important standard developing organizations present in the region.

In summary, on the local level a dense network has evolved that represents the different and common interests of the heterogeneous actors that range from globally active lead firms (mainly *Airbus*), various

[74] In November 2017 Liebherr Aerospace opened a new liaison at the ZAL Tech center and in January 2018 the Start-up 3D Aero (a joint venture between Lufthansa Technik and Pepper and Fuchs) has been founded under the roof of the ZAL https://www.zal.aero/en/news/.

[75] http://www.hcatplus.de/ueber-uns/#c121

SMEs, politicians and government agencies as well as education and research facilities. The network(s) is/are governed by several PPP associations from which HAV can be considered as the umbrella organization representing the aerospace industry of the region (cf. following Figure 30).

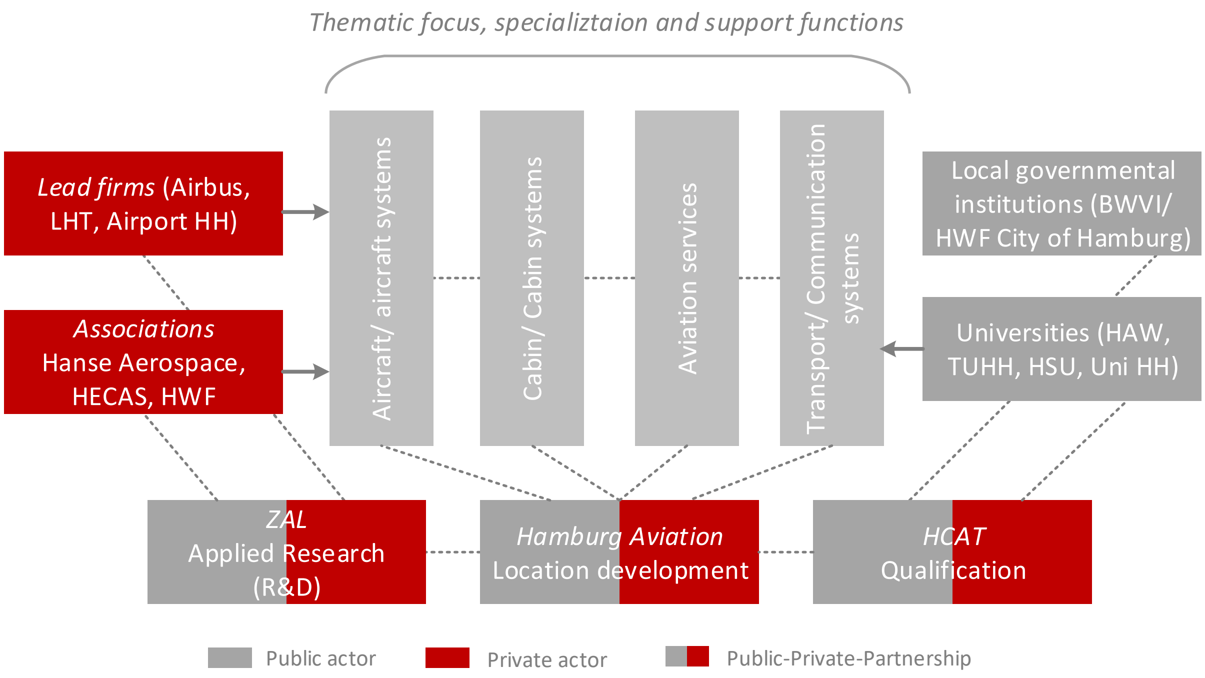


Figure 30: Overview local industry networks and public-private partnership initiatives

Within a strategic workshop of the cluster members in 2014, the members identified the protection of intellectual property, openness and the lack of standardized processes and contracts as the major challenges actors in the cluster have to cope with in terms of collaboration. These can be considered as direct outcomes of modular transition processes, because modularity in design and organization demands for sharing codified knowledge (i.e. standards) across firm-boundaries and protecting competitive knowledge at the same time. The strategic modularization has reached the local level, but actors have not been enough included in building the necessary infrastructure (cf. chapter 4.1.3).

Throughout the workshop, they decided to develop guidelines, SOPs and common rules. However, they were not able to agree who, where and how this should be done. Actors were concerned that there is a severe discrepancy between the demand for a “culture of openness” and the restrictive NDAs usually imposed by the focal companies. There have been severe doubts, if the focal companies would alter their own existing standards and adopt new standards developed by the HAV cluster community. Creating reliability and compliance has been identified as the major challenge in this regard (PD28-DOC-CLUSTER-STRAT). Here the power asymmetries become particularly visible. *Airbus* and its strategic partners (first tier suppliers) have already developed standards within global epistemic communities and networks of compliance, which they impose on supplier on lower tiers via coercive and normative pressure. Actors on the local level have now recognized the need for codification and common standards development, but are too late and lack resources and knowledge to participate in existing standards networks.

4.2.5 Summary and conclusion

The strategic modularization of product architectures initiated the reorganization of the production network into segregated "working packages" and the diffusion of the so-called Tier 1 Model (cf. chapter 4.1.2). The more integrative functions an actor carries out, the higher the structural network embeddedness. At the same time the actual relationship between actors (relational aspect of network embeddedness) can be only weak (loosely coupled) and the length of communication paths between actors can be long (no direct face-to-face contact) since they are replaced by the codified link. Hence, relations in modular production networks rely more on systemic forms of trust in the design rules and interoperability and interface standards on which they are based. This has resulted in profound relational changes in the *Airbus* production network that became visible at the local level (i.e. in Hamburg) in the disembedding of production relations and an increasing network distance of local suppliers to *Airbus* despite their geographical proximity and long-term established relationships.

Many local suppliers have been cut off and are not part of the production network anymore. Since the definition of module boundaries has been predominantly led by the procurement strategy of the (new) management and not by technological expertise, technological, proprietary and organizational interfaces have not been harmonized carefully enough resulting in the destruction of existing trust relations. Suppliers on lower tiers have been reintegrated by first tier suppliers and "forced" to collaborate, in order to share interface and interoperability related knowledge and information. This led to tensions within the supply base and distrust and suspicion spread. Two main areas of conflict and tension opened up. From a strategic point of view, the lead firm faces the conflict between cost- and efficiency-driven decisions of its management division and technological needs and interdependencies engineers are facing, if module boundaries are not harmonized carefully with proprietary and organizational interfaces. Secondly, suppliers are forced to operate between the poles of cooperation and competition, or in other words, between sharing knowledge and protecting intellectual property (i.e. disclosure).

From a **knowledge-based perspective**, the fragmentation, reorganization and disruption of knowledge bases, competencies and working packages that happens during strategic modularization raises the overall need of technical documentation, specification and common standards. In order to cope with the new challenges, suppliers (as far as they have the opportunities) try to vertically (re-)integrate competencies, in order to be able to provide bigger integrated products, systems or service bundles. The lead firm engages more in knowledge codification, standard formation and diffusion related activities in order to ensure architectural integrity and enable this inter-organizational division of knowledge and labor. Formal technology standards codify knowledge (technical data) within a specific language developed in the epistemic communities of standard setters. From the knowledge integrators point of view, standardization practices that accompany an industry during modularization foster global collaboration and enable the control and distribution of design and process specific information and its architectural integrity. But at the same time, there evolve tensions between this very formal technocratic codification infrastructure when confronted with local realities. Those tensions mainly arise in terms of translation (i.e. understanding/decoding that information), trust, as well as related processes of inclusion, exclusion and marginalization.

The re-embedding of local actors into the new knowledge infrastructure has not been taken place so far. Regional development depends on both strong internal as well as external linkages. Whereas there are dense horizontal networks on the local scale and many associations and organizations have formed to bundle and represent their interests and strengthen cooperation and the building of relational ties, local actors have failed to couple to external linkages and broader global knowledge infrastructures. The following figure summarizes the main findings and demonstrates the cross-dimensional changes when an industry moves towards more modular forms of organization. Concerning the knowledge infrastructure and the dimension of the artifact, idiosyncratic technical specifications become replaced by standardized modules. As opposed to the former rather captive linkages between actors in the production network, the common knowledge infrastructure is developed in horizontal global epistemic networks of standard setting organizations apart from the competitive market setting, whereas production relations become hierarchically cascaded and reorganized in the first tier model. On the local scale this has resulted in the disruption of existing inter-personal trust relations and the local disembedding of and at the same time global integration of exchange relations.

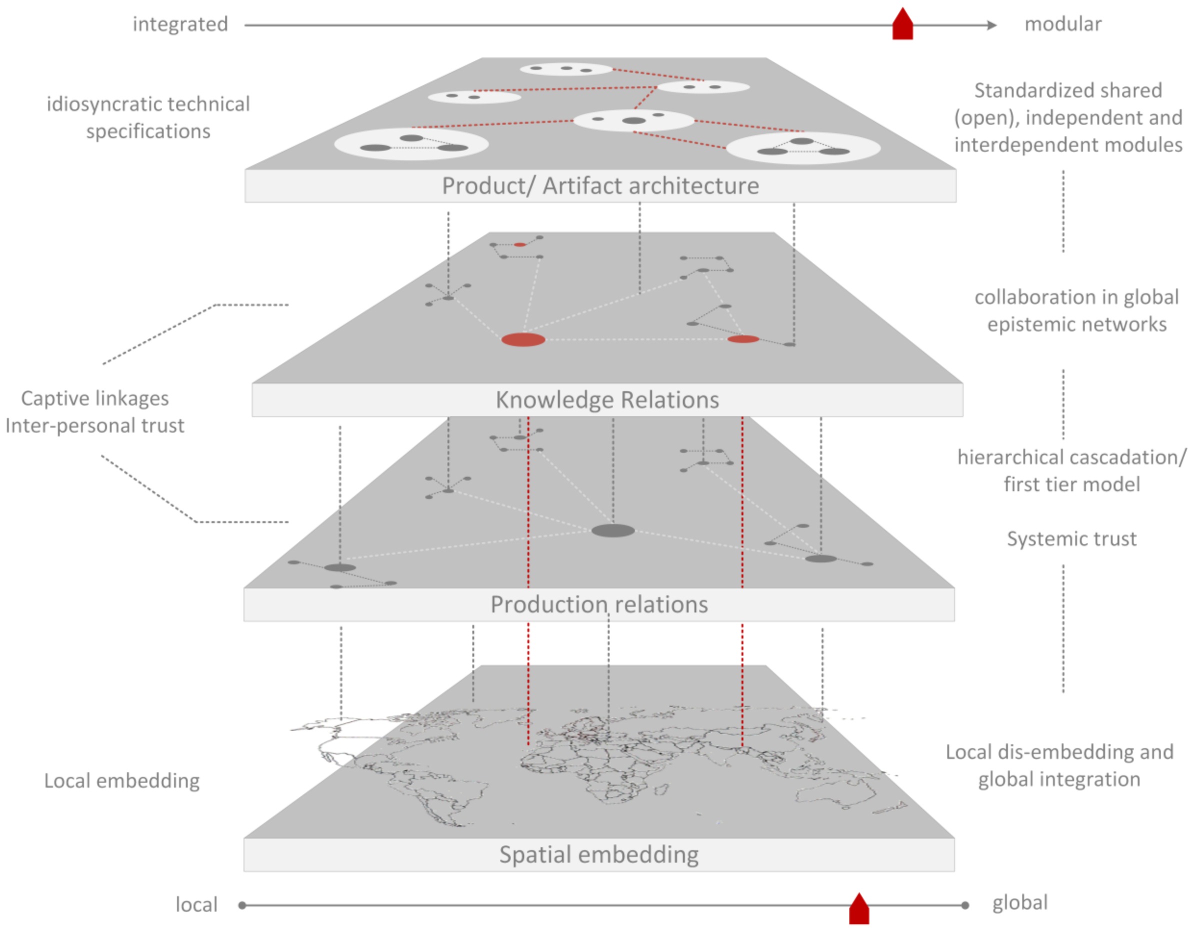


Figure 31: Modular transition and its multi-dimensional consequences (case specific)

The following table summarizes what processes of disembedding and re-embedding occur on the different dimensions (social, network, territorial) during modular transition.

Table 9: Processes of disembedding and re-embedding during modular transition

	Relational network Dimension of embeddedness	Structural Network Dimension of embeddedness	Territorial Dimension of embeddedness
Knowledge exchange relations (horizontal)	Disembedding of knowledge exchange relations through codified links and expert systems, Decreasing role of interpersonal trust and face-to-face interaction Increasing need for systemic trust	Re-embedding and emergence of new networks of trans-local actors that codify and distribute architectural knowledge	Disembedding of knowledge codification and standard formation from the local context and re-embedding into trans-local networks of standard setters

	Homogenization of cognitive frames		
Production relations (vertical)	Disembedding of idiosyncratic relations via codified only loosely coupled links	Vertical disintegration and reintegration into modules on different tiers leading to disembedding, growing network distance, hierarchical cascadation	Relocation, re-embedding and global integration or disintegration of actors in distant regions

5 Conclusion and discussion of results

The final chapter summarizes the central findings from the empirical case study and discusses them against the background of the conceptual model and theoretical insights from chapter 2. It further abstracts generalizable patterns from the case-specific empirical data with regard to the impact of modularization and standardization, but also highlights some limitations of the study. It emphasizes the contribution of the results to the field of economic geography and especially the study of global production networks and territorial development. Finally, it briefly reflects upon the practical implications of the research results for regional development policies and the strategic positioning of local SMEs. The chapter concludes with an outlook for future studies.

The case study has demonstrated how a local cluster changes due to changes of the underlying knowledge infrastructure within the aerospace industry. Modularization and standardization - as complementary strategies – result in multi-dimensional relational changes that also affect spatial relations, and hence the cluster, that is embedded in broader structures of the *Airbus* production network.

By integrating the dimension of the technological artifact, the interrelations between changes in the system architecture and the structure and nature of knowledge and exchange relations in the production network could be captured analytically. This does, however, not mean that modular products simply lead to modular, non-hierarchical organization of production relations as suggested by authors in management studies that adopt the "mirroring hypothesis" (Frenken and Mendritzki, 2012; Hoetker, 2006; MacCormack et al., 2012) (cf. chapters 2.3 and 2.4). The analytical separation of knowledge and production relations in the given case study emphasizes that the structure of knowledge relations necessary in order to build a modular knowledge infrastructure differs from the proprietary structure of the buyer-supplier relations that are indeed hierarchically cascaded as in a captive value chain configuration and organized in vertically integrated modules.

Knowledge codification practices are key to (post-)modern complex globalized industries that move towards an increasing digitization and the spread of cyber-physical systems. Against this background, the concept of knowledge infrastructures suggested here has been proven a valuable perspective for examining how technological standards are embedded in broader socio-technical and organizational contexts, how they emerge and diffuse. The distribution of an infrastructure can be imagined along a technological–social and a global–local axis. Depending on the reach and scope of the production network it links different places and conventions of practice. In any case, it is learned of as part of membership (cf. chapter 2.2.6). Hence, the embeddedness of the creators and users of this knowledge infrastructure plays a crucial role in terms of the enactment of technologies, standards and in the case of modularization architectural paradigms. Standards homogenize knowledge within spatially dispersed production networks thereby enabling coordination and knowledge diffusion across contexts and places, and at the same time, they constrain modes of engagement and the selection environment of firms in a region. This interrelation between global and local dynamics of industry standards becomes epitomized in the given case study. Here, the diffusion of standards led to a disembedding of local knowledge, conventions and exchange relations (cf. chapter 4.2). With the introduction of new standards and related qualification processes, the selection environment of local SMEs with regard to technological solutions as well as possibilities to participate and couple with the *Airbus* production network have been constrained. Knowledge codification and standard setting is carried out by distant epistemic communities and then enforced upon local suppliers via coercive pressure of the lead firms. The local actors and their idiosyncratic knowledge and competencies that is mostly not specified or codified within rules lose their ability to relate to the new codification schemes. The knowledge governance pattern of "normalizing" that is enabled by codified links is, in a Weberian sense, legitimated by authority since behavioral rules (design rules and technical standards) are embodied in a code that is either legally binding (de jure standards set by the EASA) or a prerequisite for participating in joint value creation (e.g., *ARINC*, *SAE*, *NadCap* standards etc.). Within most of the literature from organizational studies, this form of governance is related to more horizontal forms of organization and the voluntary consensus based approach in standard setting activities is considered to be a democratic pattern of decision-making (Murphy and Yates, 2009; Ponte et al., 2011; Ponte and Cheyns, 2013). Nevertheless, as the case analysis has shown, traditional categories of power linked to economic resources and strategic interests are still existent. Power asymmetries and structural inequalities are affecting the process of negotiating about consensus, excluding, manipulating or controlling more marginalized groups of actors, because actors defining standards or assessing conformity to standards are also embedded within national, local and institutional contexts and hierarchical power structures, which leads to the reinforcement of existing local power inequalities as the case study has demonstrated. Besides being global production networks in a functional sense, they are always simultaneously rule regimes that are structured by different interests and the struggle of creating and legitimization knowledge and rules.

Morevover, the diffusion of standards and formal codes has the potential to destroy existing trust relations and routines in local clusters as the example of the *Hamburg Aviation* cluster has shown (cf. chapter 4.2.4). Before modularization, idiosyncratic linkages prevailed and highly formalized knowledge was in any case unnecessary due to geographic and cognitive proximity as well as interpersonal trust relations that facilitated knowledge exchange and economic transactions. The growing network distance and change of the nature of exchange relations led to an increasing alienation of knowledge and production relations on the local level. This has been already emphasized in earlier studies on SMEs in the European aeronautics sector (Benzler and Wink, 2010; Wink, 2010). To conclude this thought, modular approaches further disembed production from its particular social and spatial context and, moreover, they further decrease the role of interpersonal relations in knowledge sharing/knowledge diffusion in the favor of impersonal technocratic structures that are more predictable and less vulnerable to disturbances.

On the spatial dimension, relational changes towards modular configurations have hitherto mostly been associated with the offshoring of production processes and the relocation of work due to the outsourcing of the production of standardized modules to contract manufacturers in “low-cost” countries (Gereffi et al., 2005; Kleibert, 2015; Sturgeon et al., 2008). In the very few existing literature and empirical case studies that consider modularization from a spatial perspective, codification and standard formation processes are conceptualized as essentially localized practices (Sturgeon, 2003), whereas the developed codification schemes aim at making idiosyncratic (and personal) linkages rather obsolete and knowledge globally accessible. This case study has, in contrast, shown that codification also takes place in global epistemic communities of standard setting organizations constituted of representatives of firms that actually compete on the market. The adoption of standards set by consortia of private industry actors that also pursue commercial interests (i.e. their adoption by local economic actors so they can gain revenue via conformity assessment, i.e. regular audits) is a precondition in order to gain access to the *Airbus* production network. Thus, intermediary businesses for conformity assessment and certification emerge that are intertwined with national and international public regulatory agencies, since certification and approval heavily relies on standards developed by industry-controlled private consortia and their for-profit subsidiaries. This phenomenon has been described by several recent studies of standard setting in the IT sector (Blind et al., 2012; Meyer, 2012; Schoechle, 2009) as well as from the perspective of political economy (Büthe and Mattli, 2011). Those studies, however, lack a spatial perspective. The given study revealed that standard-formation related activities in the aerospace industry take place in global epistemic communities of practice (meeting 2-3 times a year in changing locations), whereas standard-diffusion related activities are enforced by public and private regulatory agencies in specific locations that profit from rent seeking and the co-location of lead firms.

Finally, what can be drawn from the analysis in terms of more general patterns and processes of change? On the one hand, the analysis has captured change induced by modularization in the changing structure and qualities of production and knowledge relations. On the other hand, it has emphasized the ongoing cross-dimensional interactions between different entities (i.e. components at the artifact level, knowledge and production relations at the network level) stressing their multi-scalar embeddedness. Via describing the multi-dimensional processes of dis- and re-embedding of knowledge and production relations the emergence and development of socio-technical and socio-spatial development trajectories and their specific place-dependency could be captured (cf. Figure 32).

Patterns that are more easily generalized can be found in the identified phases. In chapter 2.4.3, modularization has been conceptualized as a cyclical model consisting of phases of transition (codification and standard formation), modular maturity (standard diffusion) and modular decline (de-codification, rejection of codes). Since socio-technological, organizational and spatial development trajectories are intertwined, regional clusters are affected by these cycles, too. During the phase of modular transition, actors involved in standard setting and diffusion related activities profit from an increasing diffusion of their knowledge infrastructure creating opportunities for regions in which standard setting organizations and especially regulatory agencies are located. At the same time, modularization limits the selection environment of firms in other regions suddenly confronted with a new knowledge infrastructure by changing the codes for getting engaged.

With regard to the research question of how the development of a new knowledge infrastructure affects the development of a local industry cluster that is plugged into a global production network, one can conclude that the source of industrial path dependence is not the development of technological knowledge *per se*, but the evolution of organizations and institutions that develop around it. Accordingly, the development and diffusion of a knowledge infrastructure in modular industry configurations influences path- and place-dependent socio-organizational trajectories and impacts the genesis and development of territorial development (cf. Figure 32).

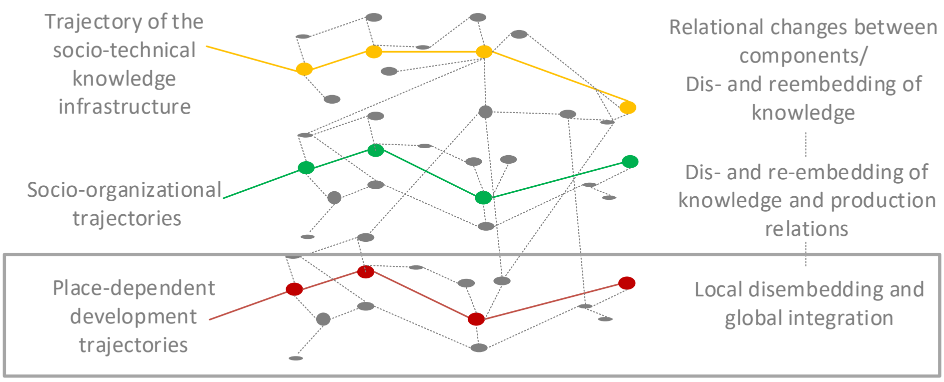


Figure 32: Place-dependent development trajectory during modular transition

5.1 Contribution to the field of economic geography

GPN and GVC analysis conceptualize economic and regional change predominantly around the dynamics of capital flows building upon the rationale of transaction cost economics (Coe and Yeung, 2015) and macro governance structures (Gereffi et al., 2005; Gereffi and Lee, 2016). Hence, change is considered to be driven by capitalist dynamics as the main drivers for firm and non-firm strategies that in turn lead to various economic developmental outcomes depending on the governance structures they are embedded in (i.e. market versus captive and relational linkages) (cf. chapter 2.1.2). It grounds divergent trajectories of economic and industrial development on the role of strategic choices made by actors that can be capitalist firms as well as other state and non-state institutions that are embedded within these industries (Coe and Yeung 2015). Hence, a large number of empirical studies investigate territorial change in terms of industrial upgrading understood as “moving up the chain” of value added activities or “social upgrading” understood as creating “better” conditions for workers (cf. chapter 2.5.1.) Both rely on a positivist view on socio-economic change.

The present thesis has emphasized the essential role that knowledge infrastructures play in terms of change. Knowledge infrastructures are neither about tacit knowledge that generates competitive advantages and innovation, nor about specific imaginations of social responsibility, but about how technological knowledge gets codified and is exchanged and shared throughout a complex cyber-physical system and the surrounding distributed production network. It contains both virtual as well as face-to-face channels of transmission. However, this only becomes evident if one integrates the dimension of the artifact into the analysis. This enables researchers to reconstruct knowledge and knowledge relations embedded in the artifact and the processes used to create it.

From a dynamic perspective, technological modularity standards and the knowledge infrastructure they are embedded in can enfold its potential for development only if actors and regions are able to connect to codification schemes developed in different socio-spatial and institutional contexts. Studies on regional knowledge and knowledge processes that emphasize the role of external linkages usually stress their positive role for development conceptualizing them, for instance, as “global pipelines” for knowledge diffusion (Bathelt et al., 2004; Trippl et al., 2009). In the given case study, the diffusion of codified knowledge and the new knowledge infrastructure has, however, *de*valuated local knowledge and disembedded local knowledge relations in favor of global knowledge networks that are specialized in codification processes and the development of common notations and norms. Hence, the case study reveals the ambivalent nature of standards for economic development by enabling development in specific regions and constraining it in others. It also reveals the dialectics between structure and agency. GPN analysis “seeks to operate at the intersections of structure and agency” and aims to understand the way in which strategies and actions can reconfigure and reshape wider structural constraints and are influenced by them at the same time (Coe and Yeung 2015, p. 18). The given case has illustrated how actors have developed technological standards and standard modular product architectures based on strategic decisions of designers and managers around which organizational routines have been established. However, the diffusion and distribution of the knowledge infrastructure that has emerged in this way imposes structural constraints on actors in other regions or actors with a different structural and relational network embeddedness. This dual nature of standards as a form of codified (expert) knowledge has been extensively studied in sociology (cf. chapter 2.2.3 - 2.2.5 for examples). On the one hand, standards enable and facilitate social interaction, but on the other hand their normative character leads in the long run to technical and social norms and conventions (establishment of a certain structure), which does not only impact the path of technology, but also the institutional frame in which (economic) actions can take place. Standards are, thus, always both at the same time: intermediaries as well as constraints.

The present thesis has, thus, contributed to deepen the understanding of how global production networks and the regions plugged into them change.

5.2 Practical implications and consequences for regional development policies

Several practical implications arise from the insights of the existing case study for actors in the role of system integrators, for local SMEs as well as for regional development politics. I will briefly elaborate on them in the following.

Architectural and system integrators who carry out strategic modularization should carefully harmonize technological, socio-organizational and proprietary module boundaries. The given case has shown that technological problems and tensions between actors that are otherwise unwilling to share their knowledge might occur that significantly affect the design and production process. In order to create common infrastructures *openness* and *sharing* knowledge become key values in the design of future cyber-physical systems[76].

SMEs in the local cluster need to further diversify into neighboring industries, especially engineering service providers and material and component manufacturers who provide cross-sectoral services and skills, in order to reduce their strong dependency on *Airbus*. If they want to stay in the *Airbus* production network, they need to connect to the developed codification schemes via accreditation and certification if they have the resources to do so. This often also enables them to contract with other big companies in the aerospace industry. In any case, they need to connect more to global knowledge networks and system suppliers located outside of the cluster.

Finally, prior strategies of cluster policies in the *Hamburg Aviation* case have mainly focused on bringing local actors together by fostering a common identity and knowledge transfer via networking events and common platforms. In the present case, several circumstances posed barriers to this strategy. First of all, regional cluster politics should be aware that when cluster policy strategies aim at fostering a common identity, interpersonal trust and the mutual sharing of knowledge, they might be entirely impeded, when employed in a phase of growing modular maturity. Product development and production, in this phase, can be actually carried out with strangers since all the relevant technical

[76] Practical implications and concepts of knowledge management in distributed value co-creation have been published in the frame of the BMBF-project "Development of a Knowledge Management System for the Hamburg Aviation Cluster" (cf., e.g., Krenz et al. 2013, 2014a, 2014b; Redlich et al. 2014).

information is already codified. If it, secondly, aims at generating product innovation for the aerospace industry, it should be aware of the dominance of lead firms and the resulting power asymmetries on the local level (cf. chapter 4.2.4). The problem here is that SMEs develop products or processes for the lead firms. If they are asked to collaborate with *Airbus*, interview data revealed that they fear to lose their competitive knowledge and that the lead firm will just absorb it. However, if they succeed they nevertheless need to connect their solution to the existing web of standards and integrate it into the overall knowledge infrastructure.

In the given case, cluster policies have overemphasized the meaning of local ties. The focus needs to be set on a further embedding within global knowledge networks and exchange relations.

5.3 Limitations and Outlook

Several limitations arise from the generated results. First of all, generalizations drawn from a single case study are always problematic. The aerospace industry and especially the A380 case are extreme examples. Aerospace manufacturing is one of the most regulated and codified industries. State actors, standard organizations and regulatory agencies have always played a significant role as compared for instance to the computer industry. Other dynamics might play a more significant role in other high technology sectors. Moreover, the boundaries of the given case have been limited to the *Airbus* production network. *Boeing*, *Bombardier* and other up-coming aerospace manufacturers have also established modular structures. A comparative case study needs to proof whether the here identified dynamics also count for other comparable cases.

Nevertheless, the trend of cyber-physical systems and concepts of “Industrie 4.0” highly rely on modularity as an underlying architectural paradigm as well as knowledge infrastructures that operate across contexts, places and corporate boundaries. Research on cyber-physical systems is assumed to have an impact especially in the field of future mobility concepts. The need for common standards will, therefore, also rise in many other sectors and private industry consortia are on the forefront in forming technological trajectories that also affect the economic development of regions and industrial clusters. The multi-dimensional framework of a production system as well as the cyclical model of modularization suggested here can be used by future studies, in order to analyze multi-dimensional processes of change during modularization. It would be particularly interesting to investigate how the phase of modular decline affects regional development and creates opportunities as well as challenges for actors linked within global production networks.

Appendix

Please note that transcriptions of the interviews conducted have not been included in the Appendix, in order keep a manageable document size. They can be provided on request and under the provision to respect the anonymity that has been assured to the interviewees. The same counts for data sheets prepared and analyzed in ATLAS t.i. and Excel.

Coding	Type of data	Group	Date	Setting	Duration
PD1-INT-CM	Interview	Representative of Cluster Management (CM)	13.12.2011	Office *Hamburg Aviation*	01:50 h
PD2-INT-LF	Interview	Management Lead Firm (LF)/ R&D Division	15.12.2011	Office Company Site	01:51 h
PD3-INT-ESP	Interview	Engineering Service Provider, SME (ESP)	04.11.2011	Office Company Site	01:30h
PD4-INT-ESP	Interview	Engineering Service Provider, SME (ESP)	18.04.2012	Office Company Site	01:25h
PD5-INT-BC	Telephone Interview	Aerospace Business Consultant	17.04.2012	Telephone Interview	00:50 h
PD6-INT-LF	Interview	Management Lead Firm/ R&D Division	16.04.2012	Office Company Site	01:55h
PD7-INT-DLR	Interview	Research and Education Institute	04.11.2011	Office Institute	01:10h
PD8-INT-PO	Interview	Public Official (City of Hamburg/ Division for Economy, Traffic and Innovation)	27.10.2011	Helmut-Schmidt-University	01:23h
PD9-INT-PO	Interview	Public Official (City of Hamburg/ Division for Economy, Traffic and Innovation)	01.12.2011	Helmut-Schmidt-University	01:41h
PD10-INT-AP	Interview	Management Airport	19.03.2012	Office Airport	01:14h
PD11a-INT-CM-1	Interview	Contract Manufacturer/ SME	20.03.2012	Office Company Site	01:20h
PD11b-INT-CM-1	Interview	Contract Manufacturer/ SME	22.04.2012	Office Company Site	01:37h
PD12-INT-SME-ASSO	Interview	Representative of Local SME Association	19.12.2011	Office Association	02:14h
PD13-INT-PE	Interview	Production Engineer	26.03.2016	Helmut-Schmidt-University	01:42h
PD14-INT-ESP	Interview	Engineering Service Provider, SME (ESP)	15.12.2011	Office Company Site	01:24h
PD15-INT-CM	Interview	Cluster Management	31.08.2011	Office *Hamburg Aviation*	
PD16-INT-PODIUM-1	Transcription of Panel discussion		23.02.2012	Spitzen-clustertagung Berlin	01:30h
PD17-INT-PODIUM-2	Transcription of Speeches		23.02.2012	Spitzen-clustertagung Berlin	01:30h

PD18-INT-PO	Interview	Public Official (City of Stade/ CFK-Valley)	11.09.2015	Office Stade	02:33h
PD19-INT-SE-LF	Interview	System Engineer	22.10.2015	Helmut-Schmidt-University	2:42h
Coding	**Type of document**	**Publisher**	**Date**	**Location/ Occasion**	**-**
PD20-DOC-STRAT	Strategy Paper	Cluster Management/ Cluster Initiative (Application for Excellence Cluster Initiative of the BMBF)			
PD21-DOC-FIRST-TIER	Power Point Presentation: Konsolidierung im Supplier Market – zwischen Chance und Bedrohung	CEO Diehl Aerosystems (First Tier Supplier)	15.09.2011	BDLI Regional Forum	
PD22-DOC-LF	Power Point Presentation: Herausforderungen für Airbus und Chancen für Zulieferer	Lead Firm	15.09.2011	BDLI Regional Forum	
PD23-DOC-LF	Power Point Presentation: Airbus Procurement Stratgey	Lead Firm	Nov 2012	Ontario Aerospace Council	
PD24-DOC-OPENIMA	Power Point Presentation: Open Integrated Modular Avionics A380	Lead Firm (Jean-Bernard Itier)			
PD25-DOC-PRO-1	Power Point Presentation: Airbus Procurement and Organisation of Major Suppliers	Lead Firm	2010/2012		
PD26-DOC-PRO1	Power Point Presentation: Procurement situation in Airbus and supply chain policy and supply	Lead Firm, Olivier Cauquill (SVP, Procurement Strategy & Business Operation.	30.11.2010	Toulouse	
PD27-DOC-AI	Power Point Presentation: Strategic Outlook of the Aircraft Industry	Christian Scherer EVP, Head of Strategy and Future Programmes	2011	Aviation Forum	
PD28-DOC-CLUSTER-STRAT	„HAV – Fortentwicklung der Strategie“ Strategie-Workshop Ergebnisdokumentation		23.05.2014		
PD29-DOC-PRESS	(Stern Artikel): „Es passt nicht: Airbus – die Geschichte eines deutsch –		19.10.06		

	französischen Missverständnisse“			
PD30-DOC-PRESS	(FAZ Artikel): „Die Flugzeugbauer von Airbus haben sich total verheddert“		08.10.05	
PD31-DOC-*NadCap*1	Airbus Use of *NadCap* EASA Workshop	Pascal Blondet (Lead Firms)	10.05.2011	EASA Workshop
PD32-DOC-*NadCap*2	Airbus Supplier *NadCap* Accreditation – Airbus Policy	Lead Firm		
PD33-DOC-EASA	Questionnaire: European Aviation Safety Agency	European Aviation Safety Agency		Design Organisation Approval (DOA) Implementation Workshop
PD34-DOC-GLS	Accreditation Procedures	GLS		
PD35-DOC-E2S	Airbus E2S Strategy Paper Sogitech			

Coding	Fieldnotes	Occasion/ Event	Date	Location	-
PD36-FN1		Aerospace Manufacturing Workshops/ Task Force Meetings	15.01.2013 12.02.2013 21.03.2013 26.04.2013 28.05.2013 11.07.2013	ZAL GmbH Airport Hamburg (old headquarter)	
PD37-FN2		Aerospace Manufacturing Workshop/ Task Force Meeting	26.04.2013	Airbus Finkenwerder	
PD38-FN3		HaV Cluster Meeting/ SCW Partner Meeting	22.01.2013	Airbus Finkenwerder	
PD39-FN4		40. HAV Forum	19.06.2014	Hotel Hafen Hamburg	
		42. HAV Forum	19.02.2015	Hotel Hafen Hamburg	
		45. HAV Forum and Opening of new ZAL Tech Center	07.03.2016	ZAL Tech Center Finkenwerder	
		47. HAV Forum	13.10.2016	Hotel Hafen Hamburg	

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AIA	http://www.aia-aerospace.org/
AIAA	https://www.aiaa.org/default.aspx
Airbus	http://company.airbus.com/company/worldwide-presence/germany.html
Airbus	http://company.airbus.com/careers/apprentices-and-pupils/In-Germany/In-Germany-training-locations/schuler-ausbildungstandorte.html
ARINC ITC	http://aviation-ia.com/standards/index.html
ARINC ITC	https://www.aviation-ia.com/
ASD	http://www.asd-europe.org/about-us/asd-at-a-glance
ASTM	https://www.astm.org/ABOUT/full_overview.html
ATA/ ATA eBusiness	http://www.ataebiz.org/Pages/standards.aspx
ATA/ ATA eBusiness	http://www.ataebiz.org/Pages/default.aspx
AWC	https://www.aviationweather.gov/info
EASA	https://www.easa.europa.eu/
eAudit Net	https://www.eauditnet.com/eauditnet/ean/user/mainpage.htm
EDA[77]	https://www.eda.europa.eu/
EUROCAE	https://www.eurocae.net/about-us/our-history/
FAA	https://www.faa.gov/
Hanse Aerospace	http://www.hanse-aerospace.net/en/association.html
HAV	http://www.hamburg-aviation.de/start.html

[77] EDA, FAA, ICAO, IEC, ISO, NATO, RTCA, SJAC homepages have been only used as sources for geographical mapping in Figure 24 and are not directly cited throughout the main text.

HAV	http://www.hamburg-aviation.de/netzwerk/standort.html
HCAT	http://www.hcatplus.de/ueber-uns/#c121
HECAS	http://www.hecas-ev.de/ziele/
HECAS	http://www.hecas-ev.de/files/hecas_newsletter2015.pdf
IATA	http://www.iata.org/Pages/default.aspx
ICAO	https://www.icao.int/about-icao/Pages/default.aspx
IEC	http://www.iec.ch/about/contactus/?ref=toplinks
ISO	https://www.iso.org/contact-iso.html
NATO	http://www.nato.int/cps/en/natohq/topics_49284.htm
NSF	https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.htm
PRI	http://cdn.p-r-i.org/wp-content/uploads/2012/11/EADS.pdf
Rockwell Collins	https://www.rockwellcollins.com/Data/News/2013_Cal_Yr/RC/FY14RCNR13-*ARINC*-close.aspx
RFID Journal	http://www.rfidjournal.com/articles/pdf?4986
RTCA	http://www.rtca.org/content.asp?pl=49&contentid=49
SAE ITC	http://itc.*SAE*.org/
SJAC	http://www.sjac.or.jp/en_index.html
Transport Canada	http://www.tc.gc.ca/eng/menu.htm
U.S. DoD	https://www.defense.gov/About/
Wikipedia	https://en.wikipedia.org/wiki/Reverse_engineering
Wikipedia	https://de.wikipedia.org/wiki/Glasfaserverst%C3%A4rktes_Aluminium
Wikipedia	https://de.wikipedia.org/wiki/*ARINC*
ZAL[78]	http://www.zal.aero/en/research-development/ https://www.zal.aero/en/news/

[78] Please note that the ZAL has meanwhile updated and changed the content of its homepage, yet the links are still the same.

Declaration on oath

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Hamburg, 30th of April 2018 Sonja Buxbaum-Conradi