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Matthias Aistleitner, Claudius Gräbner and Anna Hornykewycz

JOHANNES KEPLER UNIVERSITÄT LINZ

ICAE
INSTITUTE FOR COMPREHENSIVE ANALYSIS OF THE ECONOMY

Institute for Comprehensive Analysis of the Economy
Johannes Kepler University Linz
Altenbergerstraße 69, 4040 Linz
icae@jku.at
www.jku.at/icae

THEORY AND EMPIRICS OF CAPABILITY ACCUMULATION: IMPLICATIONS FOR MACROECONOMIC MODELLING*

WORKING PAPER

Matthias Aistleitner

Institute for the Comprehensive Analysis of the Economy
Johannes Kepler University Linz
matthias.aistleitner@jku.at

Claudius Gräbner†

Institute for Socio-Economics
University of Duisburg-Essen
&
Institute for the Comprehensive Analysis of the Economy
Johannes Kepler University Linz
claudius@claudius-graebner.com

Anna Hornykewycz

Institute for the Comprehensive Analysis of the Economy
Johannes Kepler University Linz
anna.hornykewycz@jku.at

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ABSTRACT

The accumulation of new technological capabilities is of high empirical relevance, both for the development of countries and the business success of firms. In this paper, we aim to delineate strategies how these processes of *capability accumulation* can be considered more accurately in comprehensive macroeconomic models. To this end, we conduct an interdisciplinary review of the literature specialized on capability accumulation by analyzing both empirical as well as theoretical literature on the firm and aggregated level. In doing so, we collect evidence various determinants and mechanisms of capability accumulation and align them with the current representation of capability accumulation in macroeconomic models. Based on these results, we make some suggestions on how macroeconomists may integrate these determinants derived from the specialized literature into their models.

Keywords Capability accumulation · complexity · economic development · innovation · technological change · agent-based modeling · endogeneous growth · knowledge accumulation and learning

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†Corresponding author.

1 Introduction

The relevance of *technological capabilities* for growth and development on the national and regional level, as well as for the business success on the firm level has been documented by numerous empirical investigations (e.g. Baumol, 2002; Hidalgo and Hausmann, 2009; Romer, 1990). In the macroeconomic literature, it is argued "that countries tend to approach the level of income associated with the capability set available in them" (p. 10570 Hidalgo and Hausmann, 2009), while on the firm level, "[...] technological capabilities are central to [a firm's] identity, its strategies, and its potential for success" (Aharonson and Schilling, 2016, p. 81).

Researchers working on macroeconomic questions are, therefore, faced with both a challenge and an opportunity: on the one hand, the literature clearly shows that capability accumulation (hereafter CA) is an important determinant for macroeconomic dynamics, therefore offering a possibility for more accurate models of growth and development. On the other hand, transferring the fine-grained results on CA into a comprehensive macroeconomic model is difficult and often conflicts with the challenge to keep the complexity of these models manageable. This challenge is exacerbated by the fact that, notwithstanding a substantial body of research, there is no consensus about the mechanisms underlying CA. Hidalgo *et al.* (2018) recently point to this challenge by highlighting that while there are numerous empirical results on CA, a lot of authors remain silent on the "variety of mechanisms by which economies and organizations learn"(Hidalgo *et al.*, 2018, p.452)". In a similar vein, Hidalgo and Hausmann (2009) stress that their work on economic complexity "has not emphasized the process through which countries accumulate capabilities, but has instead focused on their measurement and consequences" (p. 10575).

The prime objective of the present paper is to make a contribution that helps to address the challenge of considering CA within comprehensive macroeconomic models by (1) providing an overview over current strategies to integrate CA into macroeconomic models, (2) reviewing the empirical literature on CA on the micro- and macroeconomic level and (3) discussing specialized models dedicated to the investigation of CA processes and, thereby, delineating promising channels for integrating results from the specialized literature into comprehensive macroeconomic models. This would not only allow for the construction of more realistic models, but also to study how mechanisms of CA interact with other macroeconomic processes.

Unfortunately, there is no unanimous and generally accepted definition of CA. In this paper we focus on the question how agents – comprising here both firms and countries – accumulate capabilities, where we understand capabilities broadly as "the knowledge that goes into the making of products" (The Growth Lab at Harvard University, 2019). It is worth noting that numerous similar – and partly synonymous – terms are currently used in the literature and that the most commonly used terms differ across disciplines. First, the topic of CA is obviously related to the topics of *collective learning* or *knowledge accumulation*, two keywords that also pop up frequently in the literature. CA as understood in this paper can be interpreted as a special form of learning, i.e. learning new or better ways to conduct certain economic activities. To avoid the more general and less precise notion of 'learning' we use the term 'capabilitiy accumulation', well aware that the latter is a subset of the former.

Second, there is a close connection to the terms *innovation* and *technological change*, most commonly used in management studies and economics, respectively. *Innovation* has been defined as "ways to exploit the latent potential of ideas" (Francis and Bessant, 2005, p. 171) or, more elaborately, "the recognition of opportunities for profitable change and the pursuit of those opportunities all the way through to their adoption in practice" (Baumol, 2002, p. 10). Thus, the term *innovation* tends to embrace all measures that transform an idea into a new approach to doing things and, therefore, seems to include – but is not limited to – technological capabilities. For our literature review, we considered papers studying *innovation* by deciding on a case-by-case basis whether the term is defined and used in a way that comprises our definition of *capabilities*. We took the same approach when it came to the term *technological change* which is particularly common in economics. In a seminal paper, Romer (1990) defines technological change as "improvement in the instructions for mixing together raw materials" (p. 72). Technology is, thus, understood as the set of knowledge, actions and instruments available that can be used to transform input into output. The term is most often used with regard to the production process and the creation of new products. In contrast to *innovation*, which is mainly used in the context of firm and sector analysis, *technological change* is used both on the micro- and macroeconomic level – often including aspects such as physical capital – and, thereby, in a broader sense. Again, we decided on a case-by-case basis whether authors use the term *technological change* in a way that is consistent with our definition.

As indicated above, the aim of this paper is to facilitate the integration of insights on CA into more comprehensive models of macroeconomic development. To this end, we proceed as follows: we begin in section 2 with a description of the *status quo*, i.e. we provide an overview on how processes of CA are currently considered in macroeconomic models. Then, we summarize central results on CA of the more specialized literature in section 3, considering both empirical and theoretical contributions on the micro and the macro level. In section 4, we discuss how insights regarding CA derived from the theoretical and empirical literature on CA can be better integrated into macroeconomic models. Finally, in section 5 we summarize and conclude.

2 CA in macroeconomic models

The challenge for macroeconomic models is to take into account CA as an empirically highly relevant economic process, while at the same time keeping the overall complexity of the model manageable. This comes with trade-offs: a more complete depiction of the CA process makes it *ceteris paribus* more difficult to also include an adequate description of, for example, the central bank, the government or household behavior.[3] In this section, we review how this challenge is currently addressed in different modeling frameworks and how CA has been integrated in macroeconomic models so far. To keep the overview concise, we focus on two representative, yet very different modeling frameworks: *endogenous growth theory*, which in many ways also provides the building blocks for CGE and DSGE models, and *agent-based macroeconomics*. What unites both approaches is that both consider CA processes mainly through their treatment of *innovation* and *technological change*, as discussed in the introduction.

Endogenous growth models (EGMs) are among the most common approaches to study macroeconomic dynamics and development. Many of the theoretical building blocks developed within this framework also found their way into more applied models such as DSGE or CGE models. The historical motivation to develop these models was the desire to study the role of CA for economic development *endogenously*, rather than treating it as an exogenous factor. Consequently, in EGMs CA is the outcome of the investment activities of (profit maximizing) agents, as well as the assumed market environment (for an extensive overview see, e.g., Acemoglu, 2009). A concise summary is given in table 1.

EGMs highlight different mechanisms according to which CA takes place and operates, most of which are related to the R&D decisions of firms. A number of standard treatments of these mechanisms have emerged: in one of the first contributions to the EGM literature, Rivera-Batiz and Romer (1991) subsume CA under a very general definition of *technology* which, aside from technological capabilities, comprises machinery, process knowledge and the quality of physical inputs. Here, CA takes place as an immediate consequence of firms investing into R&D or machines and reduces the marginal cost of production for the firm – the process of production becomes more efficient and CA is conceptualized as a kind of *process innovation*. A similar treatment dates back to Romer (1990), for whom the carriers of capabilities are skilled workers who benefit from the knowledge accumulated by older generations. In effect, CA, which again gets triggered by R&D investment, involves the process of inter-generational *knowledge spillovers*, and takes place in a cumulative way, where current generations build upon and expand the stock of technological capabilities accumulated by previous generations. The implications of CA are similar and refer to the increased productivity of firms.

A slightly different perspective is offered by the models in the spirit of Grossman and Helpman (1991a,b), where CA is also the result of investment into R&D, but where it leads to the production of new product varieties, instead of an improvement of the production process of existing products. Thus, for firms, CA pays off not by the reduction of

[3]Models that do not face this trace-off since they are dedicated to the modeling of CA processes as such are dealt with in section 3.3 below.

Building blocks of CA in macroeconomic models I: endogenous growths models (EGMs)		
Consideration of CA	**Effect of CA**	**Seminal papers**
Firms invest into ***R&D*** to acquire ***better inputs***, such as machines, processes and skills	Reduction in production costs	Rivera-Batiz and Romer (1991)
Firms invest into ***R&D*** to develop ***new variants*** of products, which may come with temporary monopoly rents due to consumers' preferences for variety	Temporary monopoly rents	Grossman and Helpman (1991a,b)
Firms invest into ***R&D*** , but the carriers of CA (e.g. scientists) are 'scarce', so sustained growth is possible only due to ***knowledge spillovers*** from the past: CA happens cumulatively and via interpersonal knowledge diffusion	Increased productivity	Romer (1990)
Entrant firms invest into ***R&D*** and ***replace incumbents***, mostly by offering higher-quality versions of existing products; in effect, CA is enforced by the danger of ***creative destruction***	Temporary monopoly rents (for successful innovators)	Aghion and Howitt (1992)
An important set of growth models formalizes ***barriers to technology adoption***, (such as extractive institutions), and focus on why CA does *not* take place	Persistent differences in levels of income and capabilities across the world	Howitt (2000), Acemoglu *et al.* (2007)
People learn to use particular technologies, thereby closing the possible ***mismatch between knowledge and technologies***; in effect, CA happens cumulatively	Slow or no CA taking place; this implies lack of catch-up across countries	Atkinson and Stiglitz (1969), Acemoglu and Zilibotti (2001), Acemoglu (2002)

Table 1: Implementation of the CA process in selected macroeconomic endogeneous growth models.

production costs but because of temporary monopoly profits on the market. This mechanism is more similar to what is often dubbed *product innovation*, although it is only about the development of new varieties of existing products, rather than the invention of brand new products.[4] Temporary monopoly rents are also the main implication of CA in the models building upon Aghion and Howitt (1992), where R&D investments lead to the production of better products, which then eliminate their predecessors. Because of the resulting competition between incumbent and entrant firms as well as the resemblance of a process of *creative destruction*, these models are often labeled as 'Schumpeterian models'. Here, CA is something firms must strive for in order to survive in the market.

In much of the newer literature, the main interest of researchers has shifted to the explanation of uneven CA on the global level. Starting with the contributions of Howitt (2000) and Acemoglu *et al.* (2007), the investigation of *barriers* to CA, such as incomplete contracts, extractive institutions or social conflicts, is now an active area of research. While these models are less concerned with the question of how CA takes place, their treatment of barriers to CA allows to derive conjectures on these processes as well. A similar observation can be made with regard to models dealing with the *mismatch between skills and technology* (e.g. Acemoglu and Zilibotti, 2001; Acemoglu, 2002). This literature implies that processes of CA involve processes of *learning-by-doing*, and highlights the need to distinguish between knowledge and machines, as discussed in the introduction, although less effort has been spent on developing models of the separate diffusion of knowledge and machines.

[4]This distinction has relatively little impact on the mathematical structure of the models, yet represents very different aspects of the real world innovation and CA process, which is why we consider it important to highlight this difference.

While EGMs continue to be very successful in macroeconomics and have highlighted important systemic implications of CA processes on the firm level, they necessarily take a birds eye perspective on the process of CA, i.e. they abstract away most of the particular learning activities on the firm and employee level. This helps to focus on the macroeconomic implications of CA, but also shallows the concrete mechanisms of CA on the micro level from the general analysis.

This is potentially different in the case of agent-based models (ABM), which have grown in popularity over the previous years due to their success in replicating a respectable number of stylized facts on the micro, meso and macro level (for a survey see, e.g., Dawid and Delli Gatti, 2018; Dosi and Roventini, 2019). These models consist of an artificial population of agents whose interactions are simulated directly and analyzed numerically without an *a priori* equilibrium assumption.

In contrast to EGMs, these models necessarily contain explicit protocols for all processes taking place within the model, including those of CA. On the one hand, this might entail the danger of *ad hoc* specifications of these processes. On the other, the flexibility of ABMs and the required explicitness might facilitate the inclusion of results of the specialized literature on CA. In the following, we will ask to what extent this inclusion has already taken place. To this end we discuss five different models, each representative for a particular 'family' of macroeconomic ABM.[5] An overview is given in table 2.

Macroeconomic ABMs usually distinguish between a production sector for consumption and for capital goods. Dosi *et al.* (2019b, representative for the 'Keynes-meets-Schumpeter' models) and Caiani *et al.* (2019, representative for the 'Benchmark' models) locate CA processes only in the sector for consumption goods. Firms invest into R&D to increase the probability to be successful in either *innovative* or *imitative* activities. If the former is successful, the firm may discover better ways to produce their final products, resulting in an increase of labor productivity. In case the latter is successful, the firm copies the manner and methods of other firms' production, which may also lead to increased productivity. Thus, both processes refer to improved ways to produce the same product, not to producing new products as such.[6]

Other macroeconomic ABMs locate the CA process in *both* the consumption and the capital good sector: Ciarli *et al.* (2018) consider two types of CA processes: first, capital good firms invest into R&D to develop higher quality versions of their capital good, which is more attractive to final good firms because it features higher labor productivity. Then, final good firms invest into R&D based on anticipated payoffs and, if successful, they produce new products (or, in the jargon of the paper, goods in higher quality). Thus, the model features a kind of CA similar to that in Grossman and Helpman (1991b) with regard to *product innovation*. This also illustrates how the explicit event protocols in ABMs allow for a more explicit and diverse representation of CA processes: in Ciarli *et al.* (2018), for example, firms decide on their R&D expenses based on anticipated payoffs, whereas in Dosi *et al.* (2019b) it is a fixed share of past profits. This introduces more degrees of freedom, but also allows for a more fine-grained alignment of the model specification with the existing empirical literature.

Hötte (2019), who extends the Eurace@Unibi-eco model (Dawid *et al.*, 2019), models the CA process both on the level of employees and firms: the firm side is similar to the models discussed above: capital good firms invest into R&D to increase the probability to invent more productive capital goods, which can then be sold more attractively to the final good firms. However, Hötte (2019) also considers CA on the level of the individual employees: employees improve their abilities to work with particular capital goods on the job, so the model effectively implements a *learning-by-doing* process. The worker's capabilities matter because the effective productivity of a firm depends on both the productivity of the capital goods used as well as the average amount of capabilities of the employees. These capabilities are tacit: if

[5] A 'family' is made up by several versions of the same underlying model. Since all instances of the respective families implement CA similarly, we focus on the most recent instance or the one that pays most attention to the topic of CA.

[6] In both cases, the new way of producing the same product is not necessarily better than the existing one, representing the inherent uncertainty of changing production processes.

Building blocks of CA in macroeconomic models II: agent-based models (ABMs)				
Model	**Locus of CA**	**Effect of CA**	**Description of CA process**	**Determinants of CA**
(Dosi *et al.*, 2019b, representative for the 'Keynes-meets-Schumpeter' models), (Caiani *et al.*, 2019, representative for the 'Benchmark' models)	Consumption good firms	Increased labor productivity	Firms invest into R&D to increase the probability for successful innovation or imitation which, in turn, may increase productivity	R&D expenses, spillovers
Ciarli *et al.* (2018)	Capital good firms	Capital goods with higher labor productivity	Firms invest into R&D based on anticipated payoffs; this increases trials for innovation activity per time step	R&D expenses
	Consumption good firms	Higher product quality		
Dawid *et al.* (2019) and Hötte (2019, representative for the EURACE@Unibi models)	Employees	Better exploitation of high productivity production technologies in the employing firm	Workers have exogeneously given general skills that determine speed of *learning-by-doing*, which increases specific skills (i.e. tacit knowledge that workers can take with them to other firms)	Experience
	Capital good firms	Potentially higher productivity of capital goods, if matched with skilled workers	Firms engage in R&D; success randomly adds higher quality vintage, which might be sold to consumer good firms	R&D expenses
Rengs *et al.* (2019)	Consumption good firms	Reduction of carbon intensity of production	Firms decide to invest into R&D directed at green technology reducing carbon intensity, or at grey technology reducing labor intensity of production; for both technologies, spillovers across firms exist	Spillovers, R&D
		Reduction of labor intensity of production		

Table 2: Implementation of the CA process in selected macroeconomic agent-based models, where it is usually discussed under the label 'innovation'. The column 'determinants' only lists the ultimate drivers of CA. We do not mention 'policies' when they impact CA only via fostering R&D investments.

a worker switches firms, they take their capabilities with them, creating knowledge flows between firms [7]. The model is, therefore, not only useful to study (barriers to) knowledge diffusion, similar to the EGMs in the spirit of Acemoglu *et al.* (2007), but also the implications of a mismatch between worker capabilities and capital equipment as in Acemoglu and Zilibotti (2001).

Finally, Rengs *et al.* (2019) distinguishes between capabilities necessary for two aspects of production: firms can reduce the amount of CO_2 emissions associated with production, or they can increase their labor productivity. When deciding on which competencies to improve upon, firms compare themselves with their competitors and follow the strategy of those firms that are making the highest profits. Firms decide on the amount of funds allocated to the improvement of their capabilities based on their past profits. The effect of their investments also depends on spillover effects from other firms: the more firms focus on one particular way of improving their products, the more effective their investments become.

In addition to the CA processes just described, many macroeconomic ABMs also study the effect of institutions and government activity on the processes of CA. For example, Dawid *et al.* (2018) study the effect of innovation policy on the speed of CA in less developed countries. Innovation policy here takes the form of (directed or undirected) subsidies for the R&D investments of firms, thus serving as a second level determinant of CA operating through the channel of R&D investment as explained above. Another example is provided by Dosi *et al.* (2018), where the authors study the effect of an active government investing into R&D activities on its own. Via knowledge-spillovers these R&D activities then affect the rest of the economy as well. Again, in this case the *fundamental* channels of CA are R&D activities and knowledge spillovers, yet it is clearly acknowledged that since the government can engage in these activities itself, its behavior affects CA in the overall economy. Finally, as evidenced by Caiani *et al.* (2019), different institutions of wage determination may also affect CA. They show that coordinated wage growth in the long run can lead to a concentration of firms and via the channel of 'Schumpeter Mark II' to higher and more targeted investments into R&D activities. As in the two examples above, the institutions determining wages here affect CA via the more fundamental channel of R&D investments. Thus, while it is important to keep in mind that many current ABMs do investigate the role of institutions and policy makers for CA, they do so via reference to the more fundamental determinants of CA explicated before, i.e. mainly R&D investment.

When comparing ABMs and EGMs with regard to the consideration of CA we may conclude that – so far – in both modeling paradigms relatively little attention is given to the precise mechanisms according to which CA takes place. Moreover, in both approaches by far the most prominent determinant for CA is R&D investment (and, to a lesser extent, knowledge spillovers), the main effect being an increase in firm productivity. Relatively little attention has been given to the role of CA for the invention of radically new products. Models that do feature product innovation consider CA as means to leading to higher quality products, or via new products emerging within an *expanding variety* framework. That being said, ABMs are distinguished by their explicit interaction protocols and, correspondingly, a more fine-grained representation of the CA process. This may lead to more detailed questions, e.g. whether firms invest into R&D based on past sales or expected profits, or whether CA takes the form of copying the ideas of related firms, or of coming up with entirely new ideas themselves.

3 Theory and empirics of CA beyond macroeconomics

The previous section was concerned with the current practice of integrating CA into comprehensive macroeconomic economic models. Here, the major challenge faced by modellers is to take into account CA processes as an empirically highly relevant economic phenomenon, while at the same time keeping the overall complexity of their model workable. In this section, after describing our research strategy and data used for our literature survey in section 3.1, we complement this information by first reviewing the empirical literature on CA in section 3.2. After a short summary of the main

[7]This mechanism is in accordance with the principle of relatedness (or, more precisely, skill relatedness), which will be explained and discussed in section 3

findings and a discussion of the general implications that may arise for macroeconomic models, we survey theoretical contributions that are directly concerned with the problem of CA (section 3.3). Later, in section 4, we synthesize the main findings from our review and make suggestions on how recent insights on CA could be used to improve the more comprehensive macroeconomic models.

3.1 Methods and Data

We conducted a bibliographic search to collect papers that address the process of CA in a broad sense – as suggested by our definition in section 1. In a first step, we collected a sample of papers by following two strategies. We started by searching the EconLit database for papers published between 2004 and 2019[8] containing the keywords and phrases *capability accumulation*, *knowledge accumulation*, *technological learning* and *product complexity*[9] – only considering papers in English language and working papers published not later than 2018. In total, this part of our search strategy resulted in 570 papers . Based on the most relevant results, we additionally applied *purposive searching* ('snowballing')[10] and added further literature referenced in these papers to our overall sample.

In our next step, we divided the identified papers into two main categories: (1) papers dealing with CA from an empirical perspective and (2) papers discussing theories or models of CA. Within the empirical category, we further split up our sample based on whether CA is discussed (a) on an aggregated (mostly national or international) level or (b) on the firm level. In the end we included 45 relevant studies into the actual paper (see Tables 3, 4 and 5).

3.2 Empirical contributions

The empirical literature on CA has reached a considerable scope and the phenomenon has become a generally recognized object of investigation. Papers on the topic are published in respectable outlets across various disciplines. In this section, we discuss the results of our search of empirical contributions based on the main determinants that are addressed in this literature.

3.2.1 Empirical results on the aggregated level

The various determinants of CA that have been found to be decisive on the aggregated level can be clustered according to three main *topoi*: (1) the *cumulative and path-dependent nature of CA*, (2) the *institutional environment*, and (3) *government activity*. Obviously, the boundaries of these *topoi* are not always clear-cut. For instance, the cumulative and path-dependent nature of CA might also manifest in the various institutional arrangements and forms of government action; and policies that shape environments might be a result of direct government action. Despite this and because a separate discussion of each *topos* might be more helpful in the development of comprehensive models, we decided to examine each *topos* and the respective determinants associated with each of them one by one. The results are summarized in table 4.

Path dependency and cumulative CA. By calling CA to be a cumulative process the literature makes the point that for the acquisition of a new capability to be successful it should somehow be related to the stock of capabilities that has already been accumulated. Dubbed as the "Principle of Relatedness" (Hidalgo *et al.*, 2018, hereafter PoR), this general claim has been examined on the basis of different operationalizations which can be considered as different but related attempts to test the abstract principle empirically:

[8] We chose this time frame in order to focus on the state of the art of the literature.

[9] We deliberately excluded the keyword *innovation* to preclude papers where the term 'innovation' is not related to our definition of CA since the keyword 'innovation' is used in a much broader way and most relevant contributions focusing on innovation in a sense that is consistent with our definition of CA also used the other keywords we were using. Moreover, while in the case of *knowledge accumulation*, *technological learning* and *product complexity* we searched for the exact phrase, the search for *CA* also includes papers containing the terms *capability* and/or *capabilities* and *accumulation*.

[10] Snowballing often appears to be a more viable approach in identifying the relevant literature compared to conventional database searching (Pawson, 2006).

Empirical findings on the aggregated level	
Findings on the CA process	**Sources**
Cumulative and path dependent nature of CA	
Skill Relatedness: CA happens through worker migration flows	Neffke *et al.* (2017)
Technological Relatedness: CA builds on preexisting capabilities	Alonso and Martín (2019), Balland *et al.* (2019), and Neffke *et al.* (2011)
Export Relatedness: Spillovers from neighboring regions lead to CA (expressing themselves in more similar export baskets)	Bahar *et al.* (2014)
CA is determined by the "product space"	Hidalgo *et al.* (2007)
Institutional environment	
CA is supported by securing and deepening (intellectual) property rights	Ang (2010, 2011) and Yu *et al.* (2015)
CA is supported by facilitating institutions of open access	Pagano (2010)
CA is supported by protectionist policies	Figueiredo (2008)
CA is supported by trade (liberalization) policies	Alonso and Martín (2019), Castellacci and Natera (2013), Figueiredo (2008), and Yu *et al.* (2015)
CA is weakened by labor market flexibilization	Vergeer and Kleinknecht (2014), Cetrulo *et al.* (2018)
CA may be supported by financial development but is negatively associated with financial liberalization (policies)	Ang (2010, 2011)
Government activity	
CA is fostered by R&D investment	Ang (2011), Castellacci and Natera (2013), J. J. Lee and Yoon (2015), and Mazzucato and Semieniuk (2017)
CA is fostered by public ownership and governance	Collinson and Wang (2012), Mazzucato and Semieniuk (2017), and Yu *et al.* (2015)
CA is fostered by active industrial policies: training programs, coordination, mediation and collaboration	Autio *et al.* (2008), Collinson and Wang (2012), Figueiredo (2008), Hobday and Rush (2007), and J. J. Lee and Yoon (2015)
CA is linked with the quality of (public) infrastructure	Castellacci and Natera (2013)

Table 3: Central empirical findings on the determinants for well-functioning CA on the aggregated level.Most studies take into account various determinants (e.g. as control variables). In our description, however, we only address the determinants which are the main focus of the respective paper.

- *Skill relatedness* (e.g. Neffke *et al.*, 2017) as measured by inter-industry labor flows: capabilities develop along similar human capital or skill requirements.
- *Export relatedness* (e.g. Bahar *et al.*, 2014) as measured by the composition of export baskets: a country's capabilities converge to the capabilities of neighboring countries, i.e. there are information spillovers between close regions.
- *technological relatedness* (Alonso and Martín, 2019; Balland *et al.*, 2019; Balland and Rigby, 2016; Neffke *et al.*, 2011) as measured by plant-level product portfolios, country-level production baskets and/or patent data: capabilities develop along regional paths of production.

Hidalgo *et al.* (2007) formalize this general idea of *relatedness* within the framework of the *product space*, a network based on trade data in which the vertices represent products, and the edges represent the probability that two products are co-exported by the same country. The authors attempt to make the PoR empirically tractable by making two major assumptions: First, the products that are produced in a country are a useful proxy for the capabilities that the people in this country have accumulated. In other words, if a country is a producer of computer chips we can conclude that its inhabitants have the capabilities required to produce computer chips.[11] Second, the products that a country exports with revealed comparative advantage are a good proxy for the products that a country produces. This assumption is made because there are good and extensive data about imports and exports, but few and poor data on actual products[12].

In effect, the product space can be seen as an empirical operationalization of the the PoR when applied to economic activities related to the production of commodities. Hidalgo *et al.* (2007) then argue that the development of a country depends on how well it has accumulated the capabilities associated with the most general area of applicability, i.e. those capabilities that are necessary to produce the products in the centre of the product space. Since they are similar to many other capabilities, the accumulation of these core capabilities facilitates further CA. Although there is no elaborated theory of CA underlying the concept of the product space, it implies that CA happens in a cumulative fashion, with new capabilities being similar to those that have already been accumulated. Hence, CA depends on local experimentation and thereby the exploration of similar, or the re-combination of existing capabilities (see also Hidalgo and Hausmann, 2009; Vermeulen and Pyka, 2014, p. 10575). The framework thus bears much similarity to evolutionary theories of learning, including the idea of technological capabilities as a solution for particular technological challenges (e.g. Silverberg and Verspagen, 2005).

In all, the empirical research associated with the PoR consistently highlights the cumulative nature of CA: capabilities are accumulated step-wise and new capabilities are similar to existing ones. It summarizes empirical findings on the firm, regional and international level.

Institutional environment. Numerous studies stress the relevance of regulatory measures at the macro, meso and micro level. Determinants include the design of property rights, trade policies, labor market policies and financial policies and can be summerized under the heading of the 'institutional environment'.

One determinant that has received a lot of attention is the *design of trade policies*. So far, however, no consensus on the impact of trade on CA has emerged. Rather, the literature suggests that the effect depends on the degree of maturity of the firms in the respective regions. Figueiredo (2008), for instance, conducts an extensive case study on the "Industrial Pole" of Manaus (Brazil), Figueiredo (2008) and argues that the now strong industries are the result of a protectionist economic policy that has triggered CA in the past: it was during the period of industrialization when policies aiming at import substitution helped firms to successfully build up capabilities (Figueiredo, 2008).

[11] While in principle being a reasonable assumption, it is violated whenever countries 'produce' products by only assembling parts that have been imported from other countries. In this case, the final product is not an indicator for the capabilities held within the assembling country itself.

[12] Again, while being reasonable in principle, there are situations in which the assumption might not hold, e.g. if a country does not want to export for political reasons, where a country is at the end of an international production chain or when a country has the capabilities to produce a product, but not to sell it on the competitive world market.

However, there are also studies that find a positive effect of trade *liberalization* policies on CA. Castellacci and Natera (2013) develop the argument that an economy's innovation system is driven by the coevolution of its "innovative capability"[13] and its absorptive capacity[14]. Depending on a country's stage of development, these two dimensions vary in their impact, with international trade being of particular importance as an absorptive capacity variable for middle-income and catching-up countries. Alonso and Martín (2019), analyze the role that imports might play for CA in Brazilian and Mexican regions. They find that while spillovers from neighboring regions play an important role for product diversification, capabilities that are imported via imported products are beneficial to the development of new products. The case of China's fast catching-up process provides further evidence for trade liberalization as a determinant of CA. In the wake of China's WTO accession, a gradual liberalization of trade and FDI regimes and a corresponding inflow of FDI resulted in the building up of labor-intensive production and the acquisition of advanced technology via joint-ventures between foreign and state-owned enterprises (Yu *et al.*, 2015).

These seemingly conflicting results might be cleared up if one is mindful of the different stages of development that the investigations refer to. The case study of Figueiredo (2008) puts forward that protectionism may serve as a precondition for successful liberalization and integration of the Industrial Pole into the world market since the 1990s. With preparing the Brazilian economy for world competition and trade openness, the regulatory environment changed significantly and government as well as policies took a more active role in stimulating CA among firms (Figueiredo, 2008). This suggests that the effects of different institutional environments are not stable over time, but depend on the current state of development of the firms and industries in question.

However, not all contradictions regarding the institutional environment can thus easily be solved. For example, there is conflicting evidence on the role of financial flows and policies. Although it is widely agreed upon that financial development generally benefits CA via inducing R&D spending, financial liberalization policies tend to impede the CA process – particularly in developing countries (e.g., Ang, 2010). A reason for this may lie in the reallocation of human capital to the financial sector, resulting in a lack of CA in the technology sector (Ang, 2011).

Another example refers to the *organization of property rights*, i.e. of the property right system in general and of intellectual property rights (IPR) in particular. Several empirical studies suggest a positive effect of private IPR institutions on CA (e.g. Ang, 2010, 2011). While Ang (2011) finds that private IPR have a positive effect in more developed countries, Yu *et al.* (2015) argue that the replacement of state- and collective owned enterprises by the implementation of property arrangements that ensure internal management (ranging from sales to foreign firms to employee/manager ownerships) contributed to the fast catching-up process of the Chinese manufacturing sector. However, there also are papers that question the positive effect of IPR, arguing that institutions of *open access* are essential for collective learning and, thereby, CA Heinrich (e.g. 2013) and Pagano (2010).

Results are less inconsistent in the case of labor market policies. Flexibilization, i.e. the removal of rigidities on the labor market has, for example, been found to create incentives for the creation of low-paid and low-skilled jobs – at the expense of well-paid jobs with a higher innovative potential. Furthermore, such policies tend to discourage worker training and the accumulation of worker experience. Both of these factors harm an economy's capacity for CA (Cetrulo *et al.*, 2018; Vergeer and Kleinknecht, 2014).

Government activity. In addition to policies on a regulatory level, numerous authors highlight the relevance of more direct government action as well, with the *entrepreneurial state* as described by (Mazzucato, 2014) being a recent example.[15] Channels through which more direct government action enhances CA include public R&D investment (Ang, 2011; Castellacci and Natera, 2013; J. J. Lee and Yoon, 2015; Mazzucato and Semieniuk, 2017), public ownership and

[13] Defined as "the ability of a country to produce and commercialize a flow of innovative technology over the long term" (Furman *et al.*, 2002, p.899 in Castellacci and Natera, 2013, p.580).

[14] For an explanation of the notion of absorptive capacity see section 3.2.2.

[15] One has to bear in mind, hoever, that there is not always a clear line to draw between active government action and regulatory policy. For example, incentive-based policies such as tax incentives for firms, who invest a share of their revenues either internally or externally into R&D (Figueiredo, 2008) might be classified into both categories.

governance of key sectors and enterprises (Yu *et al.*, 2015) or governance of research organizations, training centres and R&D programs (Autio *et al.*, 2008; Collinson and Wang, 2012; Hobday and Rush, 2007).

The possibilities for constructive government action that goes beyond the fixing of market failures have been explored in numerous case studies, for example by Mazzucato and Semieniuk (2017), who show for the case of greener technologies how public organizations can use measures such as *proactive financing of R&D* to directly foster CA. Furthermore, early-stage CA can be enabled by an entrepreneurial state via the absorption of high risk levels and uncertainty as well as by providing further incentives to meet quality standard that go beyond what is currently demanded on the markets. Figueiredo (2008) illustrate this in the context of Manaus, where government organizations acted as active development agencies in shaping capabilities of local firms by forcing them to obtain quality standards or to introduce new management and organization techniques.

Another example is provided by J. J. Lee and Yoon (2015) with their comprehensive country case study on CA for complex product systems such as military aircraft. J. J. Lee and Yoon (2015) explore a wide repertoire of government policies aimed to facilitate coordination, mediation and collaboration between relevant partners (including research institutions), such as government procurement and export policies used to establish participation of relevant actors for triggering CA processes of military latecomer industries. In a similar attempt, Collinson and Wang (2012) find in a study on the development of the Taiwanese semiconductor industry that government coordination as well as support in R&D funding was essential for advanced technology transfer. Finally, the quality of *(public) infrastructure* plays a crucial role for CA, in particular for middle income countries (Castellacci and Natera, 2013).

3.2.2 Empirical results on the firm level

The literature on CA taking place on the firm level has highlighted a much broader spectrum of determinants than on the aggregate level. We cluster these determinants around seven *topoi*: (1) *absorptive capacities*, (2) *relatedness*, (3) firm-level *R&D spending*, (4) *experience*, (5) *alliances*, (6) *spillovers* , and (7) firm-level *governance*. Similar to our procedure in section 3.2.1, we will comment on each of these in turn.

Absorptive capacities. Building on the influential work of W. M. Cohen and Levinthal (1990), various papers in our sample explicitly highlight the role of building up *absorptive capacities* as an underlying mechanism for successful development of the firm (e.g. Chuang and Hobday, 2013; Chung and K. Lee, 2015; Figueiredo and M. Cohen, 2019) level.[16]. Originally, a firm's absorptive capacities was defined as its ability "to recognize the value of new, external information, assimilate it, and apply it to commercial ends" (W. M. Cohen and Levinthal, 1990, p.128). Absorptive capacities in this sense manifest themselves in a firm's capability to exploit newly created knowledge and technology and thereby to respond to more quickly to changes in the firm's environment. It has to be noted, though, that many present studies have departed from the original definition and amended it for their purposes. This has led to an increase of ambiguity with regard to the concept of *absorptive capacities*.

The original idea of W. M. Cohen and Levinthal (1990) is, however, still very relevant. They proposed a simple model of CA where R&D investment both determines the level of technical knowledge in, as well as the level of absorptive capacities of a firm. Since then, there evolved an ongoing and rich debate on different conceptualizations of absorptive capacities and whether they are determined by factors beyond R&D (e.g. Chuang and Hobday, 2013; Chung and K. Lee, 2015; Hong *et al.*, 2019). With regard to the actual impact of absorptive capacities, most studies seem agree that absorptive capacities have a *moderating* effect on CA by positively influencing the impact of other determinants discussed in this paper (such as R&D investment or alliances), which is why Chuang and Hobday (2013) define them as a "deeper level of capability" (p. 1062). This means, of course, that any useful analysis of the effect of absorptive capacities on CA must include an analysis of those determinants of CA that are moderated by the absorptive capacitie Examples for such an undertaking include Cantwell and Zhang (2013), Chung and K. Lee (2015), Figueiredo and M. Cohen (2019), and Subramanian *et al.* (2018) who find that firm-level absorptive capacities are also affected by

[16] Castellacci and Natera (2013) introduce a model that translates the idea on an aggregated level.

Empirical findings on the firm level	
Findings on the CA process	***Sources***
Absorptive capacities	
CA is positively moderated by a firm's absorptive capacity	Chuang and Hobday (2013), Chung and K. Lee (2015), and Figueiredo and M. Cohen (2019)
Relatedness	
Skill Relatedness: CA is determined by the composition of human capital	Neffke and Henning (2013)
Technological Relatedness: CA is determined by preexisting capabilities	Balland and Rigby (2016) and Chuang and Hobday (2013)
CA through (re)combination of existing knowledge (*bricolage*)	Aeron and Jain (2015)
R&D spending	
CA achieved by *anti-learning*: higher R&D spending over time is linked with quality upgrades of products	Dosi *et al.* (2017)
CA is fostered through internal and/or external R&D spending	Chung and K. Lee (2015), Figueiredo (2008), and Wu and Wei (2013)
CA may be retarded by R&D over-investment	L. Li *et al.* (2018)
Experience	
CA is moderated by firm size	Dosi *et al.* (2019a) and Villar *et al.* (2012)
CA is moderated by firm age	Dosi *et al.* (2019a) and Villar *et al.* (2012)
CA is accomplished by *learning by doing*: cumulative production is linked with increasing production efficiency	Dosi *et al.* (2017)
Alliances	
CA is enhanced by *alliance capabilities*	L. Li *et al.* (2018)
CA is enhanced by the homogeneity of knowledge bases between alliance partners	Subramanian *et al.* (2018)
Spillovers	
CA is activated by various knowledge flows and spillovers from stakeholders (e.g. suppliers, customers, competitors) and other social networks	Aeron and Jain (2015), Chuang and Hobday (2013), Chung and K. Lee (2015), Collinson and Wang (2012), Figueiredo (2008), Figueiredo and M. Cohen (2019), J. Li *et al.* (2013), Wu and Wei (2013), and Zhai *et al.* (2007)
CA is achieved by searches beyond organizational, technological, and geographical boundaries	Cantwell and Zhang (2013), J. Li *et al.* (2013), and Wu and Wei (2013)
CA is fostered by a firm's identification with a community of practice	Autio *et al.* (2008)
Governance	
CA is enhanced through local decision making and autonomy	Collinson and Wang (2012) and Figueiredo (2008)
CA is shaped by global value chain architecture	Hobday and Rush (2007) and Marin and Bell (2010)
CA is retarded by *thick* management bureaucracies	Kleinknecht *et al.* (2016)
CA is fostered by team work and internal training arrangements	Chuang and Hobday (2013) and Figueiredo and M. Cohen (2019)
CA is activated by organizational routines	Figueiredo and M. Cohen (2019) and Zhai *et al.* (2007)

Table 4: Central empirical findings on the determinants for and functioning of CA on the firm level. Although the referenced papers identified the factors listed here as a main determinant for CA, it is worth mentioning that these factors are usually not discussed in isolation.

firm-level *alliances*, different forms of *spillovers* and *governance*. All of these factors will be discussed in the next paragraphs.

Relatedness. In addition to the PoR on the aggregated level, relatedness also appears as a relevant determinant of CA on the firm level. In particular, Neffke and Henning (2013) show that firms are far more likely to diversify into industries that are skill-related with the firms' core activities, i.e. with the human capital that the firm has already accumulated. Chuang and Hobday (2013) argue that accumulated knowledge from previous manufacturing experience is an import internal source for accumulating further technology among Taiwanese TFT-LCD display producers. Relatedness as a decisive factor is also found in Aeron and Jain (2015) in a case study on technological capabilities among Indian telecom start-ups. They find that firms try to use existing resources to develop new products by (re)combining them (*bricolage*), thus implying a continuous use of related resources in the CA-process.

R&D investment. Not surprisingly, the link between R&D spending and CA has also been found on the firm level and in general this relationship seems to be positive (e.g. Dosi *et al.*, 2017; Wu and Wei, 2013). But there are also more nuanced results: Dosi *et al.* (2017), for example, not only find for Indian manufacturing firms that R&D also has a positive impact on the degree of *learning-by-doing*, but also that there are cases of a positive relationship between production costs (and prices prices) and experience (rising production quantities), an observation they label *anti-learning*. They rationalize this that the positive of R&D spending on learning-by-doing patterns has mainly to do with quality improvements and ongoing product innovation rather than process innovation. This indicates how important the latter distinction is in practice and how it should be kept in mind during any analysis of the effect of R&D investment.

Noteworthy is also the close relationship between the analysis of R&D, the institutional environment and the relevance of spill-overs (see below) as evidenced in, for instance, the case study of Figueiredo (2008). They found not only a positive effect of regulatory policies on the aggregated level that enforce mandatory firm-level R&D investments, but also positive of resulting internal and external R&D investments, the latter referring to R&D investment that goes towards institutions external to individual firms, such as universities or public funds.

Interestingly, there are also findings of adverse effects of R&D on CA. L. Li *et al.* (2018) analyze U.S.-based small and medium enterprises (SMEs) in the biopharmaceutical sector and find that the in-house R&D stock is initially conducive for the accumulation of intellectual resources. However, later R&D played only a minor (or even negative role) for further CA. They argue that in a dynamic and complex global environment, other factors such as strong alliances might, overall, play a much more important role for successful CA.

Experience. Another important set of processes underlying CA is the accumulation of experience, the precise effect of which is often also dependent on firm size. An illustrative example for this is given by the analysis of the Spanish ceramic tile production sector (which mainly consits of SMEs) in Villar *et al.* (2012), who highlight the relevance of experience and firm size for the degree of product complexity and product innovation. They find that that experience – as measured by age – is a significant moderating variable for product innovation while firm size is a significant moderating variable for the degree of complexity of an innovation, such that both relationships are stronger for larger firms. These findings are supported and complemented by Dosi *et al.* (2019a) who analyze Indian manufacturing firms and that diversifying in terms of product scope is a strategy which is pursued by big and mature firms. Moreover, Dosi *et al.* (2017) find robust evidence for *learning by doing* – defined as the negative relation between cumulative production and production costs – as a driver of CA, although mostly for industries in developed economies.

Alliances. The literature also stresses that alliances between firms play an important role when it comes to CA. The effect of alliances, however, seems to be moderated by a number of other factors, which have been investigated mainly via numerous extensive case studies. L. Li *et al.* (2018), for example, found that the formation international alliances are an important driver of CA for U.S.-based SMEs in the research-intensive biopharmaceutical industry. The positive effect of alliances, however, is not uniform across firms and depends on their *alliance capabilities*, which the authors define as "the abilities to shape and reconfigure firms resource base by accessing the resources of its partners" (p. 820 Acemoglu *et al.*, 2012). Subramanian *et al.* (2018) also find a positive effect of alliances, but also examine the moderating role of *knowledge base homogeneity* (KBH). A firms knowledge base is defined as the subset of knowledge a firm is able to consider in the search process for new inventions (Yayavaram and Chen, 2014), KBH is the extent to which firms have similar knowledge. For partners who have a low KBH, Subramanian *et al.* (2018) find an inverted U-shaped relationship between technological distance and CA, i.e. firms profit from alliances most if they have a medium technological distance. For partners with a high KBH, on the other hand, they find a positive relationship between the two factors, i.e. higher technological distance is associated with a higher level of CA – an intuitive finding since greater similarity allows for the comprehension of relatively more advanced technology.

Spillovers. A major group of firm-level determinants that we found in the literature highlight the influence of *knowledge spillovers* on CA. Depending on the factors such as the institutional environment, sectoral specifities and the firm type, firms interact with suppliers, customers, competitors, research institutions and other social networks and stakeholders. Via knowledge spillovers, they are able to trigger and sustain CA (e.g. Aeron and Jain, 2015; Figueiredo and M. Cohen, 2019). Autio *et al.* (2008) analyze the effect of collaborative firm-level R&D programs on organizational learning in Finland. They find that the frequency of coordinated interaction among community members significantly boosts CA. Finally, evidence in the context of Chinese catching-up suggests that inter-industry spillovers at the city-level (J. Li *et al.*, 2013) as well as *beyond* a firm's organizational, technological and geographical boundaries (Cantwell and Zhang, 2013; Wu and Wei, 2013) may improve CA.

Governance. Finally, the literature has identified various forms of firm-level *governance* as another channel trough which CA may be activated. In this context, however, the evidence is mixed and many of the results still need to be consolidated. With regard to the firm level, Figueiredo (2008) find in a case study in Brazil that the accumulation of technological capabilities are strongly correlated with local management autonomy and capacitites, which have been stimulated by the government policies of the 1980s. This autonomy also strengthens the negotiation position of the firms within their value chains, being associated with a more effective upgrading within the value chain and, thereby, CA (Collinson and Wang, 2012; Figueiredo, 2008). CA within value chains has also been a topic for Hobday and Rush (2007) in their analysis of capability development in the electronics industry in Thailand. They find that, in a global value chain context, the overall technology strategy of the parent firm is a decisive determinant of CA in the sister firm and that active investment in local capability building by subsidiary firm is encouraged by more decentralized networks that allow for more openness towards domestic policies and higher local adaptability. However, this finding is in contrast to Marin and Bell (2010) who investigate the effect of local and global integration of MNC subsidiaries on technological behavior in Argentina and find that higher levels of innovative activity are linked with relatively high levels of integration within the global corporation. Thus, the precise functioning of CA mechanisms in this context still remains ambiguous and more work to consolidate the findings of the existing case studies is necessary.

Consistent with what has been discussed for the aggregate level in the previous section, more flexible labor institutions seem to be negatively associated with CA on the firm level. Kleinknecht *et al.* (2016) analyze firm-level data for the Netherlands and further confirm that deregulative reforms of labor markets may lead to higher rates of job turnover resulting in a destruction of mutual trust, loyalty and commitment. In order to monitor and control such counterproductive behavior, bloated management bureaucracies within the firm may evolve which in turn are detrimental to creativity and entrepreneurship. This line of argument is additionally supported by Chuang and Hobday (2013) and Figueiredo and M. Cohen (2019) who emphasize the role of firm-level governance in facilitating various forms of internal knowledge exchange such as formal/informal team work, R&D teams, and internal training programs.

Finally, the development of organizational routines may significantly contribute to firm-level CA. In analyzing the capability development of electronics manufacturing service companies in the Far East region, Zhai *et al.* (2007) highlight different stages of the development process. In the first stage, firms enter an industrial sector by leveraging existing resources (e.g low cost labor). In the second stage, firms draw on external resources and learn from outside (*spillovers*) but then "seek initially to explore the production chain using repetitive practices and limited diversification" (Zhai *et al.*, 2007, p.14-17). After that, in the third stage, these repetitive routines get fixed, representing a high level of knowledge regarding the production system and the supply-chain, how they change, improve *etc.*. In the final stage, the CA-process of electronics manufacturing service firms peaks on an advanced level. According to Zhai *et al.* (2007), organizational routines are a key ingredient of CA insofar as they enable firms to innovate independently. In a similar vein, Figueiredo and M. Cohen (2019) describe knowledge codification as an important internal learning mechanism of firms including various practices of accessing and disseminating knowledge; such as routines/procedures derived form internal experiments and related activities or specific protocols.

3.2.3 Taking stock

The empirical literature reviewed in section 3.2 highlights a variety of factors contributing to CA on both the aggregate as well as on the firm level. Noticeably, many of the papers in the literature analyze the determinants of CA in a very context-specific setting (e.g. specific industries such as ceramic tile vs. electronics industry, specific firm types such as MNEs vs. SMEs or specific countries such as catching-up vs. developed countries). Moreover, many paper discuss several determinants simultaneously, as can be seen by comparing the exemplary sources that are listed for each determinant in Tables 3 and 4. This suggests - not surprisingly - that CA is a highly complex process encompassing many different determinants, working on both the aggregated and the firm level. But while this means that is difficult to identify *main* channels of CA and that there seems to be no catch-all solution for triggering and sustaining CA, we may still cluster the results of the literature into four distinct areas. The first of them highlights the *contingency and context-dependency* of CA processes. This way it represents a rather fundamental challenge for modellers and should, therefore, be considered more of a call for caution when it comes to the use of models in general that does not really come with concrete and constructive implications for modellers. Then we turn to three topical areas – institutions, spill-overs and micro-macro mechanisms – that may serve as a more positive guide for scholars working on macroeconomic models.

Contingency and context-dependency of CA Numerous studies, particularly those employing a case study methodology, stress the contingency and context-dependency of CA processes, i.e. they highlight the relevance of factors that are very specific to the particular place and time (e.g. Chuang and Hobday, 2013; Collinson and Wang, 2012; Figueiredo and M. Cohen, 2019). For example, Aeron and Jain (2015) find that different stages of product development are coupled with different learning strategies. Similarly, Zhai *et al.* (2007) and Chuang and Hobday (2013) emphasise that there are different stages of firm-level capability development. In each stage, a firm has to pursue another strategy, ranging from the use of preexisting, i.e. *related*, capabilities, *governance* and external *spillovers*. Finally, a number of studies also stress the impact of singular events: Chuang and Hobday (2013), for example, explain how the financial crises of 1997 has led Japanese firms to enter cooperation agreements with Taiwanese firms, a strategy that has ultimately led to the establishment of numerous most successful transnational companies. It is hard (and maybe even counter-productive) to consider such events in comprehensive macroeconomic models, but it is important to keep their relevance in mind and to take seriously the limits of modelling when it comes to the explanation of CA processes.

Aside from this quite fundamental challenge to the modelling of CA, the literature also entails some more constructive lessons for macroeconomic modellers to consider: the following three cluster of insights summarise not only important insights on how CA processes work, their insights also seem to be not too difficult to be considered in macroeconomic models.

The primacy of institutions. The literature clearly shows that *institutions* – here encompassing both the regulatory environment as well as government activity – are crucial determinants of CA processes. This result is confirmed in case studies (such as Figueiredo, 2008; J. J. Lee and Yoon, 2015) and econometric analyses (such as Castellacci and Natera, 2013; Yu *et al.*, 2015). Although the research context and the methods of these studies differs considerably, they show consistently that in each case, implementing specific government policies preceded an ongoing and successful process of CA.[17] But institutions are not only relevant on the macro level but also lay out the grounds for the functioning of firm-level determinants that we discussed (e.g. policies facilitating various forms of *spillovers*). Considering this insight against the macroeconomic models surveyed in section 2 we conjecture that - although institutions are already considered to some extent - there still is the change to harvest some long-hanging fruits: for example, in both ABM and EBM, institutional aspects of regulation or direct government action are often merely considered in the context of barriers to technology (see 1), being reduced to "Pareto-improving policy interventions" (Acemoglu, 2009, p.483) such as subsidies to research, subsidies to capital inputs, anti-trust and patent policies. In ABMs, various forms of industrial policy (e.g. Dawid *et al.*, 2019), implications of labor regulations (e.g. Caiani *et al.*, 2019) or state-led research (e.g. Dosi *et al.*, 2018) have been considered but only via investment in R&D. This leaves room for further improvement, e.g. with regard to the investigation of the implications of public ownership and governance, the government as a facilitator of alliances among relevant actors or the role of private property and open-access norms.

Alliances and spillovers as inter-organizational processes A second cluster of findings is operating mainly on the firm level and involves *inter-organizational factors and processes* such as *spillovers* or *alliance formation*. These include both processes by which resources are drawn from various sources *outside* the firm - such as other autonomous players - as well as those from *within* the firm - such as internal R&D oder capacity building. From a methodological viewpoint, it seems to be particularly attractive to study such processes in ABM since these models are by design well suited to study direct interactions across heterogeneous actors.

The micro-macro links of CA A final lesson from the empirical literature is that the close interconnection of aggregated and firm level determinants implies that any satisfactory analysis of CA – in particular, in a modelling context – must take into account determinants on both the micro and the macro level *simultaneously*. Such a challenging task seems to be a natural topic for ABM and outside this literature there are currently only few examples for models taking this mutual interdependency of micro and macro into account (e.g. Dosi *et al.*, 2019b).

3.3 Specialized models of CA – theoretical contributions

As already discussed in section 2, modeling CA in macroeconomics comes with certain trade-offs regarding the models' complexity. Models that are not macroeconomic by nature and that focus exclusively on the mechanisms underlying CA do not face these trade-offs. One may, therefore, suppose that these models have already formalized a richer set of mechanisms that macroeconomic models, and may, therefore, serve as a useful source of inspiration for the latter. Therefore, we will now present the mechanisms that have received particular attention by this more specialized literature. Then, in section 4 we will then compare them to the empirical findings summarized above and then distill lessons for the construction of macroeconomic modeling. All of the models mentioned below are summarized in table 5.

A mechanism that has often been considered in models on CA refers to the importance of *alliances*. Usually models consider different types of alliances, such as those formed on the regional or on the interregional level. In all cases firms interact with each other and, thereby, exchange knowledge. A simple example for such a model is Vermeulen and Pyka (2014), where firms that collaborate have access to each other's set of knowledge, whereby knowledge here is operationalized as sets of artifacts and transformations. Artifacts are the input or output of the production process, i.e. products of different levels of complexity, and transformations can be understood as production technology; to keep the taxonomy in this paper as simple as possible, we will refer to artifacts as products and to transformations as technologies. In each region, firms have an initial set of technologies. In order to create new technologies, firms can either split one of their existing technologies into two new technologies or combine it with a collaborating firm's technology. Then, firms combine technologies with products they have access to in order to produce goods of higher

[17] Figueiredo (2008) is representative for this when they state that "it is important to recognize the relevance of different government policies that have been implemented over the past 40 years, especially since the 1990s in the context of Manaus. In the absence of such government policies, all these firms and some supporting organizations would probably not even have been there in the first place." (p. 84).

Specialized models of CA			
Source	**Determinants**	**Description of the CA process**	**Model type**
Vermeulen and Pyka (2014)	Alliances	Through access to a broader set of technologies and products, alliances on the interregional level lead to CA (via products of higher complexity).	ABM
Tur and Azagra-Caro (2018)	Alliances	CA depends on previous alliances and the cost of collaborating; the effects of which vary depending on the impact of both effects.	ABM
Dasgupta (2012)	Spillovers (Human Capital)	International worker mobility leads to knowledge spillovers among workers; CA is related to a reduction in inequality and an increase in individual income.	equilibrium model
Santos Arteaga *et al.* (2019)	Governance	Spillovers from differently skilled worker groups within a firm create CA; this process is in turn constrained by the technological infrastructure (and vice-versa).In order to foster CA while holding costs at a minimum, managers have to strategically employ differently skilled workers.	data envel-opment model
S. Li and Ni (2016)	Learning by doing	A monopolist's incentive to invest into CA depends on the rate of learning by doing	control model
Wersching (2010)	R&D Investment, Spillovers, Absorptive Capacities	Aiming for a competitive advantage, firms invest into R&D in order to accumulate internal knowledge and into absorptive capacities in order to gain from knowledge spillovers.	ABM
Savin and Egbetokun (2016)	Alliances, Absorptive Capacities, R&D Investment	Through alliances and absorptive capacity, firms (that aim for a competitive advantage) acquire voluntary and involuntary spillovers, respectively; R&D investment can lead to incremental innovation	ABM
Pyka *et al.* (2019)	Alliances, Learning by Doing, R&D Investment	Firms collaborate on the intra-regional and interregional level to acquire implicit and explicit knowledge, respectively. Also, they invest into R&D to expand internal knowledge. Knowledge that is used is intensified, leading to CA (via a radical or incremental increase in product complexity), whereas other knowledge is gradually forgotten	ABM
Caiani (2017)	R&D Investment, Firm-Size, Absorptive Capacities	Firms, which aim for a competitive advantage, move on a technology space. In order to reach certain points, they invest in imitative and innovative R&D with the probability of successfull increases with firm size since larger firms make higher investments. The probability of sucessfull imitation increases with size of the target industry.	ABM
Criscuolo and Narula (2008)	R&D, FDI, Absorptive Capacities, Intra-industry Spillovers	CA on the national level is determined by domestic R&D investment, FDI and international spillovers. The speed of CA (i.e. individual and national knowledge accumulation) is determined by absorptive capacities.	Differential equations

Table 5: Implementation of the CA process in selected specialized models.

complexity. In a regional setting, where firms have no contact with firms in other regions, the set of possible products is thus constrained. However, if firms extend the scope of their alliances to the interregional level, i.e. if they collaborate with firms in another region, their set of accessible products and technologies increases. Therefore, if interregional alliances are allowed, more complex products are assembled.

Another exemplary contribution focussing on alliances is Tur and Azagra-Caro (2018). In their ABM they consider CA as a function of (1) the amount of knowledge that is created from the own stock of knowledge, (2) the cost of collaborating and (3) the amount of knowledge that is created through alliances. Firms decide to collaborate with another firm based on whether they have previously collaborated and the amount of knowledge the firm has. Both factors are weighted by an exogenously determined parameter representing the institutional environment (e.g. for building trust) in the region and on the knowledge held by the contemplable firm. By changing each of the parameters of the model, the authors show that there are no linear links between alliances and CA, suggesting that policy makers aiming to improve CA be aware of the various influencing factors.

Another determinant underlying CA and often modeled in the specialized literature is the *organization of human capital*. In these models, the skills and the knowledge embodied in each individual worker are the main driver of CA and, therefore, firms have to organize their human capital strategically in order to achieve CA. In a general equilibrium model Dasgupta (2012) studies CA as a learning process which is spurred by the mobility of workers from countries and firms with higher capabilities. By moving to other firms, their knowledge is passed on to the latter firm's workers, thus leading to CA in firms as well as entire regions (as the knowledge is passed on further). Thus, CA is here understood as a social process, propelled by the interaction of people with diverse knowledge.

A similar approach to CA is taken by Santos Arteaga *et al.* (2019) in a *data envelopment analysis*[18]. Here, human capital can be accumulated by the individual worker through experience, education and spillovers from other workers with a higher skill level. Firms, in turn, accumulate capabilities by maximizing the probability of high skilled capacity; therefore accounting for spillovers on the individual level.

A third mechanism often considered in the specialized model literatuer is *learning by doing* (LBD); based on the consideration that certain capabilities (especially those associated with *implicit* or *tacit* knowledge) might only be acquired by firms through experience and practice, i.e. the repetition of production tasks. S. Li and Ni (2016) introduce an optimal control model where a monopolists maximizes profits via investment decisions under the consideration of LBD. On one hand, investment in process and product capabilities entails the opportunity of higher profits. On the other hand, such investments enter the monopolist's cost function, therefore offering the risk of underinvestment with respect to the social optimum. The (exogenously given) rate of LBD, however, reduces the cost necessary for successful CA, thereby affecting the monopolist's decision to invest in CA. That is, the higher the rate of LBD, the higher the monopolist's incentive to invest.

Up till now, we have focused on contributions that engage with the implementation of a single mechanism or determinant relevant for CA. However, as has been discussed in the previous sections, CA is a complex matter that is determined by various factors. Exemplary contributions that take this fact into account are those put forward by Savin and Egbetokun (2016), Pyka *et al.* (2019), Caiani (2017) and Wersching (2010).

Savin and Egbetokun (2016) introduce a model of CA in which they study the role of *alliances*, *absorptive capacities* and *R&D*. They situate firms on a two-dimensional metric space which they call 'knowledge space' and where the distance between two firms provides information on how similar their production technologies are. A firm's 'proximity radius', which can be extended via R&D investment, determines the knowledge the firm has potential access to. In accordance with the empirical literature (see above) the authors assume that there there is an inverted U-shaped relation between technological distance and CA, i.e. knowledge from technologically close and distant firms is less useful than that of firms with medium proximity. However, to actually absorb the knowledge of other firms in the first place

[18]Data Envelopment Analysis is a method that is used to compare *decision making units* (firms, in our case) regarding their efficiency by computing an efficiency index on the basis of the firm's inputs and outputs.

firms must either engage in alliances (leading to *voluntary spillovers*) or invest into their absorptive capacities (leading to *involuntary spillovers*). Involuntary spillovers are purely a function of absorptive capacities of a firm. Voluntary spillovers emerge from alliances, which are formed profit maximizingly, based on the expected R&D investment of the potential partner as well as the disadvantages in competitiveness that arise from the spillovers that go toward the other firm. A partnership will only be formed if the alliance is mutually beneficial. Based on the alliance decision, a firm will split up its (exogenously given) R&D investment, spending as much as needed to benefit from alliances as well as involuntary spillovers. The rest will go to the expansion of internal knowledge. The model indicates that what cooperation strategy is best in terms of competitiveness depends on the current stage of a firm and whether it is currently more dependent on voluntary or involuntary spill-overs.

Pyka *et al.* (2019) model the interrelation of three different mechanisms of CA: *R&D investment*, *alliances* and *learning-by-doing* (LBD), as well as the potential role of policies in fostering CA processes. In the model, each firm is endowed with knowledge units that can then combined to invent new products that can then be sold on a market. CA processes are modelled as the acquisition of new knowledge units. There are three options: first, firms can invest into R&D. With a given probability, this creates a new knowledge unit that differs from the existing units only within a pre-specified range, as suggested by the principle of relatedness discussed above. The second option is to copy a knowledge unit from cooperation partners with whom the firm has formed an alliance. This copies only parts of the knowledge unit, however: aspects related to the experience of the firm of applying this knowledge are not copied. Finally, firms improve upon their knowledge by *learning by doing* if they apply their knowledge to produce products. At the same time, they can also forget about knowledge that remains unused in practice. The authors then test various policy scenarios in which firms are motivated to engage in new alliances of invest more into R&D. They find that CA happens best when firms diversify their channels for CA and if they are supported by nuanced policy programs that provide firms to engage in regional collaboration.

Finally, Caiani (2017) discuss an ABM in which CA occurs through innovative and imitative R&D with the firm size determining the success of innovation and the extent of absorptive capacities. Firms move on a network-like technological space where each node that is farther from the starting point is associated with a reduction of production costs via CA. In a first step, each firm chooses a target node. In order to reach that node, firms can either innovate or imitate, whereby costs of imitating are lower than those of innovating. The probability of successful innovation increases with the amount invested into innovative R&D. Since larger firms invest more, they have an advantage. In order to imitate, a firm collects a sample of firms. If any of them has the target node in their portfolio, imitation will be successful. The number of firms that can be sampled depends – just as before – on the amount of R&D investment, giving larger firms an advantage. However, success also depends on the size and structure of the industry, with a larger industry offering a higher probability of success. The sample size represents the size of the region within which firms to imitate can be sampled and can, therefore, be interpreted as its absorptive capacities. In the first model instance, the sample is selected randomly. However, if imitation was successful, the imitated firm will be a preferred choice in the next period. Thus, industries have a different branch structure and they develop differently as firms move along, varying in size (i.e. number of firms). Both of these factors influence the benefits that can be expected from innovation and imitation such that it might me easier or harder for firms to become large and for large firms to stay successful.

A similar approach is put forward by Wersching (2010). Here, CA can occur both with respect to processes and products. Firms move on a circular technological space where they take a new spot between two occupied spots if they innovate incrementally and where they take a spot on an enlarged circle that is relatively farther away from the occupied spots if they innovate radically. Firms can invest into internal R&D or absorptive capacities in order to accumulate capabilities. Here again absorptive capacities enable firms to acquire spillovers from more distant points in the technology space. However, it is assumed that the relationship between distance and productivity of new knowledge is inverted U-shaped.

Criscuolo and Narula (2008) take a different approach and propose a differential equations model in which they generalize the original theory of absorptive capacities to the national level. Thus, in their model national CA is depends on domestic and foreign R&D investment, inward FDI and international spillovers, all moderated via national absorptive capacities. The latter depends on R&D expenditures, an institutional variable representing the ease of knowledge diffusion, and the technology gap to most advanced countries. This way, the model replicates the stylized fact that individual and national knowledge accumulation is fastest during an intermediate stage of catching-up. This way it also provides a nice formal operationalization of the ambiguous concepts of absorptive capacities.

Finally, there are models that represent the processes underlying the emergence of new technologies and their diffusion, but that are meant as rather abstract illustrations. Nevertheless, they deserve to be mentioned here because they highlight aspects of technological change that themselves affect the way CA does actually take place. One example for such a model is Silverberg and Verspagen (2005), who present a model in which new technologies are assembled from existing technologies and thereby grow in complexity. The model is able to replicate a number of stylized facts of technological change (e.g. that there are many small and few big innovations) and captures the idea of technological relatedness very nicely, yet since it does not feature any concrete firm of market interaction it is more suitable to get a very general idea of 'technological change', rather than illuminating the mechanisms underlying CA. A similar argument holds for Angus and Newnham (2013). Their model consists of finite state automata that process bit-strings (which may be interpreted as products) and that, via evolutionary selection and mutation, produce new bit-strings. This way, the model produces a certain kind of 'novelty', which is currently lacking in most economics models. A slightly different approach is taken by Desmarchelier *et al.* (2018), who propose an ABM where firms are located on the empirical product space of Hidalgo *et al.* (2007) and try to maximize their export opportunities. There is, however, no actual production or consumption taking place in the model and it remains unclear how the firms actually accumulate the capabilities necessary to move to more central parts of the product space.

4 Discussion

The prime objective of this paper was to delineate promising channels for integrating results from the specialized literature on CA into comprehensive macroeconomic models. To this end, we first summarised current strategies to integrate CA into macroeconomic models, then reviewed the empirical literature on CA on the micro- and macroeconomic level and finally searched for specialised models dedicated to the investigation of CA processes. The results of this work are summarized in table 6, which provides an overview on how empirical findings on CA have been implemented in specialized and comprehensive macroeconomic models so far.

The first lesson from the table is that the clearest alignment of the empirical and theoretical literature is with regard to the positive effect of R&D expenses on CA. This positive effect has not only been documented empirically, it has also been considered in both specific and macroeconomic models various times. Of course, the empirical literature studies R&D activities on a much more fine-grained level than is acknowledged in the models. Yet, in general there is a close alignment between the empirical and theoretical literature in this dimension.

The second, maybe more surprising, insight is that there is no clear indication on whether specialized or comprehensive macro models tend to implement empirical findings more conscientiously. Noticeably, the mechanisms listed which are related to the government and institutions have received more attention in the macroeconomic models than in the specialized models, most likely since the former include a government by definition. In taking a much narrower focus, specialized models usually do not include a government sector. At the same time, it is easier to integrate more complex processes such as *firm collaboration* or *absorptive capacities* into a model that has its main focus on CA, rather than into an already complex macroeconomic model. Also, the empirically highly relevant topic of the *relatedness* of CA has received more attention in the specialized literature. In these dimensions, there is certainly potential in taking the existing specialized models and to think about how they could be integrated into a more comprehensive macroeconomic framework.

Finally, there are also factors that – while having received considerable attention in the empirical literature – have not been considered in the modeling literature at all. The contingency of CA processes (such as time- and space-contingency) is the obvious example in table 6. Modelling contingency is difficult *per se*, since models are mostly used as a way to formalize general mechanisms. It would, however, be desirable if the mechanisms modelled allowed for the distinct and non-linear development paths that are suggested by the empirical literature. This, obviously, represents a greater challenge for analytical models, leaving the stage clear for simulation models.

Another lesson that is not directly evidenced in table 6 is the role of the modelling framework chosen. General mechanisms such as R&D investment can be deployed in analytical models rather straight-forwardly and very general results are available. However, mechanisms that refer to some kind of heterogeneity and interaction among the entities concerned, such as inter-firm or intra-firm functionalities are generally less commonly studied in analytical models. These mechanisms often play an important role in ABMs, which, by construction, are geared towards modelling interactions and heterogeneity - although one might also expect new innovative ideas to emerge in the recent HANK literature (*heterogeneous agent New Keynesian models, see, e.g.,* Kaplan *et al.*, 2018). At the same time, unlike in the analytical modeling literature, we cannot identify general benchmark models in the ABM literature, but rather a number of distinct model 'families' – although the particular implementation of certain key mechanisms, such as R&D investment is quite similar even across model families as well and some general building blocks seem to be emerging.

One crucial difference of how ABMs and analytical models study CA is due to the fact that ABMs include explicit interaction protocols. When it comes to the integration of results from the empirical literature this is a potential advantage that, however, can also turn into a source of *ad hoc* specification: on the one hand, the explicit interaction protocols of ABM allow a more detailed alignment of the model with empirical evidence and expert knowledge. At the same time, the need to be explicit can be a burden when there is no clear empirical guidance on how to build the interaction protocols. Take Dawid *et al.* (2018) as an example: the authors study the effect of directed subsidies paid to firms in poorer countries. In one scenario firms receive subsidies only when they invest money into R&D at the technological frontier. The interaction protocol for the ABM requires them to define exactly when the supervision of the firms takes place, i.e. when the authorities check whether the firms really invest at the technological frontier. Does this takes place before or after granting the subsidies? Or before or after the paid subsidies have been invested? After a particular time frame after granting the subsidies? Sometimes one can get good guidance by looking at the empirical data, talking to decision makers or experts in the field. In other cases, the decision is necessarily *ad hoc*. At the same time, in some instances such implementation decisions matter considerably, in other instances it does probably not matter much. It is, however, hard to make a definitive decision on the precise implementation. This is not a problem if one can easily test for the implications of distinct implementations, but in larger models one usually faces numerous such challenges, and testing for the implications of all of them becomes infeasible or, at least, very demanding and time consuming. Thus, the enforced explicitness of interaction protocols in ABM can in principle be an advantage, but in practice might also lead to potentially misleading *ad hoc* specifications. In any case it points to the principal possibility to use ABM to test for the systemic relevance of such implementation details and thereby to develop very nuanced policy advice.

5 Summary and conclusion

We have conducted a comparative survey of CA-related literature in order to identify possibilities to align the macroeconomic modelling literature more with recent insights from the specialized literature. The empirical literature on CA is manifold and shows that CA is not the outcome of a single mechanism but that the determinants are highly diverse. To consider this diversity in macroeconomic models is far from trivial and it is clear that there is a trade-off for models that seek to provide a comprehensive macroeconomic representation of an economy when it comes to the detailed representation of particular mechanisms. Nevertheless, given the high relevance of CA processes both on the micro and macro level we believe that working on a closer integration of them into macroeconomic models is a fruitful avenue for future research, which we hopefully have facilitated with this review.

Mechanisms in the literature			
Mechanism	**Level**	**Macro models**	**Specialized models**
'Principle of Relatedness' (cumulative accumuation of capabilities)	Aggregated, firm		
Institutional environment (regulations)	Aggregated		
Government activity (industrial policy)	Aggregated		
Government activity (public research)	Aggregated		
Government activity (other)	Aggregated		
Absorptive capacities	Firms		
R&D investment	Aggregated, firm		
Experience & learning-by-doing	Firm		
Collaboration among firms	Firm		
Human capital accumulation	Firm		
Governance	Firm		

Table 6: Mechanisms of CA in the sampled literature. (Red stands for nonexistent or rare, yellow for still under-explored and green for frequent implementation in models.)

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