The Impact of Technological Change on Wages. A Literature Review

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Executive Summary

This literature review summarizes and analyzes empirical findings on the impacts of technological change (TC) on wages. In doing so it sheds light on different approaches regarding theory and operationalization that origin from the fields of HRM and labor economics. Each of the observed approaches assumes different moderating effects on the causal link between technology and wages such as skills, tasks, bargaining power and the nature of innovation. The analysis of 26 studies finds that technology impacts wages mostly positively, especially for worker groups who are confronted with process innovations, have higher skills, more non-routine tasks and higher bargaining power. The skill-biased technological change theory (SBTC) is still most pervasive in explaining impacts of technology on wages. Results that contradict the SBTC are often found to be the outcome of endogenous technological change: Firms paying higher wages adopt more new technology. Furthermore, the author argues that matched employer-employee data are best suited for analyzing the impact of technology on wages. For future research the author suggests refining how technological change is operationalized and points out the need to consider theoretical approaches that integrate institutional arrangements and qualitative differences between different innovations and technologies into their analysis.

1 Introduction

This paper aims to analyze the state of research of the impacts of technological change on wages. The systematic literature review sheds light on the various ways technology impacts wages by examining 26 articles from the field of labor market economics and HRM. The further analysis then discusses the variety of theoretical and empirical approaches employed in this field of research.

The relationship between technological change and wages has been subject to scientific debate for decades as technology turned out to be a permanent renovator and challenger of organizational structures, employment relationships and societal welfare. The question under examination has attracted long-lasting attention of academic researchers and the vast variety of new technologies and the different means of implementing them in business and production processes. Nevertheless, there are only few economic theories and operationalization approaches that aim to capture the exact and nature of technology and its actual impact on wages. These approaches deserve our consideration and also need to be assessed critically.

Technology is an ever-changing variable in the nexus of production processes that is hypothesized to impact wages, wage inequality and task and skill demands. From our current perspective, both the economic conceptualizations of technological impact and theories about it have also evolved over time. This literature review is designed to offer an overview of the existing literature in order to keep track of these developments after decades of research. Such an overview can never be complete, but it especially attempts to confront the interested reader with different possible approaches to examine technological impact on wages by focusing on the variety of moderating effects in this causal link, such as skills, occupations, tasks and institutions.

The need for this re-examination manifests itself in the gap between the rapid progress in digital technologies and the difficulties involved in understanding its precise impacts. This paper follows the argument, that as technologies qualitatively change and continue to be advanced, the interpretation of its impacts should be reconsidered as well. Developed countries are facing the first industrial revolution whose course and impacts they are able to anticipate. The enormous impacts that the digitalization of production processes is expected to have (Brynjolfssoln & McAfee, 2014; Frey & Osborne, 2017) are urging stakeholders from politics, business and social sciences to understand the mechanisms and moderating effects that technological change involves. The ever-shorter time spans in which technologies restructure society and production make this understanding even more crucial.

Moreover, the last extensive review of this literature known to the author can be dated back to 2002 (Brown & Campbell, 2002). Their approach is designed to explain the changing wage structure in the US labor market ex post. Thus, they only rely on studies of the US labor market examining developments in the 1980s and 1990s. Conversely, this review aims to draw a broader picture of different mechanisms linking technology and wages that is neither restricted to the US nor to the 80s and 90s. Moreover, the review by (Brown & Campbell, 2002) does not account for potential task biases as it was published before the emergence of the task-biased technological change (TBTC) debate.

In the light of a growing focus on technological change due to debates about industrial internet the topic deserves a review for both disciplines, HRM and labor economics. Especially the former field does not exploit its potential of shedding light on within-firm processes of technological change (Orlikowski & Scott, 2008). A review of articles published in the most prominent HRM journals that are researching this concept reveals that there is still a gap to be filled (see also Orlikowski & Scott, 2008). The author of this review hopes to arouse HRM researchers' interest in the examination of technologies by showing how vital and versatile this field of research is.

In general, the review finds a positive effect of technology use on wages. This positive effect differs by skill groups and by occupational groups as stated by the underlying theories. Higher skilled workers and occupational groups carrying out more abstract and cognitive tasks are better off due to technology adoption. At the same time, there is a widening wage gap between these groups of workers and employees with lower skills that work on the shop floor and occupational groups whose jobs consist of routine tasks more heavily.

In some approaches further explanations for these developments have been examined. Declines and differences in the power of pay setting institutions over the last decades (Kristal & Cohen, 2017), differences in kinds of technologies (Angelini, Farina, & Pianta, 2009; Martínez-Ros, 2001) and reversed causality between firms adopting higher technology and paying higher wages are the most prominent additional discoveries among the studies under review.

The examination of the operationalizations of technological change is a further focus of this review. Different kinds of variables measuring what is referred to as “technological change” or “innovation” are presented and discussed with respect to their validity. The findings of this analysis substantiate the major critique of this review. The author suggests developing operationalization approaches that are stronger grounded in theory and enable researchers to differentiate between qualitatively different kinds of technologies.

The paper is structured as follows: In chapter two several dominant theoretical approaches from the field under examination are presented. Before the analysis, the methodology of the literature review is explained shortly in chapter 3. Then, twenty-seven articles from the fields of labor economics and HRM that research the impact of technological change on wages are analyzed in chapter 4 with respect to their theoretical foundation, their empirical approach and their findings. Chapter 5 discusses the prevalent research approaches and makes some critical notions. The paper ends with a short conclusion in chapter 6.

2 Theoretical background

During the past decades multiple scientific disciplines have engaged in the examination of the impact technological change has had on changes in wages. Especially in the field of economics, fruitful theoretical debates have led to the establishment of theories concerning this relationship (van Reenen, 1997). One trait of this theoretical debate is a diversity in the focus on different potential moderating effects in the causal link(s) between technology and wages. The skill-biased technological change theory emphasizes the moderating effect of skill distributions while the task-biased technological change theory claims the impact of technologies on routinization potentials and the resulting shifts in demand for certain tasks to be important. Other theories, such as rent-sharing approaches, point to the relevance of pay-setting and bargaining institutions. This chapter sheds light on some of the most pervasive approaches from the literature reviewed and is designed to provide the reader with a comprehensive overview of possible different moderators in the relationship between technology and wages. Another common trait among these theoretical approaches is the acknowledgement that technological change impacts different groups of workers differently. Thus, wage variables tend not to be measured in absolutes but they are also assessed via wage distributions and variables capturing relative wages.

2.1 Skill-biased technological change (SBTC)

The most pervasive economic theory concerning technological change and wages is the Skill-biased technological change theory (SBTC) (Berman, Bound, & Griliches, 1994; Davis & Haltiwanger, 1991; Juhn, Murphy, & Pierce, 1993; Katz & Murphy, 1991; Lawrence, R. Z., Slaughter, M. J., Hall, R. E., Davis, S. J., & Topel, R. H., 1993). This theory assumes that new technologies require certain additional skills from workers. The demand for workers whose skills are needed the most for successfully operating new technologies may thus be higher. The introduction of technologies such as PCs has demonstrated that these skills have been possessed primarily by higher qualified workers. Higher qualified workers are assumed to consist of management and office staff (non-production workers/ np-workers), while lowly qualified workers are assumed to be production workers (p-workers). This skill-driven labor demand difference is referred to as skill-bias.

As the demand for a certain kind of labor also determines its price, wage proportions among differently qualified workers develop correspondingly to this bias. An innovation that necessitates higher worker skills may increase demand for higher qualified workers relative to lower qualified workers and their wages respectively. On the other hand, certain process innovations that require lower qualified workers (e.g. the conveyer belt in Ford plants at the beginning of the 20th century) can increase the demand both for such workers and their wages (Goldin, C., & Katz, L. F., 1998).

The SBTC-theory has been extended by a "polarization component" in the course of the scientific debate. In their article from 2003, Autor, D., Levy, F., & Murnane, R. D. (2003) establish the polarization hypothesis according to which technological changes tend to foster an increase in the demand for both lowly as well as for highly qualified workers. The simultaneous decrease in demand for moderately qualified workers leads to a U-shape in overall demand for labor when categorized by qualification.

2.2 Task-biased technological change (TBTC)

Autor et al. (2003) trace this polarization of wages and qualifications back to each occupational groups' specific tasks. Thus, the groups of lowly qualified service workers and highly qualified management and specialist staff are supposed to execute tasks with little or no routine content. Conversely, moderately qualified workers' routine tasks are assumed to be substitutable through programmable information technologies such as the PC. This in turn leads to a decrease in demand for such workers.

Furthermore, Autor et al. (2003) differentiate between manual and analytic/ interactive tasks. This allows the authors to generate a matrix, as depicted in Graphic 1. While routine tasks are assumed to be replaceable through technologies such as the PC - whether they are cognitive or manual – technology generates complementarities to non-routine tasks to different degrees. Analytic non-routine tasks - such as medical diagnosis or legal writing - are hypothesized to have stronger complementarities with new technology than manual analytic/ interactive tasks (truck driving, janitorial services). Despite being relied on in various publications, the current relevance of the attributions between certain tasks and their possible substitution through computers has to be assessed critically (see autonomous driving, legal tech solutions).

2.3 Rent-sharing

In some articles the wage effect of newly introduced technologies is ascribed to the bargaining processes it triggers (Cirillo, 2014; Martínez-Ros, 2001; Mishra & Smyth, 2014, 2014; van Reenen, 1996). The overall rents of a firm adopting a new technology or innovation are assumed to increase. These additional rents are further assumed to be claimed by the workforce through their institutions of collective voice, such as trade unions. Thus, the rents created through innovation are shared between employers and employees.

Graphic 1: Predictions of Task Model for the impact of computerization on four categories of workplace tasks.

	Routine tasks	Nonroutine tasks
	Analytic and interactive tasks	
Examples	• Record-keeping • Calculation • Repetitive customer service (e.g., bank teller)	• Forming/testing hypotheses • Medical diagnosis • Legal writing • Persuading/selling • Managing others
Computer impact	• Substantial substitution	• Strong complementarities
	Manual tasks	
Examples	• Picking or sorting • Repetitive assembly	• Janitorial services • Truck driving
Computer impact	• Substantial substitution	• Limited opportunities for substitution or complementarity

Source: Autor et al., (2003)

Trade unions are of major research interest where employment relationships are not only determined by market forces but also by bargaining power and the respective position of labor and capital. They act for pooling and organizing labor interests in order to negotiate the distribution of rents yielded through common economic activity. Wages are seen as part of these rents and are subject to negotiations referred to as "collective bargaining agreements" (Mahoney & Watson, 1993). Microeconomists also implement rent-sharing approaches (Hannu & Antti, 2003; Hildreth, 1998; Hildreth & Oswald, 1997).

Van Reenen (1996) integrated a hypothesized effect of technological change on wages into a bargaining model. He assumes innovation rents which can result from a firm's cutting-edge efforts to introduce product and process innovations. These "first-mover-advantages" increase a firm's profits relative to its competitors' in the short run and thus generate innovation rents. According to van Reenen (1996), wages will rise due to employees' attempts to appropriate a part of these commonly produced rents through negotiations.

3 Literature review

3.1 Selection and Approach

Empirical studies are analyzed below which examine the relationship between technological change and wages. Only articles were selected, which assess this relationship analyzing a wage variable (absolute wage, relative wage between highly and lower qualified workers or "task prices"). Only studies that involve a quantitative analysis of technologies' or technology investments' impacts as independent variables on wages or wage distributions between different worker groups (dependent variable) are included in this review.

In order to find those papers, combinations of the search terms "technical change", "technical progress", "technological progress", "technological change", "innovation", "technology", “wage”, “salary” and “payment” were used in an internet research in online databases Google scholar and EBSCO. The next wave of results was found by following citations and cross references in these first articles. Twenty-seven articles were selected which were published between 1993 and 2019. The aforementioned relationships are examined in thirteen different countries (Spain, USA, Chile, China, Canada, Sweden, Germany, Italy, UK, France, Finland, Indonesia and Taiwan) while two of the articles assess multiple national states simultaneously (Angelini et al., 2009; Dela Rica & Gortazar, 2017). The observed period reaches from 1958 to 2019. The number of articles and the covered time span exceed the scope of the last comprehensive review of this topic (Brown & Campbell, 2002), which is limited to research of the developments in the 1980s and 1990s in the US. The time span this article is observing has the potential to trace the development of technological changes resulting from the third industrial revolution, namely the introduction of microelectronic technologies in production processes (such as the PC, CAD/ CAM, CNC and related applications).

3.2 Summary of studies

The selected articles have been subsequently categorized by observation level and summarized. This categorization serves three goals. First, it facilitates comparability in terms of dimension and research context. Second, this process clarifies that different approaches – theoretical and empirical ones – are used independently of observation levels. Each observation level deserves its own context sensibility and a short analysis of the institutions that operate on them. Third, Brown and Campbell (2002) point to “ambiguities between findings at the national level and at the establishment level” which lead to paradoxes in findings and biases in the interpretation of the effect strengths. The observation levels are individual (10), plant data (3), company level (6), matched employer-employee data (3), and industry level (4) (numbers of articles in parentheses).

3.2.1 Individual level

Ten articles examine impacts of technological change on wages in different national labor markets in different manners. The articles are summarized in table 1. Three of the studies (Allen, 2001; Bartel & Sicherman, 1999; Krueger, 1993) rest their assumptions on the theoretical underpinning of the SBTC approach while Bartel and Lichtenberg (1991) model their own framework which points to the importance of organizational learning. They claim that new technology demands the workers’ ability to learn which itself is a function of their effort and skills (Bartel and Lichtenberg; 1991). This leads to workers using new technologies earning higher wages than workers with comparable education, as they show higher effort and possess non-observable skills. The most recent studies in this group are embedded into the task-biased technical change debate (Adermon & Gustavsson, 2015; Bessen, 2016; Böhm, 2019; Dela Rica & Gortazar, 2017) while two studies extend it to the analysis of industrial robots (Acemoglu & Restrepo, 2017; Dauth, Findeisen, Südekum, & Wößner, 2017).

The individual observation level is the most precise one with regard to workers’ characteristics such as skills, years of education and time-invariant traits such as gender, tenure or age. The disadvantages of this kind of data are its infrequent consideration of different technologies and the circumstances of their implementation. Thus, individual level studies estimate the impacts of technology on workers by worker characteristics quite accurately while the exact triggering mechanisms that precede these impacts tend to remain unclear.

Krueger's straightforward analysis (1993) tests whether or not workers using a computer at the workplace earn more than similarly qualified workers who do not. He determines that the usage of a computer increases wages by 10 to 15% on average and adds a wage premium for higher qualified workers. He admits that this effect is an SBTC but cannot fully explain the polarization in the 1980s US labor market wage structure.

Bartel and Sicherman (1999) want to find out whether the effect of technological change on the inter-industry wage differential arises from self-selection of workers into high-tech industries or from non-observable industry characteristics. First, they identify the positive effect of higher innovative measures on wages and skill premia both for production workers (p-workers) but stronger for non-production workers (np-workers). From the missing correlation between industry premia and intensity of innovation they conclude that workers with higher non-observable skills select themselves into industries with greater innovation. They attribute the increase of the skill premium to an increased demand for skilled workers in innovative industries.

Bartel und Lichtenberg (1991) uncover a positive relationship between the newness of technologies in an industry and wages. Workers in industries deploying more recent technologies earn higher wages than comparable qualified workers in industries with older ones. They attribute the higher wages of higher qualified workers to them being better learners as pointed out in their own model.

Allen (2001) finds that wage inequality had its highest increase in industries with higher high-tech-capital intensity. Moreover, he identifies growing gaps in the wage structure between lowly and highly qualified workers which are amplified by an increase in the capital/labor intensity of an industry. Furthermore, he ascertains that the education premium for college graduates increased especially in industries in which a large scientific staff is deployed. He offers the SBTC approach to explain these results.

Bessen (2016) shows that higher automation results in, higher wage inequality within occupations. Thus, higher skilled workers earn more. Bessen suggests that this stems from higher qualification needs which only some workers can fulfill due to their costliness. He argues that automation is accountable for 45% of the growth in wage gap between the 90^{th} and 50^{th} percentile of occupations since 1990.

After developing a new method for estimating changes in task prices Böhm (2019) implements his model in an examination of TBTC. He argues that workers' wage development crucially depends on their talents and their resulting task choices rather than on their skills. Böhm ascertains that not only do task prices polarize according to the TBTC theory but also that these task price changes are parallel to the observed young male workers' development in wage inequality.

Examining the existence of a TBTC in 22 OECD countries Dela Rica and Gortazar (2017) trace the impact of ICT use on wages with an intermediate step over the task contents of jobs across countries. They find ICT use to be accountable for 10% (7.7%) of the variation in abstract (routine) tasks but no relationship with manual tasks. Furthermore, they show that abstract tasks increase wages within occupations while they decrease wages in jobs containing many routine and manual tasks.

Adermon and Gustavsson (2015) try to explain changing patterns of Swedish labor market demand. In doing so, they assume a TBTC to be the driver of corresponding changes in wage patterns. Technological change is assumed to be a determinant of change in the task content of jobs. First, they group jobs into quintiles according to their median wages which they treat as a proxy for workers' skills. In their next step, they examine the change in task content of these quintiles in order to test the TBTC hypothesis. The relationship between changes in task content and wages remains insignificant. They take into account the possible impacts of the Swedish industrial relations system, namely the solidarity wage policy that strived for wage compression until the 1980s.

Acemoglu and Restrepo (2017) develop an ambitious approach for measuring the impacts of industrial robot usage on wages and employment in local U.S. labor markets. Their approximate yet distinguished measurement of robot exposure differentiates between 722 "commuting zones" and considers differences in the composition of their economies. They show that one more robot per thousand workers leads to lower average wages for all employment groups, especially for those who are lowly and moderately qualified.

In a similar fashion Dauth et al. (2017) shed light on the situation in Germany. Inspired by Acemoglu and Restrepo's previous works they investigate the impacts of industrial robots on local German labor markets and additionally on individual workers' career paths. For local labor markets they do not find positive wage effects. The investigation of workers' career paths produces findings pointing to a SBTC. They explain their results with reference to the German industrial relations system, arguing that trade unions – which are still powerful in German manufacturing industries – bargained job security for wage increases.

The first four articles support some common trendsetting arguments. Each article confirms the observed developments to be a kind of SBTC whereas Bartel and Lichtenberg (1991) expand this approach by including an employee learning component. Each study uses at least one variable in their wage regressions that controls for education, experience and/ or qualification on the individual level in order to identify a SBTC, which is assumed to be the underlying causal mechanism.

In addition, at least three of the four articles show awareness for wage premia for workers using new technologies, which can also be traced to non-observable skills. As shown by Bartel and Sicherman (1999), arguments for a pure SBTC would be weakened if workers with higher non-observable skills would select into high-tech jobs. Beyond that, different industry effects could be revealed which can bias this causal relationship (e.g. industry premia). Methodologically, such unobserved industry and individual effects are controlled for using fixed-effects models.

While these papers primarily concentrate on individual outcomes, Allen (1996) and four of the more recent articles (Bessen, 2016; Böhm, 2019; Dauth et al., 2017; Dela Rica & Gortazar, 2017) take into account possible effects of technology on wage inequality. Bessen (2016) and Allen (2001) directly observe widening wage gaps resulting from the demand for skills in working with new technology. Testing the TBTC hypothesis, Böhm (2019), Dauth et al. (2017) and Dela Rica and Gortazar (2017) show that due to changing demands for different tasks, especially moderately qualified workers suffer from the ongoing technological advance.

Finally, the TBTC approach has successfully been incorporated into the research on technology impact. Having realized that technology changes tasks rather than whole jobs has led to new promising approaches that have shown to be consistent in their assumptions. Although the mediating role of tasks has been acknowledged, this advance comes at a price as researchers depart from the actual source of change: different technologies. The simultaneous abstraction from the nature of technology and the theoretical enrichening of its downstream impacts could potentially bias results and discussions, which is discussed further in chapter 4.

3.2.2 Plant and company level data

Both plant and company level data have the potential to be very precise in nature with regard to the question, which technologies exactly were implemented. Doms et al (1997), Dunne and Schmitz (1997) and Entorf and Kramarz (1998) illustrate this potential by examining up to seventeen different technologies. Additionally, this kind of data is able to integrate organizational variables such as firms' union density, HR system indicators (Cozzarin, 2016) and innovation strategy and training measures (Cirillo, 2014). The shortcoming of company level data is that it can only rely on aggregated distribution information about workers' wages and characteristics.

Three of the articles under examination use data that was collected on the plant level (Chennells & van Reenen, 1997; Dunne & Schmitz Jr, 1995; Laaksonen & Vainiomäki, 2001). These articles are summarized in table 2. Two of them rely on the SBTC literature of the 1980s. In contrast, Chennells & van Reenen (1997) are aware of the possible endogeneity of technological change and thus conduct a so-called technology regression in addition to their wage regression in order to investigate this possibility.

Chennells and van Reenen (1997) examine the effect of different innovation indicators on wages. In doing so they test the different impacts of direct implementations of then new technologies - such as computer integrated manufacturing – and accounting measures of innovation like R&D intensity. Their cross-cut analyses point to a SBTC. In a follow up panel analysis, they find their assumptions about technological change being endogenous to be true: a higher average wage in a plant increases the probability of that plant introducing new technologies. They provide two possible reasons for that:

1) a positive wage shock can lead to high costs for labor and its substitution for machine capital.

2) Higher paid workers are higher qualified as well and possess higher unobserved skills. It is more likely that new technologies will be entrusted to these workers as it can be assumed that these technologies can be deployed more productively in combination with their work.

Laaksonen and Vainiomäki (2001) are aware of an endogenous technological change as well and thus use fixed-effects and random-effects models in their panel analysis in order to control for non-observable worker skills. Their results imply that both overall pay and the relative wages of np-workers increase with plants' innovation activities. They cannot ascertain an ideal relationship between innovation indicators and wages, but nevertheless they conclude that their results hint at a SBTC. They have to admit that the mechanism of wage determination is not only dependent on technological aspects but also on labor market institutions - especially in countries like Finland where strong labor unions and comparably centralized wage bargaining systems are part of the institutional arrangement.

Table 1: Results of literature review for articles using individual level (or aggregated individual) data

Author	Year	Theoretical background	Independent technology variable/ Operationalization of technical change	Dependent variable	Positive/ negative relationship	Explanation/ notes	Country	Time
Böhm	2019	TBTC	occupation groups that are intensive in task content:	task prices		task prices polarized in the 1990s and 2000s. Their changes matched changes in observed wage inequality	USA	1984-1992, 2007-2009
			routine		-			
			manual		+			
			abstract		+			
De la Rica & Gortazar	2017	TBTC	1. ICT use in the workplace (level and complexity)	abstract task intensity	+	level and complexity of ICT use explain variation in cross country differences in intensity of job tasks	22 OECD countries	2011, 2012
				routine task intensity	+			
				manual task intensity	0			
			2. abstract task intensity	average wage	+			
			routine task intensity		-			
			manual task intensity		-			
Adermon & Gustavsson	2015	TBTC	changes in task content of jobs of occupation groups	wages	insignificant	impacts of Swedish industrial relation system could drive results	Sweden	1975, 1990, 2005
Krueger	1993	SBTC	computer usage (yes/ no)	wages	+	workers using computers earn 10-15% more	USA	1984, 1989
				education premia	+	diffusion of computers led to higher education premia		
Bartel & Lichtenberg	1991	learning ability	R&D expenditure / sales, age of industry's equipment, purchases of electronic and computer equipment / output	wages	+	new technologies demand learning abilities which demand more effort that has to be paid higher	USA	1960, 1970, 1980
				technology premium	+	High educated workers have higher learning abilities		

Allen	1996	SBTC	R&D intensity, C/L growth	wage inequality (returns to schooling)	+	widening wage gaps by schooling technology indicators accountable for 16% of growth in wage gaps	USA	1979, 1989
			High-Tech Capital		++			
			recentness of capital		**0**			
			TFP growth		**0**			
Bartel & Sicherman	1997	SBTC	industry's computer investments / total investments, R&D exp./ sales, TFP, number of patents, share of scientific and engineering employees	wages	**P workers** + **NP workers** ++	workers with higher unobserved abilities select themselves into industries with strong TC; higher demand for highly qualified workers (SBTC)	USA	1979 - 1993
				education premia	+			
Dauth et al.	2017	SBTC	number of industrial robots per 1000 workers by region, industry and time	wages	labor markets: **0**	parallel increase in productivity: decreasing labor share	Germany	1994 - 2004
					individual workers: **HQ** + **MQ** **--** **LQ** **-**	German industrial relations system: unions bargain job security against wage increases		
Acemoglu & Restrepo	2017	extension of TBTC	number of industrial robots per thousand workers by country, industry and time	average wage of commuting zone by demographics	**-**	displacement effect of industrial robot usage is stronger than its productivity effect	USA	1990 - 2007
Bessen	2016	neoclassical	share of workers in an occupation who use computers	within occupation wage inequality	+	new skills for using computers are costly to acquire (only for high skilled workers)	USA	1980, 1990, 2000, 2013

indicators and abbreviations: + = positive relationship, ++ = strong positive relationship, - = negative relationship, -- = strong negative relationship, 0 = no (significant) relationship, ICT = information and computer technology, TBTC = Task-biased technological change, SBTC = Skill-biased technological change, HQ MQ LQ = Highly, Moderately and Lowly qualified workers, P / NP workers = Production / Non-production workers, (L) / (CS) = longitudinal / cross section analysis

Initially, Dunne and Schmitz (1995) categorize the observed plants dependent on their main activity where plants of the group "assembling" are attributed the highest probability to use advanced technologies. The study infers that workers earn the highest wages in plants of the category "assembling" and that wages increase where advanced technology is in use. Hence, the usage of the technologies under observation is associated with higher wages. A differentiation by occupational groups shows that all workers receive technology premia. It is noteworthy that in contrast to every other study in this review this premium is highest for p-workers.

Six studies examine the phenomenon of technological change at the company level. This group of studies is characterized as locally heterogeneous as they observe six different countries: Spain (Martínez-Ros, 2001), Chile (Cirillo, 2014), Italy (Casavola, Gavosto, & Sestito, 1996), Indonesia (Lee & Wie, 2015), Taiwan (Liu, Tsou, & Hammitt, 2001) and Canada (Cozzarin, 2016). Three of these studies refer to the theoretical framework of the SBTC literature by U.S. economists (Casavola et al., 1996; Lee & Wie, 2015; Liu et al., 2001). Cirillo (2014) strives to expand this approach by not solely controlling for education and qualification but also differentiating between occupational groups. She thereby follows the task hypothesis (Acemoglu, D., & Autor, D., 2011; Autor, D., Levy, F., & Murnane, R. D., 2003), albeit this approach is not new. Martínez-Ros (2001) and Cozzarin (2016) investigate how workers benefit from rents created by new technologies referring to rent-sharing approaches. Articles using company level data are summarized in table 3.

Casavola et al. (1996) documents that in the observed time period np-worker wages increase stronger than p-worker wages. The authors observe that both the demand for and relative wages of highly qualified workers increase in innovative firms but also that a technology premium fails to appear. They trace this observation back to centralized bargaining in Italy, where strong labor unions engage for wage compression and thereby prevent this kind of premium at the industry level.

In observing the Indonesian labor market in the 2000s, Lee and Wie (2015) find out that wage inequality increased together with the demand for higher qualified workers. The authors employ innovation indicators and trade indicators to cope with the fact that Indonesia had been a technologically underdeveloped country at that time, which experienced innovation mostly through foreign investments and the import of foreign technology. Their results confirm that especially the increase in trade indicators led to an increase of np-workers' share in the overall wage sum. These findings and an increased demand for qualified workers in import-oriented firms convince the authors that a SBTC is the cause of increased wage inequality in Indonesia. Intensifying globalization which introduces further technological innovations to the country could exacerbate this development.

As a first step, Cirillo (2014) starts her analysis with a clustering of innovation strategies based on the amount of companies' innovation investments. She identifies and examines three clusters according to the amount of the firms' innovation investments. Her results verify that wage premia of innovations increase proportionally with innovation investments. This implies that the group of product-strategy innovators pay the highest wage premia while non-innovators pay the lowest ones.

This pattern is also revealed inside the cluster of product-strategy innovators when examining workers' qualifications: wages increase with qualifications for all occupational groups, except for lowly qualified manual workers. Conversely, in firms that are cost-strategy innovators wages increase only for office staff and managers while lower qualified workers even have to take losses. Cirillo concludes that a SBTC underlies these results.

Liu et al. (2001) test whether the number and type of newly implemented technologies have an impact on wages in general and differentiated by groups of p-workers and np-workers. Initially, their data points to evidence for a SBTC. However, when employing a technology regression, the observed technological change turns out to be partially endogenous and thus being a product of higher wages.

Martínez-Ros (2001) analyzes the distribution of innovation rents between employers and workers. In doing so she uncovers that product innovations have little influence on wages, process innovations have a significant and strongly positive influence on wages and that product and process innovation together have a three times stronger positive influence on wages than process innovation alone. From these results she deduces that process innovations enhance the cost structure and efficiency of a firm in the long run. This in turn generates innovation rents while product innovations only have short term positive effects for a firm's profit. It becomes clear that the type of an innovation has different effects on labor demand, and this again has different impacts on wages.

Cozzarin (2016) chooses a two-step approach in order to track the impacts of process innovation, product innovation and the introduction of advanced manufacturing technology on productivity and wages in Canadian firms. He operationalizes the intensity of innovations as expenditures and uses a variable checking which of nine advanced technologies are used in the observed firms. He shows that wages and productivity are positively impacted by process innovation expenditures. Product innovation expenditures only have a moderately positive impact on wages.

Studies analyzing plant and company level data disclose methodological developments in the investigation of this topic. They demonstrate that the SBTC-theory has not lost any of its assertiveness and valuation among scientists around the globe. Academics employ advanced techniques to exempt their research results from the possibilities of endogenous SBTC and non-observable industry or firm effects. In actual fact, endogeneity of technological change and unobserved heterogeneity (industries, firms, workers) are acknowledged to be possible biases in at least three studies (Chennells & van Reenen, 1997; Laaksonen & Vainiomäki, 2001; 2001; Liu et al., 2001).

Moreover, the studies described demonstrate developments regarding the conceptualizations in measuring technology. Most articles employing a product/process innovation differentiation are found among studies using company level data (Cozzarin, 2016; Martínez-Ros, 2011). This may be due to better availability of data on the distinction between different innovation types. The differentiation between different types of innovation in documenting TC's impact is a crucial step in developing the methodology further in this field of research. Unfortunately, the theoretical elaboration of the concept of "product/process innovation" is treated rather briefly. Table 3 shows the results of the review of articles observing the impact of technology on wages on the company level.

Table 2: Results of literature review for articles using plant level data

Author	Year	Theoretical background	Independent technology variable/ Operationalization of technical change	Dependent variable	Positive/ negative relationship	Explanation/ notes	Country	Time
Chennels & van Reenen	1997	endogenous SBTC	inquiry of new technology including microelectronics, R&D intensity	wages (LQ workers) wages (MQ workers) wages (HQ workers)	+ + +	SBTC (?)	United Kingdom	1984, 1990
			wages	technology	++	plants paying higher wages and employing highly skilled workers adopt more advanced technologies (endogenous SBTC)		
Laaksonen & Vainiomäki	2001	miscellaneous	industry's relative R&D expenditures --> 4 technology levels	average establishment wages (manual and non-manual workers)	low tech. level: **0**, med. tech. levels: ++, high tech. levels: +	SBTC, Finnish industrial relation system	Finland	1974-1993
				relative wages of HQ/LQ	high tech. level: +			
Dunne & Schmitz	1995	SBTC	inquiry of 17 computer-based technologies: number of machines in use	wages (P workers) wages (NP workers)	++ +	efficiency wage, higher techn. premia for P-workers.	USA	1987, 1988

Table 3: Results of literature review for articles using company level data

Autor	Year	Theoretical background	Independent technology variable/ Operationalization of technical change	Dependent variable	Positive/ negative relationship	Explanation/ notes	Country	Time
Lee & Wie	2015	SBTC	R&D exp. / investment	relative wages (NP / P workers)	**0**	domestic techn. activity does not impact the labor market	Indonesia	1990 - 2009
			Openness to foreign technology: FDI / investment, imported material		+	demand for skilled workers increases (TBTC) wage inequality rises due to technology demanding higher skilled workers (SBTC)		
Martínez - Ros	2001	Rent-sharing	process innovation	wages	++	innovation as source of additional rents for workers (rent-sharing)	Spain	1990 - 1994
			product innovation		+			
			Both innovations simultaneously		++			
Cirillo	2014	SBTC, rent-sharing	clusters (investment in innovation activities):				Chile	2007, 2009
			product strategy innovators	wages	+	except for unskilled manual workers		
			cost strategy innovators		+	only for clerks		
			non-innovators		**0 (ref.)**			
Liu et al.	2001	SBTC	inquiry of usage and number of 8 computer-based technologies	wages (P worker)	**0**	endogenous SBTC, positive wage effects of techn. only for NP workers	Taiwan	1991
				wages (NP workers)	+			
Cozzarin	2016	process/ product innovation	process innovation expenditures	wages	+	process innovations create additional economic rents product innovations improve firms' market position	Canada	2009
			product innovation expenditures		+			
			number of used AMTs		**0**			
Casavola et al.	1996	SBTC	intangible assets / total capital	wages (blue collar)	**(+)**	shift in supply of skills, Italian industrial relations system	Italy	1986 - 1990
				wages (white collar)	**(++)**			

3.2.3 Matched employer/ employee data

The articles by Mishra and Smyth (2014), Doms, Dunne, and Troske (1997) and Entorf and Kramarz (1998) use matched datasets for employers and employees. While the latter two articles observe data from developed industry nations (USA, France), Mishra and Smyth (2014) examine firms in a Chinese industrial region. These articles are summarized in table 4.

Matched employer-employee datasets might be the most adequate means to measure impacts of technologies on wages. They combine the advantages of individual level and company/plant level data as they can provide information on workers' characteristics as well as on technological and organizational traits of observed entities. Thus, a direct link can be observed between workers' skills and wages and the organizations' choices regarding technology adaption and organizational resources in reacting to technical change.

Mishra and Smyth show that firms with a higher R&D intensity pay higher wages. Their finding that better educated workers earn higher wages is consistent with the SBTC theory. Also, they document a relationship between company size and pay scheme, such that bigger innovative firms pay higher wages than smaller ones. Their following assessment infers that union members can expect higher wages through technological change than non-organized workers. The authors argue that this observation is be consistent with aforementioned rent-sharing approaches (Mishra & Smyth, 2014: 136).

Doms et al. (1997) analyze the workforce differentiated by the occupation groups of production workers (group 1), technical staff (group 2) and office and sales staff (group 3). The findings of their cross-cut analysis point to a SBTC: firms using advanced technologies employ highly qualified workers who earn higher wages (group 1 and 2, but not group 3). However, their panel analysis shows that more innovative firms pay higher wages before and after the implementation of new technologies. After controlling for workers' non-observable skills, they corroborate that firms having a higher qualified workforce are more likely to introduce new technologies.

Entorf and Kramarz's analysis shows similar results (1998). Their cross-cut analysis also supports a SBTC which is driven by workers' autonomy in using new technologies. Thus, medium autonomy in using new technology leads to the highest wage premium. Moreover, the authors observe that workers who use new technologies were already paid higher wages than other workers before the implementation of new technology. From this they conclude that firms only let their most skillful workers work with new technologies. Furthermore, they verify that the wage premia of those skillful workers increase with their experience with those technologies.

Papers using employer-employee data demonstrate that research design plays an important role when examining this type of data: While pure cross cut analyses as conducted by Mishra and Smyth (2014) always tend to point toward a SBTC, panel analyses uncover that technological change can be endogenous. Applying this assumption, Doms et al. (1997) and Entorf and Kramarz (1998) extend their cross-cut analyses by using fixed-effects models and detect the reversal of the aforementioned relationship: firms with a better qualified and paid workforce are more likely to introduce innovations and technology premia primarily depend on higher worker skills, even before any innovations.

Table 4: Results of literature review for articles using linked employer – employee data

Author	Year	Theoretical background	Independent technology variable/ Operationalization of technical change	Dependent variable	Positive/ negative relationship	Explanation/ notes	Country	Time
Mishra & Smyth	2014	SBTC	R&D intensity	wages (LQ workers)	+	SBTC	China	2007
				wages (HQ workers)	++			
				wages (union & party members)	+	Rent-sharing		
Doms et al.	1997	SBTC	inquiry of usage of 16 manufacturing technologies (number of used technologies)	wages (CS)	+	more innovative firms pay higher wages (SBTC)	USA	1988, 1993
				wages (L)	(+)	Higher paying firms have more skilled workers and are more innovative (endogenous SBTC)		
Entorf & Kramarz	1998	SBTC	inquiry of usage of 15 computer-based and production-based new technologies (number of used technologies)	wages (CS)	++	technology premium increases with experience in using them (SBTC)	France	1985 - 1987
				wages (L)	+	CS effects almost fully explained by selection bias or unobserved worker heterogeneity (endogenous SBTC)		

3.2.4 Industry level

This literature review includes four studies using data collected on industry level (Angelini et al., 2009; Englehardt, 2009; Feenstra & Hanson, 1999; Kristal & Cohen, 2017). Industry level data's potential to precisely measure the links between technologies, organizations, workers' characteristics and wages may seem low at first sight. The precision of technology's operationalization is on average lower than that on the observation levels discussed so far. Nevertheless, this kind of data has a great potential in unravelling the effects of institutional surroundings within and between national states, as demonstrated by Kristal and Cohen (2017) and Angelini et al. (2009) respectively. Thus, industry level data is well suited for comparative analyses taking into consideration pay setting institutions and other major economic forces such as the dependence on international trade. Articles using industry level data are summarized in table 5.

Following a less strict neoclassical approach, Kristal and Cohen (2017) examine the impacts of pay-setting institutions and computerization on wage inequality in 43 US industries from 1968 to 2012. They measure computerization as real investments in computers as a share of total non-residential fixed assets and find out that the decline in union density and in the real value of minimum wages influenced the change in wage inequality twice as much as the impacts of computerization.

Angelini et al. (2009) examine the increase of qualification-driven wage inequality in seven European countries. Relying on a neo-Schumpeterian theory framework they find their assumptions to be mostly confirmed:

1) A higher share of industries which introduce product innovations leads to a higher wage polarization

2) Process innovations have a negative impact on wage polarization.

3) Net employment growth has a positive impact on wage polarization

4) A higher share of workers with moderate education countervails wage polarization. Supposedly, their wages increase due to trainings and "upgrades".

Angelini et al. (2009) suggest that the weakening of labor market institutions and the overall decline in union density lead to a further intensification of wage polarization.

Feenstra and Hanson (1999) and Englehardt (2009) both analyze the impacts of technological change on wages in a similar way using the same dataset. First, they widen their analysis by taking those changes in the cost share for labor into account that are a product of technological changes. Second, in doing so they are able to trace these changes back to either demand changes for higher qualified workers (i.e., skill-bias) or industry effects (i.e. branch-bias).

Table 5: Results of literature review using industry level data								
Autor	**Year**	**Theoretical background**	**Independent technology variable/ Operationalization of technical change**	**Dependent variable**	**Positive/ negative relationship**	**Explanation/ notes**	**Country**	**Time**
Feenstra & Hanson	1999	SBTC & outsourcing	High tech capital share	relative wages (NP / P workers)	+	technology twice as strong in explaining rising relative wages as outsourcing	USA	1979 - 1990
Englehardt	2009	SBTC & outsourcing	investment in software	relative wages (NP / P workers)	1980s: 0 1990s: ++	software is skill-complementary	USA	1979 - 1990
			investment in hardware		-	hardware increases productivity of P workers		
Angelini	2009	Neo-Schumpeterian innovation	product innovations*net job growth	wage polarization	+	Schumpeterian nature of innovation	7 EU countries	1994 - 1996, 1998 - 2000
			process diffusion * high share of MQ workers		-			
Kristal & Cohen	2017	SBTC vs. Institutions	real investments in computers as share of total non-residential fixed assets investments	wage inequality	+	the negative changes in pay-setting institutions account as twice as much for the increase in wage inequality as technological change	USA	1968 - 2012
			union density		++			
			real minimum wage value		++			

These four studies document new possibilities for approaching this topic theoretically and methodologically. Feenstra & Hanson (1999) and Englehardt (2009) simultaneously account for technological change as well as the impact of outsourcing and labor demand changes due to international trade. Angelini et al. (2009) extend the theoretical approach to the research question employing a neo-Schumpeterian framework as the only study in this review. In doing so, the authors provide interesting insights into the impacts of conceptually *different* innovations. Widening the perspective on TC even further, Kristal & Cohen (2017) additionally take into account the role played by pay setting institutions. Several other studies in this review consider trade unions to have some kind of influence as well but Kristal and Cohen (2017) make labor market institutions a central aspect of their approach. Their results point to the usefulness of such considerations.

4 Analysis

In this section the findings of the reviewed articles are presented in more detail in relation to their respective theoretical approach. Naturally, each theory has to face both positive and negative resonance in field studies. This resonance is summarized and then complemented with some remarks on potential restrictions to each theoretical approach. In the next section a closer look at the literature will be conducted for their empirical approaches as well. Specifically, we want to look at their conceptualizations and operationalizations of technological change.

4.1 Theoretical approaches

The most pervasive theoretical approach in the observed time span is inarguably that of Skill-biased technical change (SBTC). Resulting from modifications of the canonical approach to labor demand and supply changes it established *the* way of thinking about technological progress's impacts in economic disciplines. Seventeen studies in this review rely on its theoretical framework and find results that can be interpreted in its light or are able to transcend it. Positive feedback to its propositions comes from eight articles (Allen, 2001; Bartel & Sicherman, 1999; Cirillo, 2014; Dauth et al., 2017; Feenstra & Hanson, 1999; Krueger, 1993; Lee & Wie, 2015; Mishra & Smyth, 2014) of which four operate on the individual level. However, four articles observe a reversed causality, which is referred to as endogenous technical change. It implies that companies that will later be more innovative than others pay higher wages and have a higher qualified workforce in the first place (Chennells & van Reenen, 1997; Doms et al., 1997; Entorf & Kramarz, 1998; Liu et al., 2001). They illustrate a new approach of researching the causal chain between technology and wages using fixed effects models and technology regressions. One further article whose results cannot ultimately support the SBTC hypothesis is that by Dunne and Schmitz Jr (1995), who trace back their results to efficiency wage arguments. The use of advanced technology is connected to higher wages for all occupational groups under observation which might result from the need to reward innate abilities of workers with higher-than-market-clearing-wages. Bartel and Lichtenberg (1991) produce similar insights. Their results point to an endogenous SBTC and they complement them with notions about their learning ability hypothesis. It states that higher skilled workers gain higher technology premia as they are better learners in using technology. They conclude that these higher learning efforts are rewarded with efficiency wages.

The five articles that find mixed results are equally interesting as they are able to expand on the view of the questions at hand. Englehardt (2009) tries to differentiate between the impacts of mutually non-exclusive high-tech capital investments ending up in a questionable separation of hardware and software.

There are a few studies in this review pointing to the potential influences of institutions, namely industrial relations systems. Three of them can be found in the SBTC nexus. Casavola et al. (1996) observe the predicted increase in demand for HQ workers resulting from more advanced technology usage. However, they cannot observe the hypothesized wage premia for those workers. As one of few studies they integrate labor market institutions into their explanation. As Italian bargaining is quite centralized and trade unions try to uphold a certain degree of wage compression within the workforce, large technology premia are absent. Quite similar is the argumentation by Laaksonen and Vainiomäki (2001) on the situation in Finland. Their results point to a SBTC but they admit that they cannot attest a relationship of higher significance. Thus, pointing to the highly centralized Finnish bargaining system, they also present wage setting processes as more differentiated than can be explained by SBTC alone. Kristal and Cohen (2017) compare the influences of institutional influences against that of technological change in order to gain understanding of the importance of each in determining higher wage inequality. They surely find a SBTC, but it is not as influential in determining wage inequality between P and NP-workers as is the decline in unionization and in the real value of the minimum wage. Overall, SBTC has been a successful approach in explaining impacts of technological change on employment and wages. Moreover, the empirical investigations relying on it pointed to potential next steps in conceptualizing wage setting processes resulting from technology, namely pay setting institutions.

The successor of the SBTC theory is the task-biased or routine-biased technical change hypothesis which was developed by Autor, D., Levy, F., & Murnane, R. D. (2003) and from there on has been raised continually by a growing scientific community. Arguing that technical change in the sense of computer innovations does not necessarily change or eliminate whole jobs but certain routine tasks, it emerged as the current prevailing approach of mainstream economics in explaining the impacts of computer innovations. Six of the reviewed studies take this approach into consideration. Three studies find support for the TBTC hypothesis. Böhm (2019) shows that task prices polarize; manual and abstract tasks increase and routine tasks decrease in price as predicted by the TBTC. He validates this finding with changes in task prices matching changes in wage inequality.

De la Rica & Gortazar (2017) find similar support for the TBTC in their individual-level research approach with the exception of manual tasks and their prices (=wages) also being adversely affected by computer technology. Although they draw their insight from the observation of skill groups, Lee and Wie also suggest that their findings point to a TBTC (2015: 248). In opposition to these findings Adermon and Gustavsson (2015) do not find a significant relationship between changes in tasks and wages. Similar to Laaksonen and Vainiomäki (2001) and Casavola et al. (1996) they point to the potential influences of national industrial systems on wage setting processes. Mixed insights can be obtained from two studies, as their approach is not a "pure" TBTC approach as they do not search for exact compositions of task intensities. Acemoglu & Restrepo (2017), who try to identify the impact of industrial robots on employment and wages, conclude that robots indeed replace human labor in many tasks, but due to the aggregation level of their data ("commuting zones") they are unable to refer to task categories such as routine, manual or abstract.

Bessen (2016) chooses a neoclassical approach[1]. He confirms the hypothesis of computer use to be less present in routine jobs and thus lead to higher wage inequality within occupations. Furthermore, in his paper it is suggested that the new skills necessary for using computers can be obtained more easily by higher skilled workers.

The TBTC theory surely is an inspiring next step in the formulation of hypotheses of the impacts of technical change. Nevertheless, the TBTC has traits that make it at the same time more attractive for economists in a theoretical manner and less tangible for empirical practice. The notion of technology not solely interfering in the labor market but also on lower observation levels by replacing only certain tasks is the undeniable contribution of this theory. Thus, it is in some aspects far less abstract than the SBTC hypothesis. On the other hand, it departs from a differentiated analysis of the impacts of different technologies by implementing an intermediate step into the analysis, which will be outlined in the next chapter.

Far less often promoted by economic research articles are theories originating from streams of academics from industrial relations and Schumpeterian approaches. Nevertheless, they offer interesting views on what has been theorized by mainstream economics so far. They are able to integrate additional concepts such as distribution of technology premia (rent-sharing hypothesis) and the impacts of conceptually different kinds of innovation (Schumpeter) into the argumentation of researchers.

Although the rent-sharing hypothesis is not pervasive in this field of research, it takes into account certain aspects of organizational life that are less important to other theoretical approaches. It claims that newly created economic rents (e.g. by new technologies and the resulting efficiency boost) are also claimed by workers. Thereby, it resonates specific assumptions of the industrial relation research field namely that changes in wages are also due to bargaining processes over rents commonly created in organizations by workers and capital owners.

This perspective is implemented by only two studies in this review. Martínez-Ros (2001) discusses how different innovations can trigger wage developments as a result of bargaining processes. She finds evidence for her hypothesis, but she does not shed light on the operating principles of the hypothesized bargaining processes. Mishra and Smyth (2014) as well find indications of rent-sharing within organizations. According to them, the wage elasticity with regard to innovation investment (R&D) is higher for workers that are members of trade unions or the Communist Party of China. Their results are significant and they state multiple possible explanations for these observations. Each explanation is pointing to the specific traits of the Chinese variety of capitalism, i.e. party and union members being more affiliated with political elites than in other countries. The rent-sharing approach could overcome the institutional blindness of other theories in this field, but its application still leaves room for

[1] These approaches are the most canonical ones among the reviewed ones. For further research the interested reader may consult Dertouzos and Quinn (1985), van Reenen (1997) and literature on labor saving technology models with productivity and technology effects

development in terms of closer conceptualization and operationalization of bargaining processes.

The few articles concerned with the distinction between product and process innovation merely stem from a less prominent strand of economic literature which refers to itself as Schumpeterian. Building on Schumpeter's growth models, these researchers want to present a more detailed picture of how innovative activities in firms lead to growth, market power and labor market outcomes. They argue that process and product innovations have distinct impacts on technology rents and wages, namely process innovation being more advantageous in terms of wages than product innovations. Martínez-Ros (2001) and Cozzarin (2016) integrate this approach though they do not point to its Schumpeterian origin. The connection between rent-sharing and Schumpeterian approaches becomes salient in Cirillo's (2014) article, where she explains that the rents that are bargained over in rent-sharing approaches are the Schumpeterian first-mover innovation rents gained from process or product innovation strategies by firms. She finds some evidence for both hypotheses. Angelini et al. (2009) set up their "neo-Schumpeterian" theoretical framework more explicitly as described earlier in the analysis. They as well find evidence for the proposition that conceptually different kinds of innovation have different outcomes in the labor market. Surprisingly, this insight is not promoted in a theoretical matter by more canonical approaches and is therefore the contribution of these alternative theories.

4.2 Operationalization of technological change

The measurement of technological change is – in addition to aforementioned aspects such as controlling for endogeneity and heterogeneity – a crucial topic in considering the relationship under examination. This chapter will present and discuss the different conceptualizations of technological change and the variables that are employed respectively. The results from chapter 3 already pointed towards the relevance of this differentiation as they entail different implications depending on the operationalization of technological change. Furthermore, the consideration of differences in measurement is very likely to enrich one's understanding of what is indicated by the term "technological change" in its respective context. The analysis of operationalization approaches resulted in the identification of three categories of measurement.

4.2.1 Capital-related variables

The first category measures innovation activities mostly by employing accounting values. Naturally, these values are related to capital flows and therefore quantitative. They enable researchers to measure the intensity of their definition of technical change. Additionally, this data is easily obtainable from many datasets on both firm and industry level. Unfortunately, they are lacking a temporal component. This impedes time-series studies that conceptualize technology implementation as an intervention or experimental treatment with lagged outcomes. One's estimations of the overall R&D investments' impacts are prone to upward bias if high investments in marketing innovations and lower ones in production technology are done in the same year. Moreover, they do not deliver precise information about the distinct type of innovation. In order to illustrate these arguments some of the prevalent variables of this kind are discussed in the following.

Firm expenditure on research and development is arguably the most frequently used variable for measuring technological change: it is employed in eight of the reviewed articles. The variable is popular among researchers as it is easily obtainable from many relevant datasets and thus prevailed as an indicator of technological change. Also, it is quite common to relate this value to a firm's output or revenue in order to account for its ratio to the firm's size. In this manner it unfolds as "R&D intensity". However, there are some restrictions to this type of variable to be considered. First, firms could just buy new technologies at the market instead of developing it themselves, which would not result in any changes in R&D expenditures (Brown & Campbell, 2002). Furthermore, R&D expenditures/intensity tends to neglect the possibility of an endogenous technological change especially when used in wage regressions. Namely, the relationship between R&D expenditures/intensity and wages could be reversed as the former also includes wages for a specific part of the workforce. In effect, higher R&D costs are not necessarily a product of technological change but can also result from higher labor costs for the R&D staff of the firms. This circumstance biases the variable's explanatory power. The same argument holds true for the variable "share of scientists and engineers in the workforce" as well, which is employed by two studies (Allen, 1996; Bartel & Sicherman, 1997).

From a theoretical point of view, R&D expenditures are also prone to be misinterpreted as "innovation". As the OECD (1980: 15f.) states, innovation

> "consists of all those
> scientific, technical, commercial and financial steps necessary for the successful
> development and marketing of new or improved manufactured
> products, the commercial use of new or improved processes or equipment
> or the introduction of a new approach to social service."

Meanwhile, as Arundel and Smith (2013) argue, R&D is only one input to innovation. Moreover, most R&D expenditures within a market are highly concentrated in only certain firms while innovation occurs more often and is "more pervasive" (Gault, 2013). Thus, the concept of technical change in most studies using such quantitative measures should be critically examined in terms of the exact definition of their explanatory concepts and variables.

Some of the articles under examination question the explanatory power of capital related operationalizations regarding technological change. As Martinez-Rós (2001) points out, R&D variables only shed light on the input deployed for innovation while it does not refer to an innovation's output. Hence, she uses variables indicating process and product innovations. She argues that an output analysis would better demonstrate the process of firms making efforts for innovation and transforming this effort into higher profits (Martinez-Ros, 2001: 83). This view is shared by Cozzarin (2016). Similarly, Bartel & Sicherman (1997) point out that R&D variables indeed measure firms' or industries' innovative activities. But this measurement solely takes place at the point where innovation is produced and not where it is actually implemented and used. A measure that meets this concern more adequately is the number of patents in use. This variable is used in two studies (Bartel & Sicherman, 1997; Casavola, 1996). The use of patents as indicator for innovation has its own potential pitfalls though. Nagaoka, Motohashi, and Goto (2010) note that not all firms publish new inhouse innovations as patents. They point to the probability of firms protecting inventions with patents is highly influenced by a firm's size and industry respectively.

Data on investments in ICT and certain other technologies are more specific than patent or R&D data. They offer a measure of innovation activity corresponding to certain new technologies. Their differentiations between numerous types of advanced technology give interesting insights into the different effects of various innovations (Englehardt, 2009). Eight of the reviewed studies employ investment variables that more specifically focus on computer adoption. As Englehardt (2009) demonstrates, these measures of technological change can lead to inaccuracies as well. In differentiating between the effects of hardware and software investments he does not explain how lower qualified workers are able to use a computer without using software, or, more generally, why computers' and software's impacts on wages can conceptually be explained separately.

Foci on inputs to production processes depend on the theoretical proposition which researchers put forward. According to Allen (2001), technological change is – in strict economic terms - an increase in output without an increase in input. Thus, technological change appears to be indicated most adequately by total factor productivity growth (growth of ratio of output to input). However, he advises employing additional measures for technological change as total factor productivity growth is a residual and therefore quite prone to non-observable effects Allen (2001). Two studies in this review employ this measure while it is also employed in a huge number of articles from microeconomics considering technological change.

4.2.2 Intervention-related variables

This second category of variables observes the introduction and usage of certain technologies. Rather than interpreting cash flows it treats the implementation of innovations as interventions that cause changes in other observed variables (e.g. wages) over time. Furthermore, these variables are able to capture the specific kind of technology that is newly introduced. This feature enrichens the analysis of technological change as different kinds of technology have different impacts on wages (Allen, 2001). Moreover, they are capable of indicating the intensity and the temporal dynamics of technological change far more vividly than capital-related measures. Being more qualitative in nature, they are regrettably surveyed less often than capital-related variables.

Twelve of the reviewed studies employ intervention-related variables. An important point regarding this type of variable is its widely differing degree of precision. Two studies use variables such as "Share of workers in an occupation using a computer" as a more general indicator of computerization (Bessen, 2016; Krueger, 1993). While Kruger was not able to hypothesize on the ground of a TBTC, the missing observation of changes in executed job tasks after computerization has become more familiar in TBTC studies (Bessen, 2016). This grants deeper insights into the change of production processes. Further articles explicitly ask for certain technologies and even the number of used units (Chennells & van Reenen, 1997; Doms et al., 1997; Dunne & Schmitz Jr, 1995; Entorf & Kramarz, 1998; Liu et al., 2001). Operationalizations of this kind rest on the assumption that firms which adopt newer technologies are technologically more advanced. However, it remains unclear how many workers actually use the new technologies. This is not trivial, as a firm where all workers use a single advanced technology is not seen as more advanced than a firm where only one percent of the workforce is using two advanced technologies (Dunne & Schmitz Jr, 1995).

Thus, researchers get to know about the existence of technologies (e.g., industrial robots) in firms or certain labor markets (Acemoglu & Restrepo, 2017; Dauth et al., 2017) but not their integration in the production process. Again, the changes in inputs of a technically altered production process are researched while the causal chain within production processes leading to changes in wages remains to be the subject of theory. Few studies transcended this restriction in a specific manner in order to differentiate between different motivations to innovate.

Three of the examined articles try to assign different kinds of newly adopted technologies to firms' different innovation strategies. Building hypotheses on this conceptualization of technical change allows for new theoretical impulses. Cirillo (2014) executes a cluster analysis of firms in her first step in order to differentiate between "cost-strategy-innovators" and "product-strategy innovators". She uses capital-related variables to make a firm's innovation activities referable to its assumed innovation strategy. In a similar way (Martínez-Ros), Cozzarin and Angelini et al. assign different technologies to different production process steps. Arguing that product and process innovations have different impacts, they establish a conceptualization of the motivations to adopt new technologies as well.

Intervention-related operationalizations of technical change are an important step towards a better understanding of what happens in a firm's production process whenever a technology is implemented. First differentiations of motives for technological advancements are developed and temporal aspects of technology adaption (=treatment) become better observable. A next step in this development of conceptualization is taken by scholars putting forward the TBTC hypothesis who want to shed light upon what happens to jobs and tasks after advanced technology is implemented. Therefore, task-related operationalizations of technological change are discussed in the last subchapter.

4.2.3 Task-related operationalizations

The third observed conceptualization of technological change is found primarily in articles considering its impacts to be task-biased. These forms of operationalization assume that technological change manifests itself in changed task intensities. Thus, an occupation with higher abstract task intensity is hypothesized to be technologically advanced while a high task intensity in routine jobs is assumed to be automated soon. There are three studies that assume the impacts of technology on wages to be task driven in terms of their operationalization (Adermon & Gustavsson, 2015; Böhm, 2019; Dela Rica & Gortazar, 2017). Adermon and Gustavsson (2015) observe changes in the task content of jobs of occupation groups and regress changes in wages on them. Böhm (2019) divides his sample in occupation groups that are quite intensive in their routine, abstract or manual task content. Searching for their impact on task prices per efficiency unit of skill he shows that wages of workers depend more on task choices and task prices than on a certain distribution of skills in the economy. Dela Rica and Gortazar (2017) vividly expose the assumed direction of causal impacts by integrating them into their empirical approach. Variables measuring "level and complexity of ICT use" impact task intensities which again impact wages.

These operationalization approaches rest on assumptions of economic theory about technology that can be described as their progressiveness and their potential pitfall at the same time. The TBTC approach advances the economic research for technological impacts by assuming it to be more differentiated between categories that do not exclusively stem from market forces, namely tasks. In doing so it comes closer – in terms of distance in a causal chain – to the underlying mechanisms happening in firms due to technology adoption. At the same time the focus of this approach is shifted away from the assumed origin of change, namely the characteristics of technology. RBTC restricts itself to result from “computer innovations” without further defining them. Autor et al. (2003) refer to different kinds of computer technology to underline their point. At the same time the low potential of automation of their examples (e.g. autonomous driving, legal writing) have shown to be outdated. Furthermore, Fernández-Macías and Hurley (2016) argue that routine is difficult to operationalize and could lead to a circular argument: “computers replace routine tasks” and “routine tasks are those tasks replaced by computers”. Also, there are sociological arguments that point to the undervaluation of routine work through economists (Pfeiffer, 2018; Pfeiffer & Suphan, 2015). These points do not weaken the merit of the TBTC approach but show the importance of a better understanding of technologies’ characteristics in the first place.

5 Conclusion

The relationship between various forms and conceptualizations of technology on wages has turned out to be mostly positive in the majority of the reviewed articles. A wide spectrum of theoretical and empirical approaches has been developed in the last decades to examine this relationship. The economic literature has been able to find many paths and moderating factors connecting technology and wages such as skill and task distribution, differentiations between process and product innovations, efficiency wage arguments and bargaining processes.

The main finding can be summarized as a result of the growing polarization in wages. Fourteen of the studies in this review find a growing wage inequality between different worker groups independently of country, observed time span and observation level. These worker groups differ especially in skill levels (SBTC) and task intensities (TBTC). Wages grow for workers that have higher qualifications or exercise jobs with a higher share of cognitive, non-routine tasks. At the same time, wages for workers with lower qualification or jobs with a higher share of routine tasks do not grow as fast as the other group’s wages.

In addition, the review examined further moderating effects linking technology and wages aside from skills and task content of jobs. Those are the kind of innovation (Angelini et al., 2009; Cirillo, 2014; Martínez-Ros, 2001) and different bargaining positions that are due to institutional surroundings such as trade unions or industrial relations systems (Adermon & Gustavsson, 2015; Casavola et al., 1996; Cirillo, 2014; Dauth et al., 2017; Kristal & Cohen, 2017; Laaksonen & Vainiomäki, 2001; Mishra & Smyth, 2014). The author suggests developing these approaches further in future research. Although the presented approaches are promising, there is still the need for the establishment of a more holistic theoretical framework taking into account the mechanisms by which institutions and different kinds of technologies act in relation to workplace outcomes.

The most prevalent problem in measuring technologies’ impacts is endogeneity. This can result from pure crosscut analyses and/ or crude operationalizations of technological change. Capital-related variables measuring technological change are prone to be correlated with wages (e.g. R&D expenditures) and the inability to employ fixed effects models in crosscut analyses reduces the researchers’ ability to check for biases such as workers’ unobserved abilities. Four studies in this review observe an endogenous technological change at the matched-employer-employee, plant and company level (Chennells & van Reenen, 1997; Doms et al., 1997; Entorf & Kramarz, 1998; Liu et al., 2001). These observation levels seem to be best suited for endogeneity checks, when combined with a longitudinal analysis of intervention-related operationalizations of technological change.

The operationalization of technology remains subject to critique after this review. In this context the author substantiates the comments of Brown and Campbell (2002), which emphasize that articles find a "correlation between technology and wages but cannot complete the chain of causality linking the two." and that "measurement that is not grounded in theory may be difficult to interpret and may be consistent with several interpretations." However, the researcher community's sensibility toward this topic has only developed in non-neoclassical theories, such as the neo-Schumpeterian ones.

This review's goal is to understand and disentangle these approaches for the interested reader in labor economics and HRM disciplines. An analysis of the traits and potential blind spots of each approach was meant to acknowledge the work thus far conducted and to provide impulses for the further development of technology adaptation research in economics.

As the examination of technologies' impacts on employment and wages is a broad field this review does not claim to be fully comprehensive. The review covers twenty-six studies that empirically trace the connection between technology (however it is conceptualized), wages and related concepts such as wage inequality and often the parallel development of employment in the observed skill and occupation groups.

For further research the author suggests acknowledging the approaches thus far developed and to be critical towards one's own understanding and conceptions of technology and its measurement. The topic under examination deserves context sensitivity with respect to institutional settings, constitutions of technologies and observation level as it will continue to have economic and societal impact for generations to come.

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