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Abstract

The essay deals with the complex and articulated relationship between technology and employment, offering food for thought about the effects of the current technological trajectory on qualifications and tasks.

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JEL codes: O33

1. *Technology and employment: an ongoing relationship*

In the past decades, the emergence of a paradigm based on Information and Communication Technologies (ICT) has contributed to a significant adjustment of the employment structure - both in quantitative (employment levels) and qualitative terms (skills) - in all the industrialized economies. With some delay, this trend is now also affecting emerging and developing countries (see Vivarelli, 2014; Haile et al., 2017).
More recently, the increasing use of more powerful technologies able to perform tasks normally requiring human intelligence (such as speech recognition, visual perception, decision-making and translation of languages) has raised again a widespread fear of a new "technological unemployment" wave (see Brynjolfsson and McAfee, 2011 and 2014). Moreover, not only employment in agriculture and manufacturing appears at risk, but employees in services - including jobs where cognitive skills are dominant - are no longer protected: see for instance how IBM Watson may displace the majority of legal advices, how Uber (just a software tool) is significantly crowding out taxi companies and how Airbnb is rapidly becoming the biggest business model of "hotel company" in the world.
In addition, the evolution of labour demand, linked to the needs brought about by these new technologies, seems to negatively affect routine jobs, while creating opportunities in professional categories significantly different from previous ones (see Autor et al., 2006; Goos et al., 2014).
Finally, these trends turn out to be interlinked with the recent financial and economic crisis and with the slow recovery afterwards characterized by its jobless nature. Indeed, international organizations, such as UNIDO and OECD, are increasingly concerned with the issue of avoiding jobless growth (see European Commission, 2010; Crespi and Tacsir, 2012; UNIDO, 2013; OECD, 2016).
Given this framework, the purpose of this article is to provide a critical survey of the quantitative and qualitative works studying the multifaceted impact of innovation on employment across countries,

industries and companies. Conclusions will emphasize main results from the literature and will present open issues requiring additional attention of researchers and policy-makers.

2. *Compensation mechanisms*

The assessment of the effects of technological change on employment is a well-known controversial issue for theoretical economists. On the one hand, technological unemployment is considered a direct worrisome consequence of labour-saving process innovations; on the other hand, economic theory underlines the existence of indirect effects able to compensate for employment reduction. In addition, product innovations generally present a labour-friendly nature.

By definition, process innovations aim at producing the same amount of output with a lesser extent of production factors - especially labour - and, therefore, they destroy jobs. However, the economic theory, since its beginnings, has pointed out the existence of economic forces able to positively impact on employment, compensating the immediate negative effect.

In more detail, at the time of the classical economists, two views competed in assessing the employment impact of technology: the "working class opinion" – in Ricardo's words - was characterized by the fear of being dismissed due to innovation (see Ricardo, 1951, p. 392), whilst the academic and political debate was mainly dominated by an *ex-ante optimistic* confidence in the market compensation of dismissed workers. Ironically, while English workers were destroying machines "stealing" their jobs under the lead of Ned Ludd (see Hobsbawm, 1968; Hobsbawm and Rudé, 1969), the economic discipline was trying to dissipate all concerns about the possible harmful effects of technological progress on a basis of a rigorous (and counter-intuitive) theory.

In particular, in the first half of the XIX century, classical economists defined a theory that Marx later called the "compensation theory" (see Marx, 1961, vol. 1, chap. 13 and 1969, chap. 18). This theory was made up of five different market compensation mechanisms

which were triggered by technological change itself and which could counterbalance the initial labour-saving impact of process innovation (for an extensive analysis, see also Vivarelli, 1995, chaps. 2 and 3; Petit, 1995; Vivarelli and Pianta, 2000, chap. 2; Pianta, 2005; Coad and Rao, 2011). In the presentation of the compensation mechanisms, we also briefly discuss the potential existence of serious drawbacks often either ignored or mis-specified by the economic conventional wisdom (see Vivarelli, 2014 for an in depth discussion of the potential limited efficacy of the compensation mechanisms).
Adopting an intuitive approach, the five compensation mechanisms can be described as follows:

a) "New machines"
The process innovations which displace workers in the user-industries, create new jobs in the capital-sectors where the new machines are produced (Say, 1964, p. 87). However, labour-saving technologies can spread around in the capital goods sector, as well. In addition, new machines can be implemented either through additional investments or simply by substitution of the obsolete ones (scrapping). In this latter case - the most frequent one - there is no compensation at all (Freeman et al., 1982).

b) "Decrease of prices"
To be economically acceptable, process innovation should lead to a decrease in the unit costs of production and - in a competitive market - this effect should be translated into decreasing prices. In turn, decreasing prices might stimulate an additional demand for products and induce supplementary production and employment (Steuart, 1966, vol. II, p. 256). Nevertheless, this mechanism ignores that labour-saving technology initially decreases the aggregate demand due to the cancellation of the demand previously associated with dismissed workers. So, the compensation mechanism affecting prices deals with an initial shrunk demand that has to be more than counterbalanced. In addition, the presence of a competitive market cannot be taken as granted.

c) "New investments"

In a world where the competitive convergence is not instantaneous, the gap between the decrease in costs - associated to technological progress - and the consequent fall in prices (see previous mechanism *b)*), generates extra-profits. These may be accumulated by innovative entrepreneurs, which might invest them in new productions and new jobs (Ricardo, 1951, vol. I, p. 396). Nonetheless, pessimistic expectations may imply the decision to postpone investments even in presence of cumulated profits obtained by innovation. If a substantial delay in compensation happens, it may cause structural technological unemployment.

d) "Decrease of wages"

The direct effect of job-destructive technologies may be compensated within the labour market. In fact, assuming free competition and full substitutability between labour and physical capital, technological unemployment implies a decrease in wages- This should support a reverse shift back to more labour-intensive technologies (Wicksell, 1961, p. 137). More in general, decrease in wages can induce firms to hire additional workers, but – from the opposite perspective - the associated decreased aggregate demand might lower employers' business expectations suggesting them to engage fewer workers.

e) "Increase of incomes"

Directly in contrast with the previous compensation mechanism (therefore, they are – in a sense – quite alternative), this one assumes trade unions that take part to the distribution of the fruits of technological progress. A portion of the cost savings due to innovation can be translated into higher incomes and, hence, larger consumption. This increase in demand leads to an increase in employment (see Pasinetti, 1981; Boyer 1988 and 1990). However, nowadays, the distribution of income follows different rules (not always sharing productivity gains) and labour markets have returned to be competitive and flexible.

Summing up, the economic theory cannot claim to have a clear answer in terms of final employment impact of process innovations. Depending on the different institutional and economic contexts, compensation can be more or less effective and the technological unemployment might be only partially reabsorbed.
However, the overall picture cannot ignore the potential job creating effect of product innovation which might have a "welfare effect" connected to the creation of new branches of production. Nonetheless, even in this case, it has to be compared with a potential "substitution effect" caused by the displacement of mature products[1] (see Katsoulacos, 1984 and 1986; Hall et al., 2008).
Indeed, in different historical periods and institutional contexts, the balance between the direct labour-saving effect of process innovation and the counterbalancing impacts of compensation mechanisms and, partly, product innovation, can significantly vary (Freeman et al., 1982; Freeman and Soete, 1987; Freeman and Soete, 1994). The economic theory does not provide a clear-cut answer about the quantitative employment effect of innovation, since this depends on institutional factors, crucial parameters such as price and income elasticities, demand and profit expectations and other contextual factors. In addition, this literature does not pay attention to the qualitative "aspect" of workers (it may be the case that some skills/tasks are no more necessary after innovation has been introduced, while others become extremely relevant). This is why the attention of the economists is nowadays largely focusing on the empirical studies which are discussed in the following sections.

3. *Measures of innovation*

Whilst theoretical economists have been developing stylized models about the employment impact of process and product innovations, applied economists had to identify proxies to measure them and their employment impact. In doing this, a number of critical issues arise.

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[1] For example, the MP3 music format is a product innovation currently displacing the compact disk which, in turn, displaced the vinyl.

Even if innovation is a multifaceted phenomenon, among the most used proxies, simple process and/or product innovation dummies (yes/no variables) capture the existence of the innovation phenomenon in a specific point of time.
Looking instead at continuous indicators of technological change, most of process innovations are implemented through the so-called "embodied technological change" (ETC)[2], introduced with gross investments. This technological input - which is often dominant in economies and sectors where small and medium enterprises are prevalent - is generally very difficult to be measured due to the complexity in singling out the different components of capital formation (those merely expansionary and those characterized by ETC). In this frame, few studies have had the opportunity to isolate ICT investments, which should better capture automation and digitalization processes.
Indeed, the most commonly used continuous indicator is expenditure in Research and Development (R&D). This indicator is specific and it is often available on an annual basis directly from companies' accounts. Its main limitation lies in being a measure of an innovative input that not necessarily generates an innovative output. Moreover, while R&D is the most available and used variable, it has to be noticed that it is mainly correlated with labour-friendly product innovations. Therefore, adopting this kind of proxy for innovation might imply an "optimistic bias" in terms of assessing the employment impact of innovation.
Turning our attention to continuous measures of innovative outputs (which are obviously more directly linkable to their possible employment impacts), two are the most common indicators used in empirical studies. On the one hand, a number of works use the "sales derived from new products" as a continuous measure of product innovation. On the other hand, other studies rely on patents. Patents

[2] The embodied nature of technological progress and the effects related to its spread in the economy were originally discussed by Salter (1960) and Solow (1960) who underlined that technological progress might be incorporated in new vintages of capital introduced either through additional investment or simply by scrapping (see also Hulten, 1992; Hercowitz, 1998; Wilson, 2009).

are a robust output indicator. However, it is well-known that not all the innovations can be patented, patenting is a very expensive procedure and different patents may have dramatically different economic impacts (that is why most accurate studies use patents weighted by citations).

4. *Quantitative employment impact of innovation*

Together with the choice of a proper indicator of technological change, it is crucial to clearly identify the level of investigation, whether macroeconomic, sectoral or firm-based.

Country-level studies explore the direct effects and compensation mechanisms at work in the aggregate. While they are attractive from a theoretical point of view, on the minus side they are often severely constrained by the difficulty to find a proper aggregate proxy of technological change. In addition, the final employment national trends are co-determined by overwhelming institutional and macroeconomic determinants difficult to disentangle and to control for.

Vice-versa, microeconometric (firm-based) studies have the great advantage to allow a direct firm-level mapping of innovation variables, both in terms of innovative inputs and/or outputs. Indeed, only the microeconometric empirical analysis can grasp the very nature of firms' innovative activities and their employment impact. However, there are limitations associated to this level of analysis, as well. Firstly, the microeconomic approach cannot take fully into account the indirect compensation effects which operate at the sectoral and country levels. Secondly, even when the innovation is intrinsically labour-saving, microeconomic analyses generally show a positive link between technology and employment since they do not take consider the effect on rivals, which are crowded out by the innovative firms ("business stealing" effect).

Finally, the empirical studies devoted to the relationship between innovation and employment have mainly focused on high- and middle-income countries, especially OECD countries (basically because of data availability), meanwhile only recently the phenomenon has been under investigation in low-income countries (see Vivarelli, 2014 for a survey and Mitra and Jha, 2015, for a recent application to the Indian case).

Keeping these remarks in mind, we turn our attention to a detailed discussion of previous studies, grouped together according to their level of analysis.

In general, macroeconometric studies have tested the validity of the compensation mechanisms in a partial or general equilibrium framework.

In the very first empirical paper analyzing this topic, back in 1981, Sinclair, using US data, proposed a macroeconomic approach and concluded that a positive employment compensation could occur if elasticities of both demand and factor substitution were sufficiently high. In Vivarelli (1995, chaps. 7, 8 and 9) the direct labour-saving effect of process innovation and the different compensation mechanisms have been represented and estimated through a simultaneous equations model over the period 1960-1988. Estimations based on Italian and US data showed the most effective compensation mechanism turned out to be the one related to decrease of prices in both countries. In addition, the US economy resulted to be more product-oriented than Italy. Simonetti et al. (2000) extended the macroeconomic model of Vivarelli (1995), using US, Italian, French and Japanese data over the period 1965-1993. The authors found that the more effective compensation mechanisms were both the decrease of prices and the increase of incomes (especially in Italy and France till the mid-eighties). Finally, product innovation significantly revealed its labour intensive potentiality only in the US.

On the whole, the (few) aggregate studies available on the subject reveal - not surprising - that technological change can display its labour-friendly nature only when markets are characterized by competition and flexibility and a higher substitutability between production factors.

Switching to a more disaggregated level of analysis, the sectoral studies are particularly important in investigating the overall employment impact of innovation connected to the secular shift from manufacturing to services. In manufacturing new technologies seem to be implemented mainly through labour-saving ETC, only partially counterbalanced by market compensation mechanisms. Vivarelli et al. (1996) found evidence that in Italian manufacturing the relationship between productivity growth and employment appeared to be negative and, in particular, that product and process innovation had, respectively, positive and negative effects on the demand for labour. Pianta (2000) and Antonucci and Pianta (2002) found an overall negative impact of innovation on employment in manufacturing industries across five European countries. Meanwhile, this scenario may change if service sectors are considered. Evangelista (2000) and Evangelista and Savona (2002) found a positive employment effect of technological change (only) in the most innovative and knowledge-intensive service sectors. Taking manufacturing and services jointly into account, Bogliacino and Pianta (2010), considering industries in 8 European countries in 1994-2004, found a positive employment impact of product innovation (which turned out particularly obvious in the high-tech manufacturing sectors). In addition, Bogliacino and Vivarelli (2012), covering 25 manufacturing and service sectors for 15 European countries over the time-span 1996-2005, found that R&D expenditures showed a job-creating effect, especially in high-tech industries. Interestingly enough, the labour friendly nature of R&D emerged in both their flow and the stock specifications. Finally, Piva and Vivarelli (2018) updated (1998-2011) the previous analysis and provided evidence of a labour-friendly impact of R&D expenditures. This positive employment effect appeared to be entirely due to medium and high-tech sectors, while no effect was detected in low-tech industries. Moreover, capital formation was found to be negatively related to employment suggesting the alleged labour-saving effect due to the ETC.

Summarizing the available sectoral evidence, a labour-saving tendency emerges in low- and medium- tech manufacturing, while a dominant labour-friendly impact has been detected in the high-tech manufacturing sectors and in the knowledge-intensive services, i.e. those sectors where product innovation is prevailing and demand is more dynamic.

Turning our attention to the firm-level studies, the empirical literature devoted to the microeconometric investigation of the link between technological change and employment is the most flourishing one. Starting from the UK, Van Reenen, back in 1997, matched the London Stock Exchange database of manufacturing firms with the SPRU innovation database over the period 1976–1982. Robust evidence of a positive employment impact of innovation emerged. Consistently, Blanchflower and Burgess (1998) confirmed a positive link between innovation (although roughly measured with a dummy) and employment using datasets for both British and Australian establishments. In France, an interesting analysis was conducted by Greenan and Guellec (2000) on more than 15,000 companies from manufacturing industries over the 1986-1990 period. According to this study, innovating firms created more jobs than non-innovating ones, but the reverse turned out to be true at the sectoral level, where the overall effect was negative and only product innovation revealed its job-creating nature. This controversial employment impact of innovation at the firm and sectoral level is likely to be due to the "business stealing" effect. Even taking the "business stealing" effect fully into account, in the case of Italy, Piva and Vivarelli (2004 and 2005) found evidence in favour of a positive effect of innovation on employment over the period 1992-1997. The authors provided evidence of a positive, although small in magnitude, impact of firm's gross innovative investments on employment. Furthermore, still in Italy, Hall et al. (2008), on a sample of Italian manufacturing firms over the period 1995-2003, found a positive employment contribution of product innovation, while no evidence of employment displacement due to process innovation was detected. As far as Germany is concerned, Lachenmaier and Rottmann (2011) - using a very comprehensive dataset of manufacturing companies over the period 1982-2002 - showed a significantly positive impact of different innovation measures on employment, but, partially in contrast with expectations and previous contributions, the authors found a higher positive impact of process rather than product innovations. Turning our attention to Spain, Ciriaci et al. (2016), using a dataset of more than

3,000 firms over the period 2002–2009, showed that innovative, smaller and younger firms were more likely to experience high and persistent employment growth episodes than non-innovative ones.
When moving outside Europe, Yang and Lin (2008), using data for almost 500 firms listed on the Taiwan Stock Exchange over the period 1999-2003, included four measures of innovation (R&D, patents, patents addressed to process innovation and patents addressed to product innovation). Their results pointed to a positive and significant employment impact of all the four technological proxies where the entire sample was tested, while process innovations revealed a labour-saving impact when low R&D-intensive industries were considered. In Colombia, Mejia and Granada (2014), who used data on manufacturing and services companies over the period 2007-2011, showed that the sales due to new products turned out to have a positive and significant employment effect. Interestingly enough, when manufacturing data were split into high and low-tech sectors, the labour-friendly nature of product innovation lost its significance in the low-tech industries. Finally, as far as the US are concerned, Coad and Rao (2011) focused on high-tech manufacturing industries over a long period (1963-2002) and investigated the impact of a composite innovativeness index (comprising information on both R&D and patents) on employees. The main outcome of their analysis was that innovation and employment were positively linked and innovation had a stronger impact for those firms that revealed the fastest employment growth.
Other more recent studies try to overcome a single-country dimension. For instance, Bogliacino et al. (2012) - using data of approx. 700 European manufacturing and service firms over the period 1990-2008 - found that a positive and significant employment impact of R&D expenditures was detectable in high-tech manufacturing and service sectors but not in the more traditional manufacturing sectors. Also dealing with European firms, Evangelista and Vezzani (2012) found, using data for six European countries, that the substitution effect of process innovation on employment was not statistically significant. Using firm level data

four European countries (Germany, France, UK, Spain), Harrison et al. (2014) put forward a testable model able to distinguish the relative employment impact of process and product innovations. The authors concluded that process innovation tended to displace employment, while product innovation was fundamentally labour-friendly. However, compensation mechanisms were at work, especially in the service sectors, and revealed to be particularly effective through the increase in the demand for the new products. More recently, Van Roy et al. (2015) estimated - covering almost 20,000 firms from Europe over the period 2003-2012 - that forward-citation weighted patents had a labour-friendly nature. However - interestingly enough and consistently with previous studies - this positive employment impact of innovation was statistically significant only for firms in the high-tech manufacturing sectors, while not significant in low-tech manufacturing and services. Finally, Dachs et al. (2015) investigated the employment impact of product innovation (proxied by the sales due to new products), process innovation (dummy) and organizational change (dummy) over the different phases of the business cycle. Using firm-level data from 26 European countries over the period 1998-2010, they found that product innovations were labour-friendly in all the phases of the business cycle, while process innovations and organizational change exhibited a labour-displacing nature during both upturn and downturn periods.

On the whole - although the microeconometric evidence is not fully conclusive about the possible employment impact of innovation - the vast majority of recent investigations provide evidence of a positive link, especially when R&D and/or product innovation are adopted as proxies of technological change and when high-tech sectors (both in manufacturing and services) are considered. A weaker evidence of a labour-saving impact of process innovation is also detected by some studies, especially when low-tech manufacturing is at the core of the analysis.

5. *Skill-bias Technological Change*

The "quality" of workers comes in as a critical variable due to the fact that new technologies ask for specific skills, creating different dynamics among different categories of workers. This is the "Skill-bias technological change" (*SBTC*). Initially proposed by Griliches (1969) and Welch (1970), the SBTC hypothesis is based on the idea that there is complementarity between new technologies and skilled workers, given that only the latter are able to implement effectively and efficiently those technologies. Therefore, a positive relationship between new technologies and skilled workers is expected (and generally confirmed); meanwhile a substitution effect between new technologies (especially when they determine process innovations) and unskilled workers is likely to happen.

When the skill dimension of employees is considered, the classification used is based on the educational level (tertiary education is the common threshold) or on the occupational level (white-collars, who do not undertake manual work, and blue-collars, who undertake manual work). Although correlated each other, the indicator based on education partly reflects the continuous increase in the supply of educated people, meanwhile the indicator based on occupations is more directly connected with the evolution of the demand for labour.

Overall, the strong empirical dimension of these studies start from the consideration that during the last three decades - while the ICT were rapidly spreading - OECD countries have been rapidly showing a significant change, both in the composition of the labour force and in the wage shares, in favour of the skilled component of the labour force (see, for instance, Nickell and Bell, 1995). In accordance with different institutional systems and specific degree of flexibility of the labor markets, economies were able to provide evidence of a dominant role either of the "employment effect" or the "wage effect". In particular, while in the continental European countries the increase in wage differentials between skilled and unskilled has been more limited, rapidly increasing wage differentials were recorded in the UK and in the US. Symmetrically, in the continental European countries - compared to UK and US - there has been a greater impact on employment figures, with higher unemployment levels partly caused by the reduction of the employment of the unskilled workers.

We present the extant literature focusing on the "employment effect", again grouping works together by its geographical focus and starting from the oldest ones. In general, skill is measured with occupation.

In France, Mairesse et al. (2001) - using firm level data for 1986, 1990 and 1994 - showed how the negative impact of ICT on less-qualified labor was robust in time-series. However, Goux and Maurin (2000) provided evidence of how an increased spread of new technologies explained only 15% of the change in labour demand between 1970 and 1993. In Italy, Casavola et al. (1996) used data for 36,000 Italian firms in the 1986-1990 time-span to study the effect of technological change on the labor demand and wages for skilled workers. They found that the wage difference between categories in Italy was lower than elsewhere, but that technological change had a positive effect on the employment of skilled workers. However, Piva and Vivarelli (2002) showed - on a sample of more than 400 manufacturing firms (1991-1997) - that the link between R&D and the skill-bias was not confirmed. The main explanation to drive upskilling was found in organizational rather than technological change. The role played by organizational change jointly with technological change was later investigated by Piva et al. (2005). Their results confirmed that upskilling was more a function of reorganizational strategy than a consequence of technological change alone. Moreover, some evidence of superadditive effects between the two changes emerged. Looking at Spain, Aguirregabiria and Alonso-Borrego (2001) used a panel of approximately 1,000 manufacturing firms. Using as technological variable a dummy on the "introduction of technological capital", the SBTC hypothesis was confirmed. In addition, in the Spanish case Luque (2005) – through a decomposition methodology – showed that the raise in the demand for skills came mainly from surviving firms increasing their skill-mixes in response to the re-tooling or upgrade in technology.

Furthermore, firms belonging to high-tech sectors accounted for the majority of the increase in the skill-mix.
Turning to more flexible labour markets countries, UK and US, results mainly confirm the SBTC hypothesis. In the case of UK, Machin (1996) – using both firm-level data and sector-level data – showed a positive relation both between the use of computers and skilled labor in the case of the firms and between R&D intensity, number of innovations produced and number of innovations used, and skilled labor in the sector analysis. His results were supported by a study by Haskel and Heden (1999) at firm-level (during the '80s) in which the positive relation between investment in computers and skilled labor was confirmed. In the US, Berman et al. (1994) analyzed the dynamics of 450 US manufacturing sectors. Their analysis showed how the shift in employment structure in favor of skilled workers was significantly determined by investments in computers and R&D. Autor et al. (1998) extended the previous study over a longer period, 1950-1990, also including non-manufacturing sectors, and confirmed the complementary relationship between investment in computers and the skill structure.
Finally, some authors tried to go beyond the national level. Machin and Van Reenen (1998) set up a dataset at the manufacturing-sector level for 7 countries (Denmark, France, Germany, Japan, Sweden, UK and US) and showed that the relative demand for skilled workers was positively linked to R&D expenditure. The robustness of the results was confirmed with reference to alternative statistical specifications. More recently, Los et al. (2014) proposed a new method to analyze the changing skills structure of employment based on 10 countries. They studied the relative importance of changes in technology, trade and consumption for the period 1995-2008 on skills. They provided evidence that the most important role has been played by technological change as the main culprit regarding downward pressure on employment of low-skilled and medium-skilled workers.
On the whole and at least till the overturn of the XX century, the evidence in favour of the skill-biased nature of new technologies is

robust and proved across different OECD countries, various economic sectors and different types of innovation.

6. *Task-biased Technological Change*

In the most recent years, a new employment trend - quite generalized and pervasive in developed countries - has emerged: an increasing job polarization together with a decreasing demand for middling occupation. This means that, if jobs are ranked by their initial wage, increases in employment share are observed at the bottom and top of this distribution, whereas those jobs that are in the middle have lost employment share over time. More in detail, laborers and elementary service occupations (the low-paying) are slightly increasing and the professionals ones (the high-paying) are considerably growing, while middling occupations (such as operators of machinery/electronic equipment) are declining. A U-shaped curve represents the polarization phenomenon (see McIntosh, 2013, for a survey).
This evidence has induced to revise the SBTC into the new "Task-biased Technological Change" (TBTC), assuming that the main cause of the polarization is the routine-nature of tasks. Repetitive tasks can indeed be easily replaced by recent technologies, while non repetitive tasks may grasp benefits from these technologies, determining a complementary effect. The falling cost of computing power of new potent technologies, such as artificial intelligence (AI) and machine learning, are additionally accentuating this trend. However, as suggested by Bessen (2018)[3], the overall effect might be that new technologies do not just replace labour with machines, but, in a competitive market, automation is able to reduce prices. In addition, technology may improve product quality, customization or speed of delivery. All of these phenomena might increase demand. If

[3] Bessen (2018) presents a model focusing on the impact of technology on employment. It is able to predict the actual labour demand - over a historical timeframe - reasonably well for cotton, automotive and steel. If results are extended to potential implications of AI, demand is sufficiently elastic and AI does not completely replace humans, then technical change will create jobs rather than destroy them. In this case, a faster rate of technical change will actually create *faster* employment growth rather than job losses.

demand increases sufficiently, employment (especially non-routine employment) may grow even if the labour required per unit of output declines. In a sense, this dynamics is the modern version of the "compensation theory" discussed in Section 2.

Therefore, "task" turns out to be more relevant than "skill" as it better captures the intrinsic nature of a job/occupation. Tasks are, therefore, classified in "routinized", when they can be expressed as a repetitive step-by-step procedure (a protocol), and "non-routinized", when there is more space for mental flexibility or physical adaptability. As a result, the nature of the task (routinezed or not) can be associated to either cognitive or manual activities. Routine tasks are largely located in the middle of the wage distribution.

Differently from the SBTC case, this degree of analysis is hardly applied to the company-level since databases with this detail of investigation are generally not available at micro-level[4].

Turning to the papers included in this section, a distinction is necessary as some of them emphasize the polarization itself assuming that technological change is the implicit driver of this phenomenon, others explicitly test the role of technological change.

There is evidence of "job polarization" especially in the UK (see Goos and Manning, 2007) and in the US (Autor and Dorn, 2009). To illustrate their results, and in particular their most surprising finding that employment was growing in the lowest level jobs, Goos and Manning (2007) listed the ten occupations that had seen the largest increases in employment share between 1979-1999, using Labour Force Survey data. This list was dominated by high-level jobs in business and finance, but in positions 1, 6 and 7, respectively, there were care assistants, education assistants and hospital assistants. Other studies have confirmed the results of Goos and Manning, using different datasets and studying slightly different periods. For example, Holmes and Mayhew (2012), for the 1981-2008 time-span, ranked jobs by early mean average pay, and then divided into deciles. They found that employment share grew in deciles 1, 9 and 10. A similar pattern of polarization has been observed in the US.

[4] However, Seamans and Raj (2018) argue for more systematic collection of info on the use of these technologies at the firm level.

Autor and Dorn (2009), using US census data over the period 1980-2005, showed the usual U-shaped curve, with positive changes in employment share observed up until the 15th percentile, and then from the 60th percentile upwards. Even in other institutional contexts, evidence of polarization has been provided. For instance, Spitz-Oener (2006) created her own 'Skill index', based on predicted levels of education, and ranked occupations - over the period 1979-1999 - in Germany into deciles on the basis of this index. She obtained similar findings to those in the UK and the US, with a rising employment share for deciles 1, 9 and 10. Kampelmann and Rycx (2013) extended the period under consideration to 1985-2008 and confirmed that the usual polarisation pattern remains over this longer period.

Recently, in a different institutional context, Adermon and Gustavsson (2015) showed that - between 1975 and 2005 - Sweden exhibited a pattern of job polarization with expansions of the highest and lowest-paid jobs compared to middle-wage jobs. Their estimates did not support TBTC for the 1970s and 1980s, but a stronger evidence, although not final, was found for the 1990s and 2000s. In particular, there was both a statistically significant growth of non-routine jobs and a decline of routine jobs.

Moving from the aggregate statistical evidence of polarization into more granular studies, the seminal contribution by Autor et al. (2003) has zoomed into the relationship between new technologies (mainly computers and ICT) and skills, sustaining indeed that innovations can replace human labour when it is mainly based on routines, but they can hardly replace non-routine tasks where technologies are complements, and not substitutes of the existing tasks. Thus, when the price of computing power fells - as it has done exponentially in recent times - routine jobs are the most at risk. In order to carry out their analysis, the authors defined the tasks involved in each one of the 450 occupations included the Dictionary of Occupational Titles. The tasks considered were classified according to one of five types: non-routine cognitive/analytic, non-routine cognitive/interactive, routine cognitive, routine motor (manual) and non-routine motor. Each occupation received a score for each of the task measures. The resulting scores were consistent with expectations (i.e., for example, the highest-scoring task amongst managers was non-routine cognitive/interactive, etc.). They then studied the evolution of the five tasks derived. Moreover, they measured technological change by the change in the fraction of workers in the industry who used computer in their jobs in the 1984-1997 time-span. Regressing the change in task involvement on the change in computer use revealed that technological change was positively related to the increased use of non-routine cognitive tasks. On the other hand, routine tasks (both cognitive and manual) were strongly negatively related to technological change. As far as non-routine manual tasks are concerned, they turned out to be unrelated to technological change until the 1990s, when a positive and significant relationship between them has emerged[5].

Considering multi-country studies, Michaels et al. (2014) undertook their analysis at the industry level in eleven countries (nine European countries, Japan and US). The dataset covered the 1980-2004 time span. The authors distinguished between high, middle and low-qualified individuals (correlated to more likely job tasks), and measured the wagebill share of each group within each industry-country-year observation. The main explanatory variable of interest is ICT capital. The results revealed a positive coefficient of ICT in the high-qualified workers, a negative coefficient of ICT in the mid-qualified equation, and a positive but insignificant coefficient in the low-qualified workers. Under the assumption that highly-qualified workers are employed in high skill level jobs, these results are consistent with the TBTC hypothesis. As much as recently, Goos et al. (2014) tested, beyond the TBTC hypothesis, offshoring and the global competition hypothesis in 16 Western European countries over the period 1993-2010. They found that changes in wages across occupations were not strongly related to the technology and

[5] In a more recent work in the US, Autor and Dorn (2013) extended the basic model to a spatial equilibrium setting, providing evidence of reallocation of low-kill workers from routine-task intensive occupations into service occupations (due to TBTC) and showing how service occupations co-locate with demanders of their services.

offshoring variables. However, they turned out to affect employment levels. Authors suggested that this result is due to labour market institutions that prevent flexibility of wages in many European countries, particularly at the bottom end of the wage distribution. Naticchioni et al. (2014), analyzing Europe overall, matching four different source covering the 1995-2007 time-span, showed how technological changes had an effect especially on polarization of jobs, but not on polarization of wages.

Even more recently, Marcolin et al. (2016a, b) put forward a study based on sectoral data from 2000 to 2011 for 28 OECD countries, split employees into four categories depending on the degree of routine intensity. The analysis relied on a new country-specific measure of their routine intensity built using individual-level information from the OECD Programme for the International Assessment of Adult Competencies (PIAAC) survey. A new routine intensity index (RII) was constructed using responses to four PIAAC questions. RII, which was calculated for countries, occupations and sectors in an independent fashion and at fairly disaggregated levels, was used to group occupations into four routine-intensity classes: non-routine, low routine-intensive, medium routine-intensive and high routine-intensive. In order to test the TBTC, ICT intensity, to proxy innovation, exhibited a positive correlation with employment levels in non-routine occupations, and a negative one with high routine-intensive occupations. Finally, Gaggl and Wright (2017), studied the short-run causal effect of ICT adoption on UK employment and wage distribution. Exploiting a natural experiment generated by a tax allowance on ICT investments, they found that the primary effect of ICT was to complement non-routine, cognitive-intensive work. They also showed that the ICT investments led to organizational changes that were associated with increased inequality within the firm. Finally, in an already very cited work of Frey and Osborne, recently published (2017), the authors, using a Gaussian process classifier applied to data from the US Department of Labor - predict that 47% of the occupational categories were at high risk of being automated, due to the routine-nature of their tasks, including a

wide range of service/white-collar/cognitive tasks such as accountancy, logistics, legal works, translation and technical writing.
As a summary, it is obvious that new technologies affect skills and tasks in all the economic sectors. However, a trend is detectable over time: in the first decades of the ICT revolution (since the late ‘70s to the late ‘90s) a SBTC impact has been obvious, especially with regard to manufacturing and production activities. Later (since the late ‘90s to nowadays) and especially in the world leading country (the US) the TBTC has emerged as a powerful driver of an increasing polarization of jobs and wages, involving both manufacturing and service sectors.

7. *Conclusions*

As the reader of this manuscript should be now aware, the relationship between innovation and employment is multifaceted, far from being a simple one. Technological change generates a direct impact and many indirect effects. In more detail, process innovation implies a labour-saving effect, while product innovation is generally labour friendly. However, process and product innovations are often interrelated and this is a first source of complexity.
On the one hand, together with their labour-saving impact, process innovations, even the most recent ones, involve decreasing prices and increasing incomes and these in turn boost an increase in demand and production that can compensate the initial job losses. However, these compensation mechanisms can be hindered by the existence of severe drawbacks and their efficacy is dependent on crucial parameters such as the degree of competition and the elasticity of substitution between capital and labour. On the whole, depending on the different economic contexts and phases of the business cycle, compensation can be more or less effective and the technological unemployment due to process innovation may only partially re-absorbed.
On the other hand, the job creating effect of product innovation may be more or less effective, as well. Indeed, the introduction of new products and the generation of new industries have to be compared

with the displacement of mature products. However, historically, the labour friendly nature of product innovation seems to be largely dominant. Indeed, most of recent studies provide evidence of a positive relationship between technological change and jobs. In particular, the job-creation effect is obvious when R&D and/or product innovation are adopted as proxies of innovation and when high-tech sectors (both in manufacturing and services) are considered. Whilst some evidence of a labour-saving impact of process innovation is also detected in few studies, especially when low-tech manufacturing sectors are considered.

Together with the quantitative employment consequences of technological change, its qualitative impact has to be taken into account. In particular, new technologies ask for specific skills, creating different dynamics among various categories of workers. Indeed, innovations are complementary to human capital and the "Skill-Biased Technological Change" hypothesis can be put forward. Furthermore and more recently, the SBTC hypothesis has been encompassed by the "polarization" dimension. According to this approach, new technologies tend to destroy routine jobs (also including some cognitive and middle-skill tasks), while creating opportunities in professional categories and skills which turn out to be novel and different from previous ones (also including personal services and manual jobs not necessarily characterized by a higher level of human capital).

On the whole, although theoretical economists keep on developing complex models about the employment impact of innovation, the economic theory does not have a clear-cut answer about the quantitative and qualitative employment effects of innovation. Indeed, the actual employment and skill impacts of the new technologies depend on the balance between process and product innovation, the values of the different parameters assessing the efficacy of the different compensation mechanisms, the institutional and legislative context and the particular skill-bias and task-bias of the considered technologies. Most of the literature points out that - while until the late '90s a SBTC impact has been obvious, especially with regard to manufacturing and production activities - more recently the task-biased technological change (TBTC, that is innovation destructive of routinized jobs) has emerged as a powerful driver of an increasing polarization of jobs and wages, involving all the economic sectors.

In terms of policy implications, evidence point out the likely destructive impact of innovation against the low-skilled, low-educated and routinized jobs. This means that policy makers should couple R&D and innovation policies with education and training policies, able to shape a safety net for those workers who are the most vulnerable to the adverse impact of technological change.

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