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The composite link between technological change and employment: A survey of the literature

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Abstract

The role played by technological change in employment trends has long been debated and investigated, but the evidence has proven to be inconclusive. This paper aims to shed light on this topic by critically reviewing a broad and heterogeneous body of literature on the employment implications of technical progress. To this purpose, it briefly discusses the main theories and models that underpin the empirical analysis and reviews the literature following two main criteria, namely, the proxy for technological change and the level of analysis. It also accounts for the effect of technical progress on both overall employment and on distinct occupational, educational and demographic groups. Particular attention is devoted to the results of some very recent studies that attempt to unfold the impact of complex automation technologies, especially robots, and to provide a preliminary account of the evolution, distribution, challenges and potential of Artificial Intelligence.

KEYWORDS

Artificial Intelligence, automation, employment, robots, technological change

1 | INTRODUCTION

Technological progress is widely regarded as a pivotal driver of economic progress, but throughout history, it has generated cultural anxiety. During the past two centuries, there have been periodic warnings that new technologies may cause a widespread substitution of machines for labor, which in turn could lead to technological unemployment and a further increase in inequality in the short run, even if the long-term effects can be beneficial. The best-known early example is the Luddite movement of the early 19th century, in which a group of English textile artisans protested against the automation of textile production by seeking to destroy some of the machines (Autor, 2015; Mokyr et al., 2015). In the end, the fears of the workers were not realized: the mechanization of the early 19th century could only replace a limited number of human activities and increased the demand for types of labor that were complementary to the capital goods embodied in the new technologies. Importantly, technological progress also took the form of product innovation and thus created entirely new sectors for the economy, a development that was neglected in the discussions of the economists of that time (Mokyr et al., 2015).

However, worries about the disruptive impact of automation would periodically surface in the course of the 20th century, especially during periods of economic slowdown and during great innovative waves, and have been recently renewed by the ongoing technological revolution, which is probably the very first one with such an accelerated pace and pervasiveness (Barbieri, Mussida, et al., 2019). The fears and skepticism about the latest outstanding technological advances have been amplified by anecdotal evidence in the popular press, but also by scientific publications. As an illustration, the widely discussed book, *The Second Machine Age*, by MIT scholars Erik Brynjolfsson and Andrew McAfee (Brynjolfsson & McAfee, 2014) offers a gloomy picture of the likely effects of automation on employment, and Frey and Osborne (2017) predict that almost half of total US jobs, including service/white-collar/cognitive jobs in accountancy, logistics, legal and financial services, trade and retail, could be automated over the next decade or two.

The impact of these studies on the policy debate has been significant: national policymakers, trade unions, entrepreneurs, and international economic organizations have started a lively discussion on the most appropriate actions designed to reap the benefits and to minimize the risks posed by such radical digital transformation. The discussion has also involved distinguished academic researchers, and entire issues of some high-profile academic journals (e.g., the symposium “Automation and Labor Markets” of the *Journal of Economic Perspectives* in 2015, and the issue “Technology and the Labour Market” of the *Oxford Review of Economic Policy* in 2018) have been devoted to it; however, there is still limited consensus about how and to what extent technical progress has affected and will affect labor.

The present paper aims to achieve a better understanding of the complex and multidimensional nexus between technological change and employment using a thorough survey that bridges different traditions and streams of research devoted to this topic. To this purpose, it presents the main theories and models underpinning the literature on the effect of innovation and technical change on employment and then reviews a considerable number of studies that have recently tackled the implications of disembodied technological change and/or technological change embedded in the capital inputs.¹ The literature under scrutiny, which is chiefly empirical, is reviewed following two main criteria, namely, the proxy of technological change and the level aggregation/unit of analysis.

This work adds to the extant surveys on the link between technological change and employment, in particular to the one carried out by Calvino and Virgillito (2018), from which it departs in

the following main respects: it primarily focuses on the effect of the *adoption* of new technologies; it devotes particular attention to the nascent but promising strand of research that explores the latest advances in robotization and digitalization, and to the first attempts to unravel the impact and potential of breakthrough technologies related to Artificial Intelligence (AI); it inspects the effect of technological change both on overall employment and on different categories of workers defined according to the task content of their occupation, their educational level or their demographic characteristics. In doing so, it complements and extends the review by Barbieri, Mussida, et al. (2019), who briefly summarize the Routine-Biased Technological Change (RBTC) literature and touch upon the employment implications of robots, automation and AI.

This study is organized as follows: Section 2 presents the theoretical background and briefly describes the compensation framework and the substitution framework with a focus on the RBTC hypothesis and the related task-based model; Section 3 examines the literature on the link between technological change and employment through the lens of the type of technical change and the level of aggregation; Section 4 summarizes the main considerations that emerge from the review and devotes more attention to the role played by the dimension under scrutiny (i.e., firm, sector, occupation, individual, country); Section 5 concludes.

2 | TECHNOLOGICAL CHANGE AND EMPLOYMENT: THE THEORETICAL BACKGROUND

2.1 | The compensation framework

Since its foundation, the economic discipline has stressed that the direct harmful effects of technological change on employment are counterbalanced in the long run by the indirect effects of market compensation mechanisms, which can operate at the sectoral or economy-wide level. Such mechanisms were condensed, during the first half of the nineteenth century, in a theory which Karl Marx later labelled “compensation theory.”

During the 20th century, the compensation theory was discussed and augmented with the contributions of different schools of thought. Freeman et al. (1982), Pianta (2005), Vivarelli (1995), and more recently, Vivarelli (2014) and Calvino and Virgillito (2018) have identified the following main mechanisms of compensation/job creation which are triggered by technological change, including the latest wave driven by new digital and automation technologies:

1. New machines: the introduction of new machines (e.g., robots) generates an increase of jobs in the machine-producing sector which offsets the labor displacement in the machine-using industry.
2. Decrease in prices: the increase in productivity due to the introduction of new technologies induces a reduction in the unit costs of production, which, in a competitive market, translates into decreasing prices; the latter, in turn, lead to higher demand, and therefore higher employment.
3. Decrease in wages: the workforce displacement leads to an excess of labor supply and then to a reduction in wages which, in the presence of free competition and full substitutability between labor and capital, can trigger an increase in the demand for labor.
4. New investments: in a world where competitive convergence is not instantaneous, innovative entrepreneurs can accumulate extra-profits in the gap of time between a cost decrease due to technological progress and a subsequent fall in prices generated by the former, and

subsequently invest these profits in physical capital, expanding the productive capacity and hence boosting labor demand.

5. Increase in incomes: when workers manage to appropriate gains from the increase in productivity, technical progress can lead to an increase in wages and consumption, which in turn prompts labor demand and then employment.
6. New products: when technological change takes the form of the creation and commercialization of new products, new economic branches develop, stimulating consumption, and additional jobs emerge.

The first four mechanisms are attributable to the classical and neoclassical schools, which embrace an *equilibrium perspective*, whereas the fifth and the sixth ones (“increase in incomes” and “new products”) have been put forward by the Keynesian-Schumpeterian tradition, which adopts a *disequilibrium perspective* (see Calvino & Virgillito, 2018 for a discussion). Additionally, mechanisms 1–5 compensate the initial labor-saving effect of process innovation (Vivarelli, 2014), most of which, as suggested by earlier prominent studies (e.g., Dosi, 1988; Nelson & Winter, 1982; Rosenberg, 1976) and confirmed by more recent microeconomic analyses (e.g., Conte & Vivarelli, 2005; Parisi et al., 2006) is implemented through investment in new machines and equipment, also known as “embodied technological change.” Conversely, mechanism 6, which is sometimes labeled “Schumpeterian mechanism,” captures the job-creating effect of product innovation and is mainly related to disembodied technological change.

Some studies have provided a conceptual framework and an empirical analysis of the employment effect of Information and Communication Technologies (ICT)-induced innovations taking into account both the labor-saving effect and the compensation mechanisms. Earlier contributions include the macroeconomic analyses of Vivarelli (1995) and Simonetti et al. (2000) (see Vivarelli, 2014, for a review).

Recently, Dosi et al. (2021) have presented a model that, using a partial disequilibrium perspective, accounts for both the labor-creating and the labor-displacing effects of technological change and identifies the different impacts attributable to the production (product innovation) versus the adoption (process innovation) of new technologies. Specifically, the model describes a two-sector vertically integrated economy in which the upstream sector produces new machinery and equipment (product innovation), while the downstream sector is the adopter of the machines themselves (process innovation). The vertical structure of the model directly highlights the labor-friendly nature of product innovation in the upstream sector (i.e., the “new products” mechanism), the potential labor-saving nature of process innovation in the downstream sector (the “new investments” mechanism), and the role of the “new machines” mechanism captured by the increasing production of machines in the upstream sector. Accordingly, the net employment effect of technical change depends on either its expansionary or its replacement (“scrapping”) nature, and also on the general macroeconomic conditions concerning aggregate demand, wage formation and the business climate affecting the investment decisions.

Unfortunately, the compensation arguments are subject to several limitations (see for instance Calvino & Virgillito, 2018; Dosi et al., 2021; Vivarelli, 2014, for a review) which hinder or even neutralize their ability to counterbalance the harmful effect of technological change. In particular, many aspects intertwine, such as macroeconomic and cyclical conditions, labor market dynamics and institutional aspects, undermining the possibility of any ex-ante exhaustive prediction about their relative efficacy (Calvino & Virgillito, 2018; Vivarelli, 2014). As an illustration, both the price and income compensation mechanisms can be more or less effective depending on the degree

of market competition, the demand elasticity, and the “animal spirits” and agents’ expectations, since the latter can delay the translation of additional profits and wages into effective demand (Bogliacino & Vivarelli, 2012). Conversely, the reduction of per-capita working time, the definition of social safety nets and proper union strategies would help alleviate the labor-saving effect of innovation (Pasinetti, 1981; Vivarelli, 2014).

Next, the potential “cannibalization” effect of new products on older ones may weaken the job-creation impact of product innovations (Barbieri, Mussida, et al., 2019; Calvino & Virgillito, 2018). Additionally, the relationship between technical change and employment is likely to be affected by the ongoing business cycle, as changing economic conditions, such as credit constraints, the opportunity cost of investing in innovation, and the appropriability and demand conditions, shape the innovation behavior of firms, which, in turn, affects their ability to generate jobs (Dachs et al., 2020; Peters et al., 2014).

Ultimately, the potential labor-saving impact of process innovation, the compensation mechanisms, the hindrances to the effectiveness of such mechanisms, and the labor-friendly nature of product innovation can combine in many diverse outcomes, and economic theory does not provide a clear-cut answer about the employment effect of technological change. Therefore, empirical evidence is crucial, but applied economists face relevant empirical challenges (Vivarelli, 2014).

For instance, it is typically complicated to separate the impact of technology from the impact of other factors, whose identification also depends on the level of aggregation (Barbieri, Mussida, et al., 2019; Vivarelli, 2014). In particular, firm-level studies, on the one hand, allow a direct and precise firm-level mapping of innovation both in terms of innovative inputs (R&D and/or ETC) and/or output; on the other hand, they do not allow determination of the net industry-level employment effect, since selection and competitive dynamics, such as “business-stealing” (i.e., firms which are relatively more innovative, efficient and dynamic could grow in terms of market share, and plausibly also in terms of employment, at the expense of less innovative firms), firm entry and exit, and the relocation of activities, which may lead to very different employment patterns at higher levels of aggregation, cannot be identified (Calvino & Virgillito, 2018; Dosi et al., 2021).

These trends become observable at the sectoral level of aggregation: industry-level studies can identify the overall effect of technological change, accounting for both its direct impact on innovating firms and the indirect effects that operate within the industry (Mastrostefano & Pianta, 2009). Notably, different sectors typically present distinct patterns of innovation and employment outcomes (Bogliacino & Pianta, 2010; Malerba, 2002; Mastrostefano & Pianta, 2009²), and a technology that can be regarded as product innovation in one sector (e.g., telecommunications) may represent a process innovation in another (e.g., manufacturing; Dosi, 1984; Dosi et al., 2021). Sectoral analysis is thus able to capture competitive dynamics and sectoral specificities, but, at the same time, does not provide the detailed overview of firm-level innovation and adoption of technology inputs offered by microeconomic studies and overlooks intersectoral linkages and complementarities and economy-wide compensation mechanisms, which would only be captured at a macroeconomic level. As a result, analyses performed at each level of aggregation offer a different piece of the puzzle (Calvino & Virgillito, 2018).

On the whole, it can be argued that the nexus between technical progress and labor is tangled and multifaceted, and that it is difficult to predict whether the compensation mechanisms overcompensate the labor-saving effect of technological change. However, a look at different levels of aggregation can help obtain a clearer and more complete picture of this phenomenon.

2.2 | The substitution framework and the bias of technological change: Skills versus tasks

In light of the limitations of the compensation framework, it is unlikely that the countervailing mechanisms will always be able to offset the labor displacement attributable to the adoption of innovative technologies. The economic theories and views that focus on the displacement effect fall within the realm of what Sabadash (2013) labels the substitution framework. The latter also includes pessimistic views of a “near-workless world” (Rifkin, 1995) which, in past decades, have been mainly fueled by public activists, political advisors with various educational backgrounds, technology journalists and software executives, but which have gained new momentum during the ongoing digital revolution (see for instance Ford, 2015 the popular book by Brinjolfsson & McAfee, 2014 and Benzell et al., 2016, theoretical model that predicts human obsolescence and labor immiseration).

Nonetheless, an extensive strand of literature has demonstrated that technological change substitutes only certain types of skills and tasks and that in doing so, displays heterogenous effects on different types of workers. Two main theories that scrutinize the so-called qualitative effect of technical progress have been put forward. The first one, which dominated the economic debate on this topic during the eighties and the nineties and is known as the Skill-Biased Technological Change (SBTC) hypothesis, posits that Information and Communication Technologies complement high-skilled/educated workers and replace low-skilled/low-educated workers. The second theory, which was advanced at the beginning of the new millennium and is generally referred to as the RBTC hypothesis, focuses on workers’ tasks, rather than on their education level, and postulates that ICTs substitute routine tasks and complement non-routine tasks. A brief discussion of the two aforementioned theories is provided below.

2.2.1 | The skill-biased technological change hypothesis

The nature of technological change has changed remarkably over time. In the 19th century, the introduction of machines in manufacturing allowed low-skilled workers to engage in the production of goods that previously required specific expertise in artisanal shops. Technology thus substituted high-skilled labor and complemented low-skilled labor. This pattern started reversing in the early 20th century, when advances such as the electrification of factories reduced the need for large numbers of unskilled manual workers, raising the demand for relatively skilled workers. Such complementarity between technology and skills was reinforced in the second half of the 20th century, with the widespread adoption of ICT and computer-based technologies (Goldin & Katz, 1998). Especially during the eighties, this demand for relatively skilled workers, coupled with an increase in the supply of (medium-)skilled relative to unskilled workers due to the rapid expansion of the education system, led to a process of skill upgrading in the overall economy and an increasing gap, in terms of wage and employment, between high-educated/high-skilled workers and low-educated/low-skilled workers (Katz & Murphy, 1992).

According to the SBTC hypothesis, these labor patterns were at least partly attributable to ICT-induced technical progress. The basic idea underlying this theory is that ICTs are “skill-biased,” namely, they increase the relative productivity of high-skilled workers, who are typically more able to use new technologies, and consequently increase their relative labor demand, compared to low-skilled workers (Katz & Murphy, 1992; Tinbergen, 1974).

The intellectual foundation of this literature, which is mainly empirical (Vivarelli, 2014), was conceptualized by Acemoglu and Autor (2011) in the so-called canonical model. This framework includes two skill groups defined according to the level of education (for instance, workers without a college degree vs. workers with a college degree) performing two distinct and imperfectly substitutable task groups or producing two imperfectly substitutable goods: any given job is assigned to a certain category, and workers from the other category cannot perform it (i.e., a job is either a high or a low skill job). Thus, technology, which takes a factor-augmenting form, complements either high- or low-skilled workers. In conclusion, the canonical model predicts a positive monotonic relation between skills and employment growth. The implication is that we should observe an increase in employment for high-skilled individuals, while the low-skilled ones would suffer employment losses and, if demand shifts faster than supply, we would see also rising wage premia for higher skills. In other words, ICT complements high-skilled labor and substitutes low-skilled workers (Sebastian & Biagi, 2018).

The SBTC hypothesis has been proved empirically adequate in accounting for the trend in the skill premia and employment experienced by the United States and other OECD countries especially during the seventies and the eighties (see the influential study by Katz & Murphy (1992), and a number of relevant contributions that summarized and extended the large subsequent literature, such as: Acemoglu, 2002; Acemoglu & Autor, 2011; Autor et al., 1998; Goldin & Katz, 2008; Katz & Autor, 1999). However, it presents several limitations.

First, the SBTC hypothesis cannot properly explain the fall in employment in middle-skilled jobs and the increase in high-skill and low-skill occupations, a phenomenon typically referred to as job polarization, observed during the nineties in the US, as well as in some European economies, including the UK (Autor et al., 2006; Goos & Manning, 2007; Goos et al., 2009; Wright & Dwyer, 2003).

In addition, although the SBTC argument was often used to explain rises in wage inequality, the literature has identified a range of determinants, including trade and institutional factors (in particular, labor market institutions), thus pointing to a less pronounced potential contribution of technological change to this trend compared to the one implied by the SBTC framework (e.g., Beyer et al., 1999; Fortin & Lemieux, 1997; Hacker & Pierson, 2011; Kristal & Cohen, 2017; Lee, 1999; see also the surveys on the determinants of income inequality recently conducted by Kurokawa, 2014, and by Nolan et al., 2019). Besides, Kurokawa (2014) asserts that most of the empirical studies on SBTC have ignored the intersectoral linkages that operate through the use of intermediate products, and the related intersectoral technology-skill complementarity (since, as shown by Voigtländer, 2014, the skill upgrading in one sector goes hand-in-hand with increasing skill demand in many other sectors because of these linkages).

Moreover, the SBTC setting marks the correlation between technological change and labor demand, without explaining the cause or mechanism behind the relative shift in productivities and the higher demand for educated workers (Autor et al., 2003; Lauder et al., 2018).

Importantly, it relies on a simplistic classification of skilled and unskilled jobs where skills are identified by the level of education, while the relevance of tasks and their relationship with skills are neglected (Sebastian & Biagi, 2018). In particular, since the augmented factor, either capital or labor, becomes uniformly more productive in all tasks, potentially important changes in the task content of production are not accounted for (Acemoglu & Restrepo, 2019b; for a more exhaustive discussion on the SBTC hypothesis and its drawbacks, see Lauder et al., 2018). The distinction between skills and tasks becomes particularly relevant in the ICT era, when workers of a given skill level can change the set of tasks that they perform in response to changes in technology and organization of production (Sabadash, 2013). For these reasons, from the early 2000s, a growing

number of researchers have investigated how the task content of jobs helps explain the effect of technological change on labor demand.

2.2.2 | The routine-biased technological change hypothesis and the task-based approach

Autor et al. (2003) propose a nuanced version of the SBTC hypothesis, known as the RBTC, that relaxes the one-to-one mapping between skills and tasks and operationalizes the way technology affects the labor market through the job tasks performed. According to Acemoglu and Autor (2011, p. 1045), who refine Autor, Levy and Murnane's framework, a task is defined as a "unit of work activity that produces output (good and services)," whereas a skill is a "worker's endowment of capabilities for performing various tasks."

Autor et al. (2003) classify job tasks according to a two-dimensional typology, namely, routine as opposed to non-routine, and manual as opposed to cognitive; this leads to four broad categories of occupational task inputs, that is, non-routine cognitive (in turn, subdivided into non-routine cognitive interactive and analytical), non-routine manual, routine cognitive and routine manual. The model predicts that, faced with an economic-wide decline in the price of computer capital, industries and occupations that are initially intensive in labor input of routine tasks make relatively larger investments in computer capital; subsequently, they reduce the labor input of routine tasks, for which computer capital is substituted due to the increasing ability of machines to perform routine tasks, and increase demand for non-routine task input, which computer capital complements. Accordingly, unlike the SBTC framework, this model implies that computerization has a non-linear effect on labor demand. To test these predictions, Autor, Levy, and Murnane pair representative data on job task requirements from the Dictionary of Occupational Titles (DOT) with samples of employed workers from the Census and Current Population Survey to form a consistent panel of occupational task inputs over the four-decade period from 1960 to 1998.

The RBTC hypothesis may rationalize the documented patterns of polarized job growth observed in the US and other advanced countries (e.g., Autor et al., 2006; Goos & Manning, 2007; Goos et al., 2009). Intuitively, as jobs that are intensive in either non-routine cognitive or non-routine manual tasks are generally found at opposite ends of the occupational skill spectrum, whereas jobs that are intensive in routine skills are often middle-paid, computerization may rationalize the documented patterns of polarized job growth.

2.2.3 | Further developments of the task-based model

A number of subsequent contributions enrich and extend the task-based approach originally proposed by Autor et al. (2003). Autor et al. (2006) develop a model of computerization in which computers complement abstract (i.e., non-routine cognitive) tasks, substitute routine tasks and have little impact on (non-routine) manual tasks, and use it to explain the polarization patterns observed in the US labor market. Autor and Dorn (2013) build a general equilibrium model of "routine-task" replacing technological change and extend it to a spatial equilibrium setting where local labor markets have differential degrees of specialization in routine-intensive industries. Then, drawing on Autor, Katz, and Kearny's task classification, they build a Routine Task Intensity (RTI) indicator and use it to estimate the degree of routinization at local labor market

level, pioneering a relevant strand of literature aimed at assessing the patterns of occupational task content in local labor markets or similar constructs.

Building on Autor and Dorn (2013), Goos et al. (2014), and Gregory et al. (2019) elaborate and test a task-based setting that, focusing on aggregate labor outcomes rather than on relative ones, distinguishes between tradable and non-tradable goods in order to model the spatial reallocation of labor demand resulting from RBTC. It identifies three channels through which RBTC impacts aggregate labor demand: a negative substitution effect, as declining capital costs incentivize firms in the high-tech tradable sector to substitute capital for routine labor inputs and to restructure production processes towards routine tasks; a positive product demand effect, as declining capital costs reduce the price of tradables; a positive product demand spillover effect (i.e., the generation of product demand spillovers in the non-tradable sector), as the increase in product demand raises local incomes, which are partially spent on low-tech non-tradables. Hence, the final effect of RBTC on aggregate labor demand depends on the size of these three forces.

In recent years, the task-based approach has served as the starting point of a rapidly growing line of research that estimates the susceptibility to automation, or job automatability (namely, the risk or probability that an occupation is displaced by machines in the near future) of different occupations. Specifically, in their seminal study, Frey and Osborne (2017) revise Autor, Levy, and Murnane's model to enable computer capital to rapidly substitute for labor also across a wide range of non-routine tasks. In so doing, they identify three sets of job tasks (i.e., creative intelligence, social intelligence, and perception and manipulation tasks) which are supposed to have a low risk of automation due to the presence of engineering bottlenecks. Then, using data from O*Net and the US Department of Labor and with the support of a Gaussian process classifier, they classify 702 detailed US occupations according to their probability of computerization, which is based on the degree to which those bottlenecks persist.

However, Arntz et al. (2016) contend that Frey and Osborne's probabilistic classification model does not account for the fact that it is typically a task, rather than a whole job, that is automated or not, and that an occupation comprises a variety of tasks. In light of these considerations, Arntz et al. (2016, 2017) and other researchers (e.g., Brussevech et al., 2019; Dabla-Norris & Khalid, 2019; Dengler & Matthes, 2018; Egana del Sol, 2020; Filippi & Trento, 2019; Nedelkoska & Quintini, 2018; Stephany & Lorenz, 2019) estimate the job susceptibility to automation in several countries using a task-based approach, which makes it possible to capture within-job, between-task heterogeneity, and, as a result, typically produces less pessimistic figures.

Finally, the task-based framework also underpins Acemoglu and Restrepo's (2019b) comprehensive model of the complex interactions between machines and humans, which provides a sound theoretical background to the recent but fast-growing body of literature on the labor impact of robotization. Building upon Acemoglu and Restrepo (2018a), as well as on Acemoglu and Autor (2011), Acemoglu and Restrepo (2019b), Autor et al. (2003) and Zeira (1998) identify three classes of technological advances: automation, which corresponds to "the development and adoption of new technologies that enable capital to be substituted for labor in a range of tasks" (Acemoglu & Restrepo, 2019b, p. 30), such as robots (see Acemoglu & Restrepo, 2020); the introduction of new tasks in which labor has a comparative advantage, as automation has historically been accompanied by other technological developments that generate employment opportunities in new occupations; factor-augmenting technological improvements, which make labor or capital uniformly more productive in all tasks.

The authors illustrate how each of these classes affects labor demand. First, an increase in automation in a given sector exerts contrasting effects on aggregate labor demand: a negative displacement effect, as automation directly displaces workers in the tasks now performed

by technology; a positive productivity effect, as automation causes a reduction in the cost of production and an increase in the sectoral value-added, which in turn raises the demand for labor from non-automated tasks; a composition effect, which captures the reallocation of value-added across sectors, and which contributes positively to aggregate labor demand if the expanding sector has a higher labor share than the contracting sector. Second, since workers are reinstated into new tasks, the introduction of new tasks is associated not only with a productivity effect, but also with a *reinstatement effect*, which has positive implications both for labor demand and labor share. Finally, in contrast to automation and new tasks, factor-augmenting technologies affect labor demand mostly via the increase in productivity, and secondly via a substitution effect that influences the labor share but does not alter the task content of production.

All in all, Acemoglu and Restrepo's (2019b) study suggests that the sign and the magnitude of the effect of technological change on labor significantly depend on the class of technological advances under study and the relative weight of different, sometimes contrasting, forces. The level of aggregation matters as well; for instance, the composition effect can be identified only in a multisector setting. The type/proxy of technological change and the level of analysis represent the two criteria through which the empirical literature is reviewed in this study.

2.2.4 | The limitations of the RBTC hypothesis and the task-based approach

Even though the RBTC hypothesis and the task-based approach have helped shed light on the complex and multifaceted link between technological change and labor, they present some relevant limitations.

In their review of the RBTC literature, Sebastian and Biagi (2018) summarize some conceptual, operational and empirical challenges, some of which had been previously identified by Fernández-Macías and Hurley (2014, 2017), Matthes et al. (2014). The first relevant conceptual issue arises when trying to capture the concept of routine tasks, which, in the RBTC model, are defined as codifiable tasks that can be performed by machines. However, what is perceived as routine for workers may not be so from the perspective of machine execution. To give an example, Matthes et al. (2014) argue that, even though it implies the repetition of the same basic activities and might be considered as routine from the worker's perspective, driving a motor vehicle is often regarded as a non-routine task because it also requires the use of some skills for which humans typically have (at least so far) a comparative advantage. Another conceptual problem lies in the fact that the RBTC framework implies that the dimensions of routine and cognitive tasks are distinct, whereas they are strongly linked both conceptually and empirically (see Fernández-Macías & Hurley, 2017, for a discussion).

An additional relevant issue is the relationship between the definitions of tasks and the operationalization of the theoretical concepts. Indeed, as the RBTC approach does not provide a unique framework for data analysis, not only is the classification of tasks into different typologies inconsistent between the original work by Autor et al. (2003) and following papers, but also the choice and the number of variables used to create task indices are often completely arbitrary (Sebastian & Biagi, 2018). In particular, some authors (e.g., Caines et al., 2018) adopt categorizations based on the degree of task complexity (namely, the extent to which an occupation relies on tasks involving higher-order skills, such as the ability to abstract, solve problems, make decisions, or communicate effectively) rather than on the degree of routinization, or taxonomies that partly depart from the RBTC framework (for instance, Fernández-Macías & Hurley, 2017 use, together with an RBTC-related cognitive index and a routine index, an indicator of social interactions).

Moreover, Sebastian and Biagi report some misalignments in the measurement of the same category. For example, the category of “non-routine manual” is measured as “hand-eye-foot coordination” by Autor et al. (2003), Goos and Manning (2007), and Goos et al. (2014), as “time spent performing physical activities” in Autor and Handel (2013), and as “repairing or renovating houses/apartments/machines/vehicles, restoring art/monuments, and serving and accommodating” in Spitz-Oener (2006).

With regard to data-related concerns, on the one hand, self-reported sources allow for studying the variability in task content within each occupation or job type, which cannot be studied using occupational databases based on the assessment of experts such as O*Net. On the other hand, self-reported sources are prone to introducing potential bias in the measurement, which tends to be lower in occupational databases.

Beyond the aforementioned issues, a broad limitation of the literature on routine-biased technological change is its technical and deterministic view of the economy, which is seen as a mechanical process of transforming inputs into outputs. As Fernández-Macías and Bisello (2020) point out, such a deterministic perspective, according to which a task will be performed by the cheapest factor, neglects the key role played by human agency in shaping tasks and production and service provision processes at the workplace level and lacks a proper account of the social and organizational aspects of this provision.³ In light of these considerations, and partly drawing on the previous literature, the authors propose a taxonomy of tasks which aims at connecting the substantive content of work with its organizational context, and which classifies tasks along two axes that are conceptually different: one refers to the content of tasks, namely, the “what” of a work activity, whereas the other one refers to the methods and tools used at work, namely, the “how.”

The approach proposed by Fernández-Macías and Bisello has some similarities with the perspective that comes from the evolutionary theory of technical change and the capability-based theory of the firm, according to which the space of human intervention in the production process is regulated not only by the pace of technological change, but also by organizational routines (Dosi & Nelson, 2010; Staccioli & Virgillito, 2021b). A nondeterministic perspective on technology also characterizes a number of recent fieldwork analyses, which stress the role of the interplay between technological and organizational changes in the transformation of human-machine relations (see Section 3.2.3). Finally, the role of organizational change in affecting labor demand together with technological change is the main object of a separate strand of empirical literature (see, for instance: Aubert, Caroli & Roger, 2014; Behagel, Caroli & Roger, 2016; Beckmann & Schauenberg, 2007; Caroli & Van Reenen, 2001).

3 | LITERATURE REVIEW

This section reviews a significant amount of recent empirical studies on the link between technological change and employment, grouped according to the selected proxy of technical progress. Specifically, Section 3.1 summarizes the literature on the link between disembodied technological change, proxied by Research & Development (R&D), and employment, and briefly recalls a related body of literature that, mainly drawing upon survey data, relies on specific indicators of both product and process innovation. Section 3.2 covers a large and composite strand of literature that examines the employment effect of ICT and computers (3.2.1), robots (3.2.2), and a variety of automation and digital technologies (3.2.3). Section 3.3 reports preliminary evidence on the

impact and potential of AI. When possible, the level of aggregation and both the quantitative and qualitative effect on employment are taken into account.

3.1 | R&D and disembodied technological change

Expenditures and investments in R&D represent an innovation input and mainly capture product innovation, which has typically a job-creation effect related to the introduction of new products. All in all, the extant literature has reported evidence of a positive impact of R&D and product innovation on employment, especially when the analysis is conducted at the firm level. Examples of firm-level studies that detect such positive average effect are Stam and Wennberg (2009) (in start-up Dutch firms), Coad and Rao (2011) (in US high-tech manufacturing firms), Bogliacino et al. (2014) (in publicly traded European firms), Pellegrino et al. (2019) (in Spanish manufacturing firms), Barbieri, Piva, et al. (2019) (in innovative Italian firms), Mitra and Sharma (2020) (in manufacturing firms operating in developing countries). However, this labor-friendly effect seems to be mainly attributable to firms with certain characteristics, such as high-tech (e.g., Pellegrino et al., 2019; Stam & Wennberg, 2009), fast-growing (e.g., Coad & Rao, 2011; Stam & Wennberg, 2009) and large (Barbieri, Piva, et al., 2019), operating in services and high-tech manufacturing (e.g., Barbieri, Piva, et al., 2019; Bogliacino et al., 2014).

In addition, the job-creating effect of disembodied technological change is likely to be overestimated due to the inability of firm-level studies to account for selection and competitive dynamics, such as “business-stealing” (see Section 2.1). When a multisector perspective is adopted, the results on the employment effect of technical progress are more mixed; in particular, the labor-friendly impact generally dominates in high-tech manufacturing sectors and knowledge-intensive services, namely, those sectors where product innovation prevails and the demand evolution is more dynamic; on the contrary, the labor-saving tendency is relevant especially in low- and medium-tech manufacturing, low-value-added downstream sectors. Examples of industry-level analyses are the ones conducted by Bogliacino and Vivarelli (2012) (in manufacturing and service sectors of 15 European countries), Piva and Vivarelli (2018) (in manufacturing and service sectors of 11 European countries), Mitra and Jha (2015) (in 11 Indian industries), Ciarli et al. (2018) (in the local labor markets of the UK), and Dosi et al. (2021) (in manufacturing and service sectors in 19 European countries).

While the abovementioned firm-level and sectoral studies investigate the quantitative effect of R&D, a number of contributions focus, instead, on the qualitative effect. Evidence that an increase in disembodied technological change is associated with a rise in the relative demand of high-skilled/high-educated workers is provided, for instance, by: Sasaki and Sakura (2005, for Japan, at industry level); Majid (2008, for a sample of advanced countries), Meschi et al. (2011 and 2016, in Turkish manufacturing firms); Araújo et al. (2012, in Brazilian manufacturing firms). Moreover, Sharma and Mitra (2020) analyze both the quantitative and qualitative effect of technological change on employment. Some studies (i.e., Araújo et al., 2012; Meschi et al., 2011; Meschi et al., 2016; Mitra & Jha, 2015; Mitra & Sharma, 2020) focus on developing economies. However, the quantitative or qualitative effect of technological change in these countries is generally also (or mainly) attributable to the so-called import-related technological change (see for instance Conte & Vivarelli, 2011; Meschi et al., 2016; Mitra & Sharma, 2020).

The adoption of R&D to proxy for technological change and innovation may imply an “optimistic bias” in terms of its employment impact, and a partial assessment of technical progress, since the latter is mainly embodied in capital investment, especially in firms and sectors that

conduct very limited or null in-house R&D activity (Pellegrino et al., 2019). Accordingly, Barbieri, Piva, et al. (2019), Dosi et al. (2021), Pellegrino et al. (2019), Piva and Vivarelli (2018) account for both R&D and embodied technological change (ETC), and find some evidence of a labor-saving effect of technological advances incorporated in capital formation.

The juxtaposition between product innovation and process innovation also emerges in a number of firm-level and sectoral studies (e.g., Hall et al., 2009; Harrison et al., 2014; Lachenmaier & Rottmann, 2011; Peters et al., 2014), which, generally drawing upon innovation surveys, such as the Community Innovation Survey (CIS), compute an indicator of product innovation and an indicator of process innovation (or related constructs, such as the indicators of cost competitiveness and technological competitiveness proposed by Bogliacino & Pianta, 2010) and gauge the role played by each of these two macro-categories of innovation outputs in employment dynamics.

A considerable number of empirical contributions that assess the implications of innovation related to products, processes, or organizational arrangements are reviewed by Calvino and Virgillito (2018); additional related studies, published in 2019 in the Special Section “Innovation and employment” of *Industrial and Corporate Change*—Volume 28 (which also includes two articles covered in this survey, i.e., Breemers et al., 2019; Barbieri, Piva, et al., 2019) are briefly summarized by Dosi and Mohnen (2019). In line with the results of the articles reviewed in the present section, this broader body of literature points to an overall positive effect of product innovation and a more ambiguous effect of process innovation.

To sum up, R&D expenditures, which are mainly associated with product innovation and the so-called disembodied technological change, generally have a positive effect on the level or growth of employment. However, this is mainly attributable to some firms (especially large, dynamic innovative firms) and to some sectors (in particular, medium-tech and high-tech sectors). In addition, the positive employment effect of disembodied technological change may be at least partially counterbalanced by the potential labor-saving behavior of ETC, which, instead, is mainly related to process innovation.

3.2 | Technological change embodied in the capital inputs

3.2.1 | Computers and ICT

A vast strand of literature has investigated the employment consequences of the adoption of computers, or, more in general, of ICTs,⁴ which, since the eighties, have experienced great diffusion and advancement. As the “quality” of workers has turned out to be a critical variable (indeed, new technologies ask for specific skills/tasks, and then create different dynamics among different categories of workers; Barbieri, Mussida, et al., 2019), in the last few decades a considerable number of articles have investigated the qualitative effect of ICT-based technological change on employment.

The SBTC literature aiming to assess the skill premia (in terms of employment and especially of wages) associated with technological change mainly flourished during the nineties and the first years of the 2000s, and has already been extensively discussed and reviewed; for these reasons, it is not analyzed in this work. Rather, during the last 15 years or so, a considerable body of literature has embraced the so-called RBTC hypothesis and has adopted a task-based approach to gauge the implications of computerization on some labor outcomes.

In line with the theory, several studies suggest that RBTC has contributed to labor market polarization in various countries and at different levels of analysis. Evidence of changes in the

occupational employment shares that can rationalize this phenomenon has been reported, for instance, by: Akcomak et al. (2013) in the UK and the Netherlands; Kampelmann and Rycx (2013) in Germany; Bisello (2013) in the UK; Adermon and Gustavsson (2015) in Sweden; Sharma (2016) in India; Fonseca et al. (2018) in Portugal; Kim et al. (2019) in South Korea. Conversely, both Guarascio et al. (2018) and Basso (2019) argue that evidence of labor polarization and the role played by RBTC in driving recent labor dynamics in Italy is mixed.

Importantly, some researchers (e.g., Akcomak et al., 2013; Consoli et al., 2019; De La Rica & Cortazar, 2016; Ross, 2020; Spitz-Oener, 2006) resort to detailed individual-level measures of tasks to also account for within-occupation task heterogeneity and variations over time and show that RBTC has caused not only changes in employment across occupations (i.e., the extensive margin) but changes in the task content of the occupations (i.e., the intensive margin) as well.

Labor polarization has also been investigated at the within-industry and between-industry level. As an illustration, Goos et al. (2014) demonstrate that job polarization in 16 Western European economies in the period 1993–2010 occurred both within a certain industry and across different industries, and that the RBTC hypothesis explains both overall job polarization and its within-industry and between-industry components as well. Moreover, other contributions (e.g., Autor & Dorn, 2013; Autor et al., 2015; Charnoz & Orand, 2017; Consoli & Sánchez-Barrioluengo, 2019; Dauth, 2014; Moreno-Galbis & Sopraseuth, 2014; Senfleben-König & Wielandt, 2014) have analyzed employment trends in local labor markets or similar geographical units, which have generally experienced a reallocation of employment towards non-routine occupations, especially in the service sector.

The computer-driven shift in the skill/task content has also favored employment or the creation of new job titles in cities, especially in cities with higher shares of connected tasks (which require proximity) and with endowments of analytical and interactive skills (see Dauth et al., 2014, for Germany; Kok & ter Weel, 2014, and Berger & Frey, 2016 for the US). A few RBTC studies focus, instead, on firms, and find some evidence of employment polarization between firms and even within the same firm (e.g., Cortes & Salvatori, 2015, in the UK; Kerr et al., 2020 and Böckerman et al., 2019 in Finland).

While the aforementioned RBTC studies look at the amount of employment/labor demand of different demographic and occupation groups, other studies (e.g., Apella & Zunino, 2017; Bachmann et al., 2019; G. Peng et al., 2018; Ross, 2020) scrutinize changes in the employment status and job-to-job transitions. Their results tend to confirm that the degree of non-routine (routine) task content is related to positive (negative) employment outcomes. Interestingly, Ross (2020) also shows that the negative impact of a rise in within-occupation routine intensity is concentrated during periods of economic turmoil, stressing the fact that business cycle conditions can influence the link between technological change and employment.

Finally, some studies investigate the effect of routine-replacing technological change in developing economies, either in a single country (e.g., Sharma, 2016), or in a sample that includes both developing and advanced economies. For instance, Das and Hilgenstock (2018) argue that developing economies are on average significantly less exposed to routinization than their developed counterparts, but exposures have been steadily converging between the two, and Reijnders and de Vries (2018) assert that technological change increases the number of non-routine relative to routine occupations in all countries. All in all, evidence of RBTC is found in developing countries as well.

Most of the contributions in the RBTC literature use, as the key regressor, one or more indicators of task content, where changes are attributable to technological advances.⁵ Michaels et al. (2014), on the other hand, suggest examining ICT-based theories of job polarization by employing direct

measures of ICT capital. The authors, who test the hypothesis that ICTs polarize labor in the industries of nine European countries, the US and Japan, adopt an approach that bridges the SBTC framework and the task-based perspective of the RBTC literature and find that, consistently with ICT-based polarization, industries with faster ICT growth shifted demand from middle-educated workers to highly educated workers during the period 1980–2004. A similar approach is pursued, at firm level, by Akerman et al. (2015), who report that broadband adoption in Norwegian firms complements skilled workers in executing nonroutine abstract tasks, and substitutes for unskilled workers in performing routine tasks.

The link between computerization, proxied by a direct ICT measure, and job polarization is also explored by a number of studies that do not apply a task-based approach, such as: Massari et al. (2015), who find a nexus between ICT intensity and between-industry job polarization in Europe during the period 1995–2007; Breemersch et al. (2019), who, looking at the main determinants of between-industry and within-industry polarization, argue that, in European manufacturing industries ICT adoption explains a third of within-industry polarization (while Chinese net import competition contributed to a much smaller extent), whereas the process of between-industry polarization is driven by widespread deindustrialization and servitization in developed countries; Harrigan et al. (2020), who investigate trends in labor polarization at different levels in the French private sector and proxy ICT intensity with the employment share of the “techies,” namely, workers with STEM (Science, Technology, Engineering, and Math) skills. Indeed, “because of their central role in planning, installing and maintaining ICTs and other technologies, as well as in training and assisting other workers in the use of technology, they constitute the crucial link between economy-wide technological progress and firm-level technology adoption” (Harrigan et al., 2020, p.2). According to their results, aggregate polarization in France was driven mostly by changes in the composition of firms within industries (as firms that were intensive in middle-wage jobs grew more slowly than firms intensive in high and low wage occupations), and occurred mostly within urban areas. These findings stress the importance of accounting also for more disaggregated levels of analysis to properly study this complex phenomenon.

In addition, some researchers also investigate how ICT-driven technological change affects workers of various ages, especially older workers (e.g., Aubert et al., 2006; Autor et al., 2015; Beckmann & Schauenberg, 2007; Behaghel et al., 2014; Biagi et al., 2013; F. Peng et al., 2017; Schleife, 2006), or consider gender-specific employment trends (e.g., Autor et al., 2015; Lindley, 2012; Senfleben-König & Wielandt, 2014). More information on the role of age and gender in the link between technological change and employment is provided in Section 4.2.

While the aforementioned articles look at the impact of technological change on different types of workers/occupations, others investigate its net effect at different levels of aggregation. One of the most comprehensive firm-level analyses has been conducted by Pantea et al. (2017), who analyze the short-run labor substitution effects of firm-level ICT adoption in seven European countries during the period 2007–2010; the authors find no evidence that ICT substitutes labor in the short run, as its increased use within firms neither increases nor reduces the numbers of workers they employ. Some multisectoral contributions at the national level (e.g., Matteucci & Sterlacchini, 2003, for Italy, Gallipoli & Makridis, 2018, for the US) document an ICT-related decline in the manufacturing industries which is accompanied by an employment increase in services, especially in dynamic and innovative sectors.

Concerning country-industry studies, the extensive analysis conducted by the European Commission (2014) on the effect of ICT on employment in the EU fails to provide evidence of either a systematically positive or a systematically negative long-term effect of ICT on employment, either

among sectors within a single country or across countries in a single sector, especially when labor and product market regulations are accounted for.

In a similar vein, Breemersch et al. (2019) posit that a large part of the overall decline in employment that occurred in Europe, especially in low-polarized industries, is not ascribable to ICT adoption or R&D intensity, but to competition with net Chinese imports. Autor and Salomons (2018) test the labor-saving effect of technological change in 28 industries of 18 OECD countries from 1970 using a broad proxy, namely TFP growth (also instrumented by foreign patents and robot adoption) and show that technical progress has lately reduced the labor share but has not been employment-displacing.

Within the task-based literature, Gregory et al. (2019) report that the substantial decrease in labor demand and employment resulting from the substitution of capital for labor over the years 1999–2010 in 238 regions across 27 European countries has been overcompensated by the positive product demand effect and its spillovers to the non-tradable sector. The authors also highlight that the distribution of the gains from technological progress is critical for the size of the overall labor demand and employment effects (indeed, in the scenario in which only wage income flows back into local product demand, whereas the rising non-wage income is not accounted for, the positive aggregate labor demand effect is only half as large), and in doing so they stress the importance of the debates about who owns the capital (Freeman, 2015).

To conclude, this heterogenous strand of literature suggests that, all in all, ICT-driven technological change has not caused a net negative effect on employment, but has led to significant changes in the occupational composition and task specialization of employment across industries, across cities, across firms operating in the same industry, and possibly within firms as well; in doing so, computerization has contributed to the increase in labor market polarization in various countries. In addition, there is some evidence that technological change is age biased.

However, most of the studies under scrutiny rely on broad or indirect proxies of technological change which are likely to capture a heterogenous array of technologies, and which do not allow us to properly understand which ones drive the employment effects under investigation. In particular, machine-based technologies are likely to have a stronger impact on workers compared to non-machined based technologies (see Balsmeier & Woerter, 2019). Besides, some complex automation technologies, such as robots, may have a more disruptive effect than more traditional technologies and the computers that featured in the “Computer Revolution” of the eighties and the nineties. The effect of robots and a variety of advanced automation and new digital technologies are illustrated in Sections 3.2.2 and 3.2.3, respectively.

3.2.2 | Robots

A leading automation technology that started spreading during the nineties is represented by industrial robots. Following the definition provided by the International Federation of Robotics, which has been recording information regarding worldwide robot stock and shipment figures since 1993, an industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications (IFR, 2012). Since 2010 especially, the demand for industrial robots has risen considerably and, from 2013 to 2018, annual installations of robots increased by 19% on average per year (IFR, 2019).

Recent and prospective advances in robotics have renewed concerns about the potentially disruptive impacts of technological change on labor markets. Indeed, robots can perform a wide

range of tasks, including welding, painting, and packaging, with very little human intervention (Graetz & Michaels, 2018). From a theoretical point of view, however, the impact of robots on employment is not clear a priori, since it involves forces moving in opposite directions, as illustrated by Acemoglu and Restrepo's (2019b) model. In addition, demand-enhancing effects may extend to other connected markets for goods and services (Barbieri, Mussida, et al., 2019; Dosi et al., 2021). Besides, the introduction of robots may also increase the demand for complementary non-automatable tasks, such as tasks necessary to use, run and supervise the new machines, and even boost the creation of new tasks, ranging from engineering and programming functions to those performed by audio-visual specialists, executive assistants, data administrators and analysts, meeting planners, and social workers (Acemoglu & Restrepo, 2019b; Autor, 2015).

One of the first studies to empirically examine the impact of industrial robots on labor was that conducted by Graetz and Michaels (2018). The authors develop a model of firms' decisions regarding the adoption of robot technology and the use of robots in production alongside human workers which predicts the effect of robotization on a set of economic outcomes, including employment. Using data from IFR and EUKLEMS, they estimate robot density (i.e., the stock of robots per million hours worked) in 14 industries and 17 countries from 1993 to 2007, and identify the relationship between robots and several labor variables, including employment, using both OLS and 2SLS regressions. According to their findings, robots did contribute to lower low-skilled workers' labor share, but did not significantly reduce total employment.

Other industry-level cross-country analyses on the impact of robot penetration on employment are those by: Carbonero et al. (2018) (in 15 sectors and 41 countries in the years 2000–2014); Compagnucci et al. (2019) (in different manufacturing sectors of 16 OECD countries over the period 2011–2016); Blanas et al. (2019) (in 10 high-income countries and 30 industries for the period 1982–2005); Klenert et al. (2020) (in 14 EU countries over the years 1995–2015, with a focus on manufacturing sectors); de Vries et al. (2020) (in 19 industries in 37 countries from 2005 to 2015).

The results are quite mixed. Carbonero et al. (2018) find a negative effect of robot adoption on worldwide employment, which is small in developed countries but significant in developing economies. Compagnucci and coauthors' study, which resorts to a panel VAR approach, reveals that the increase in the number of robots reduces the growth rate of worked hours. However, the latter may not necessarily reflect a contraction in the number of employees; in this regard, Cho and Kim (2018), who study the link between robots and employment in South Korea using robots as the dependent variable, point to a complementary relation between the number of employees and robotization and a substituting relation between the number of working hours and robotization.

Klenert et al. (2020) find that robot use is linked to an increase in aggregate employment. Furthermore, they argue that, contrary to what emerges from Graetz and Michaels' study, robots do not reduce the share of low-skill workers in the sample EU countries under scrutiny, and that the divergencies between their results and Graetz and Michaels' ones are mainly explained by different choices concerning the data sources, the time series, the way the robot density indicator is determined and the selection of the sectors under analysis.

Blanas et al. (2019) build an indicator of a country's exposure to robotization using UN COMTRADE data on robot imports, rather than IFR data, and let it interact with an industry-specific measure of exposure to automation (proxied by the routine-share index of Autor et al., 2003) in order to investigate the impact of robots on individuals of different education, age, and gender in both the manufacturing and the service industries. All in all, their empirical analysis in a sample of 10 high-income countries and 30 industries for the period 1982–2005 suggests that the displacement effect dominates in manufacturing industries, where automation is already widely adopted, while the productivity effect seems to prevail in the service industries, where automation is at

an earlier stage. Moreover, the manufacturing industries more exposed to robots experienced a decline in their employment of low-skill, young and female workers (but further analysis reveals that the negative effect on women is only attributable to those with low or middle education), while the service industries more exposed to robots experienced an increase in their employment of medium-skill workers, all age groups, and men. The authors also stress that their estimation strategy can only detect losses relative to other industries, and then that negative employment effects do not necessarily imply a fall in the absolute level of employment.

Finally, rather than resorting to broad occupational and educational classes, de Vries et al. (2020) focus on job tasks and classify 13 two-digit occupational groups into four task-based broad categories (i.e., routine manual, routine analytic, non-routine manual, and non-routine analytic) according to their routine-task intensity. Using a panel of 19 industries in 37 countries from 2005 to 2015, they demonstrate that, in high-income countries, the increased use of robots does not reduce aggregate employment, but has a qualitative effect, since it is associated with positive changes in the employment share of non-routine analytic jobs and negative changes in the share of routine manual jobs. Instead, in emerging and transition economies these relations are not significant.

Other contributions employ a different approach, sometimes known as the shift-share approach, which assigns robots to different subnational regions based on the distribution of employment, and then exploits within-country regional variation of employment dynamics and robot exposure and accounts for local employment spillover effects between sectors. In a seminal paper, Acemoglu and Restrepo (2020) create a Bartik-style (Bartik, 1991) measure of the local exposure to robot adoption in the US that combines the national penetration of robots in each industry with the local distribution of employment across industries within each US commuting zone. Building upon Acemoglu and Restrepo's (2019b) model of automation technologies and using both data from IFR and the data compiled by Leigh and Kraft (2018) (who conducted a robotics census for the US to account for the regional variations in industry presence and the deployment of robotic capabilities), the authors show that robots negatively affected the employment level of the US local labor markets during the period 1990–2007. This prevailing displacement effect is most pronounced in manufacturing and particularly in the industries most exposed to robots and is concentrated in routine manual occupations, particularly blue-collar, namely, those that are rich in tasks that are being automated by industrial robots.

Acemoglu and Restrepo's approach was subsequently applied by: Chiacchio et al. (2018) (on 116 NUTS2 regions of six Western European Union countries); Dauth et al. (2017) (on German local labor markets); Dottori (2020) (on Italian local labor market areas). Chiacchio et al. (2018) find that robotization harms aggregate employment, but the estimated magnitude is lower than in Acemoglu and Restrepo (2020), and the authors suggest that European labor market policies could cushion the impact of industrial robots. Moreover, the negative effect, which is positive for technicians, is driven by workers of middle education and by young cohorts.

Dauth et al. (2017), who merge IMF data with detailed linked employer-employee information, conclude that robots do not cause total job losses, but they affect the composition of aggregate employment. In particular, they find a decline in manufacturing employment (which is not caused by direct destruction of existing jobs, but by a reduction of new manufacturing jobs for young people) that is fully offset, or even slightly overcompensated, by additional jobs in the service sector, and that the overall effect on total employment is neutral when employment spillovers between sectors are accounted for.

Similarly, Dottori (2020) does not find robust empirical evidence of a negative effect of robot penetration on local employment (although it has reduced new workers' likelihood of entering manufacturing). The author suggests that the analogies with Dauth et al.'s results and the depar-

ture from Acemoglu and Restrepo's main findings could partly be related to the higher similarity of the Italian economy to Germany's, compared to the US one, in terms of institutional settings (e.g., higher employment protection), economic structure (e.g., a relatively higher weight of manufacturing), and the sectoral distribution of robots (which are used more prevalently in mature sectors and less in electronics). In this respect, Aghion et al. (2020), who study the labor implications of automation technologies at different levels of aggregation (see Section 3.2.3), postulate that the heterogeneity of these studies in terms of main findings may be partly attributable to different levels of exposure to trade (for instance, Germany relies heavily on exports, while, in the US, domestic firms have a larger domestic market and are less exposed to international competition).

Caselli et al. (2021) observe that the industry shift-share approach does not account for the high degree of firms and workers' heterogeneity within an industry (as it implicitly assumes that every worker in every firm in an industry faces the same level of robot exposure and that the distribution of robots within an industry is uniform across regions conditional on the local employment shares), nor does it allow for distinguishing occupations that are complementary to robot adoption from those that are exposed (and those that are not). In their analysis of the employment consequences of robot penetration in the Italian local labor markets, Caselli et al. introduce two major novelties, namely, they match occupations and robots based on the tasks characterizing both the professions and the robots and focus on the evolution of local employment in the occupations exposed to robots, rather than resorting to broad occupational groups (e.g., skilled/unskilled, routine/non-routine, and the like). Caselli and coauthors do not detect significant changes either in the employment dynamics of the occupations exposed to robots or, like Dottori (2020), in aggregate labor market outcomes. Moreover, consistent with the view that firms hired more workers to perform activities complementary to robots (Acemoglu & Restrepo, 2019b; Autor, 2015), they find that the shares of local employment in occupations characterized by tasks that are clearly complementary to robots did expand over time.

Aggregate-level analyses do not control for heterogeneity across firms within sectors and across workers within the same firm, and do not allow to properly gauge how and to what extent robots substitute or complement labor, and which firms' characteristics favor the introduction of such automation technology (Autor & Salomons, 2018; Seamans & Raj, 2018). As advocated by Seamans and Raj (2018), some recent studies collect firm-level information on robot adoption from survey data (e.g., Koch et al., 2019) and from fiscal and administrative data (e.g., Acemoglu et al., 2020), or rely on data on proxies such as robot imports (Bonfiglioli et al., 2020; Dixon et al., 2020).

The link between robots and labor has been assessed at the firm level by: the European Commission (2016), on 3000 manufacturing firms in seven European countries; Koch et al. (2019), on Spanish manufacturing firms; Bonfiglioli et al. (2020) on French firms; Dixon et al. (2020), on Canadian companies; Acemoglu et al. (2020), on French manufacturing firms. While the European Commission's earlier analysis, which also explores the factors that increase the probability of robot adoption, but which does not control for potential endogeneity, finds that the use of industrial robots does not have any direct effect on firm-level employment, Dixon et al. (2020), Koch et al. (2019), and Acemoglu et al. (2020) find that robotization is beneficial to aggregate employment within the firms adopting robots. Conversely, Bonfiglioli et al. (2020) show that the positive correlation between robot imports and employment is driven by demand shocks and that, once these shocks are removed, increases in automation lead to job losses; at the same time, robot imports increase the employment share of high-skill professions.

Also, Koch et al. (2019) and Acemoglu et al. (2020) report negative employment effects on the robot adopters' competitors that do not employ robots. In particular, Acemoglu et al. (2020) observe that the firm-level positive effects of adopters do not translate into similar market-level

impacts because of the negative externalities on their competitors, which more than offset the employment gains.

Finally, Bonfiglioli et al. (2020) note that most of the other microeconomic analyses do not use a firm-level instrument to isolate the causal effect of robot adoption, and caution is thus required when interpreting the optimistic findings.

In a nutshell, firm-level analyses tend to find a positive or negligible effect on employment, which, however, may be overestimated when endogeneity is not properly controlled for and which, at the industry level, may be more than counterbalanced by the negative employment performance displayed by the competitors that did not adopt robots. In addition, robots' impact can vary across various workers' categories within the same firm.

Further insights on robot applications come from patent analysis.⁶ Focusing on industrial robots in the US, Webb (2020) shows that patents mostly describe robots as cleaning, moving, welding, and assembling various objects, whereas software (namely, computer programs which, as opposed to AI, only perform actions that have been specified in advance by a human) are described as recording, storing and producing information, and executing programs, logic, and rules. Consequently, the occupations most threatened by robots (e.g., various kinds of materials movers in factories and warehouses, and tenders of factory equipment, involving a considerable amount of easily automatable repetitive manual tasks) differ from the occupations most exposed to software (which include broadcast equipment operators, plant operators, and parking lot attendants). Additionally, and in accordance with Blanas et al. (2019) findings, Webb argues that robots mostly displace individuals with less than high school education and in low-wage occupations, whereas software, consistently with the evidence of ICT-driven job polarization, mainly hinders middle-wage occupations. Finally, in line with Dauth and Chiacchio, Petropoulos & Pichler's findings, robots primarily target young male workers, who tend to engage in what Webb terms "muscle" tasks.

In conclusion, in recent years a nascent but blooming strand of research has assessed the effect of robot adoption on employment at different levels of aggregation. Even though the available evidence is quite mixed, and data limitations and different methodological choices may hinder the comparability and the reliability of the results, the review presented in this section prompts the following tentative considerations: robots differentially affect employment according to the type of skills and tasks, as they generally benefit workers who carry out tasks that complement robot applications, and negatively affect workers with low levels of education and/or performing repetitive manual tasks; the industry under scrutiny matters and, within the same industry, robots tend to have a positive effect on firm-level employment in the firms that adopt robots (which, however, may be overestimated if endogeneity is not properly controlled for) and a negative effect on the nonadopters, which sometimes more than offsets the former; the net impact on employment also depends on country-specific economic and institutional factors; the human tasks and occupations mostly exposed to robotization are different from the ones most affected by computerization.

3.2.3 | Automation and new digital technologies

The ongoing technological revolution is characterized not only by widespread robotization, but also by the increasing adoption of a range of automation and new digital technologies not limited to robots. In addition, robots tend to be concentrated in specific sectors, such as the automotive one (for instance, Aghion et al., 2020, report that, in France, the motor vehicle industry accounts

for almost 60% of robots). As a result, the analyses focusing on robots only are likely to provide a partial picture of the ongoing digital transformation.

Firm-level data on the adoption of digital and automation technologies are only recently starting to be collected by national statistical offices and are not yet included in major innovation surveys such as the CIS (Balsmeier & Woerter, 2019).

As an illustration, Domini et al. (2021), who investigate how investment in automation-intensive goods impacts workers in the French manufacturing sector over the years 2002–2015, use firm-level data on imports of intermediates embedding automation technologies -which include, among others, industrial robots, dedicated machinery, numerically-controlled machines and a number of other automated capital goods identified by the taxonomy presented by Acemoglu and Restrepo (2018b), as well as 3D printers- to identify what they define as automation spikes. The authors, who account for the endogenous selection of firms into automation, show that the decision to automate has a positive impact on firms' own employment in terms of both a reduction in the separation rate and an increase in the hiring rate, probably because it improves the relative competitiveness of firms and thus enhances their expansion. Further, automation spikes do not seem to affect shares of different types of workers within firms (1- and 2-digit occupational categories, and routine-intensive vs. nonroutine-intensive), suggesting that the positive effect of technological change in the adopters is shared by various categories of labor.

Domini et al.'s results are robust to the use of an alternative definition of automation spikes, namely the one used by Bessen et al. (2019), who, looking at Dutch firms in all private non-financial industries over the period 2000–2016 and using an event study differences-in-differences design, show that automation at the firm increases the probability of workers separating from their employers and decreases the number of days worked. Older workers generally bear most of the cost of automation-driven displacement. Accordingly, in Bessen and coauthors' study the negative effect of automation prevails, but, in line with the age-biased technological change hypothesis, it is older workers that bear most of the cost of automation-driven displacement. Moreover, the authors, who also report that there are only modest differences in how male and female workers are affected by an automation event, argue that the displacement impact of automation seems mild in comparison with the effects of changing economic conditions, and does not imply net job destruction at the aggregate or firm level.

The ramifications of automation for the French manufacturing sector have also been recently scrutinized by Aghion et al. (2020), who study the effect on employment at three levels of aggregation (i.e., firm, plant, and industry) using two alternative measures of automation: a broad indicator, namely the firm-level value of industrial equipment and machines, which may include also non-automation technologies, and the measure of a plant's peak capacity for electric motive power, which refers to a more specific set of automation technologies. The empirical analysis, which relies on a shift-share IV design to allow a causal interpretation, reveals that, at the firm level and plant level, automation has a beneficial effect on employment, including for low-skill industrial workers, suggesting that the productivity effect (namely, increased automation allowing the firm to expand its sales and scale, which requires hiring additional workers for production) outweighs the displacement effect. This holds also when the analysis is restricted to the automotive industry to mostly capture the effect attributable to robot adoption. Finally, the authors repeat the analysis at the industry level to account for business stealing and other equilibrium effects. Even though the industry-level relationship between employment and automation is positive on average, there is substantial heterogeneity depending on the exposure to international trade: the link is not significant in sectors with low exposure to international competition whereas it is positive and significant in sectors that face international competition. According to the authors, this

fact can be explained by the business-stealing effect between national and foreign firms, which, in an open economy, compete for different varieties of the same goods.

Sectoral differences in employment patterns also emerge from the patent-based study of Mann and Püttmann (2019). The authors link automation patents (i.e., those patents whose text describes a device that carries out a process independently of human intervention) granted in the US between 1976 and 2014 to the industries of their use and, through local industry structure, to commuting zones. In line with previous evidence, they demonstrate that advances in automation technologies lead to a shift from routine manufacturing jobs towards non-routine service sector jobs, with a positive average employment effect at the local labor market level.

Some redistribution of jobs across sectors associated with net positive employment also emerges from the study of Vermeulen et al. (2018), who investigate the projected impact of automation on employment in the forthcoming decade. The authors identify four types of sector affected directly or indirectly by automation, namely “applying” sectors (i.e., sectors in which the technology is applied), “making” sectors (i.e., producing, developing, supplying, and supporting) complementary sectors (i.e., facilitating or inhibiting exploitation of the focal technology, such as education, legal support, and business consulting) and “spillover” or quaternary sectors (i.e., receiving local demand spillovers related to disposable income, such as leisure and traveling, entertainment and culture, sports and lifestyle). Vermeulen and coauthors show, both theoretically and empirically, that the potential job loss due to automation in the “applying” sectors is counterbalanced by job creation in the “making” sectors, as well as in the complementary and the spillover sectors, suggesting that mankind is facing “the usual structural change” rather than the “end of work.”

While the aforementioned studies focus on automation, Balsmeier and Woerter (2019) account for a broader array of new digital technologies, which includes both complex machine-based digital technologies, such as computerized automated control systems, programmable logistic controllers, rapid prototyping, computerized numerical control (CNC) and direct numerical control (DNC) machines, robots, autonomous vehicles, 3D printing and the Internet of Things, and nonmachine-based digital technologies, such as ERP, social media, or e-commerce. The authors find that firms’ investment in digitalization in Switzerland is associated with an increase in high-skilled workers and a decline in low-skilled workers. However, as they consider a single country and a limited dataset (covering firms with at least 20 employees in 2015), the authors recognize that it is too early to safely conclude that digitalization will have different effects on low-skilled labor to the technological developments of the past. A subsequent analysis that separately examines firms adopting complex machine-based digital technologies and firms using non-machine-based digital technologies reveals that only machine-based digital technologies are responsible for significant employment effects. Intuitively, machine-based technologies are expected to have a certain disruptive power since their implementation is often capital intensive, complex, requires high-skilled qualified labor, and is only profitable if it allows firms to produce at a much lower cost per unit or higher quality standards than otherwise possible. On the other hand, non-machine-based technologies are generally used to facilitate extant single processes rather than to disrupt or significantly change the whole production process.

Since high-skilled workers are the ones that own the technical know-how required to bring these technologies to useful usage, it is likely that these workers also play a role in the firm’s decisions about the adoption of new digital technologies. This is confirmed by Cirillo, Fanti, et al. (2020) study of the patterns and determinants of new technology adoption in a large representative sample of Italian firms, which highlights that workers’ skills are primary determinants of the adoption of digital enabling technologies because they are necessary conditions for the extraction of productivity gains from the new assets.

Further insights into the effect of automation and new digital technologies on employment, and on the role played by social and organizational aspects that quantitative analysis is not generally able to capture, are provided by fieldwork studies (see Staccioli & Virgillito, 2021b for a discussion). To give a few examples: Pardi et al. (2020) consider the current Industry 4.0 wave more of a hype than a revolution and argue that more subtle changes are taking place on the shop-floor of automotive factories that might result in deskilling and work intensification; Pfeiffer (2018), focusing on production workers in Germany, observes that in highly complex and heavily digitized production environments the significance of human labor is quantitatively decreasing, but its role in maintaining these complex production processes is becoming ever more important; Krzywdzinski (2020) argues that robot density is not a very adequate indicator of the degree of technological change in place in automotive factories (where, since the 1990s, robot adoption has tripled, but the levels of automation have remained largely the same); Cirillo, Rinaldini, et al. (2021) investigate the undergoing technological and organizational transformation in three high-tech automotive factories in Italy and posit that efforts devoted to the implementation of digitalization and interconnection of production equipment outweigh the push towards sheer automation.

To conclude, the blooming line of research on the impact of robotization on labor has been recently complemented by a few empirical contributions which, rather than looking at the employment effects of robots only, deal with a broader set of automation and new digital technologies. According to them, the adoption of such devices, which is not casual and is also fostered by high-skilled workers who are able to properly employ them, may benefit the firm in terms of increased competitiveness, productivity and production, which in turn may positively affect workers, even though it is possible that certain categories, especially low-skilled workers or older workers, are penalized. In addition, it seems that the potentially disruptive impact of new digital technologies is mainly attributable to those embedded in complex machines, such as robots and 3D-Printing. Moreover, automation and digitalization can differentially affect employment according to the characteristics (e.g., technological patterns and exposure to trade) of the sector under scrutiny. The paucity of detailed and extensive data on these breakthrough technologies still prevents empirical research from providing more systematic evidence and more comparable results. Nonetheless, judging from the rapid pace of growth of the empirical research on these topics, it is reasonable to expect that new evidence will be available soon. Finally, some complementary valuable insights may come from field research.

3.3 | Impact and potential of Artificial Intelligence: Preliminary findings

In recent years, three interrelated trends, namely the availability of large unstructured databases, the explosion of computing power and the rise in venture capital to finance innovative, technological projects, have boosted the development and spread of technologies based on Artificial Intelligence (AI; Ernst et al., 2018).

AI refers to a broad and rapidly expanding field of technologies, so it is not surprising that there is no single, ready-made definition (Van Roy et al., 2020). Moreover, the term is sometimes (improperly) used interchangeably with expressions that refer to more general and broader concepts, such as automation and technological change. Acemoglu and Restrepo (2019, p.1) describe AI as “the study and development of intelligent (machine) agents, which are machines, software or algorithms that act intelligently by recognizing and responding to their environment.” Even though AI includes various research areas and it is often difficult to draw precise boundaries, its

core components can be identified with machine learning, deep learning, NLP (natural language processing) platforms, predictive APIs (application programming interface), image recognition and speech recognition (Martinelli et al., 2021). More sophisticated applications include medical expert systems to analyze and diagnose patients' pathologies, automated review of legal contracts to prepare litigation cases, self-driving cars or trucks, and the detection of patterns in stock markets for successful trading (Ernst et al., 2018).

AI can be deployed in multiple domains in the economy and is often regarded as what Bresnahan and Trajtenberg (1995) define as a general-purpose technology, namely, a technology that becomes pervasive, improves over time and generates complementary innovation. While robotic technologies often involve physical manipulation and are capable of carrying out complex manual tasks, AI technologies are largely software-based and rely on iterative learning and perception (Raj & Seamans, 2019). Importantly, unlike robots, which need to receive specific instructions, generally provided by a software, before they perform any action, an algorithm can learn for itself how to map information about the environment, such as visual and tactile data from the robot's sensors, into instructions sent to the robot's actuators.

AI technologies can perform tasks usually requiring specific human capacities related to visual perception, speech, sentiment recognition and decision-making, which robots are not able to do building upon traditional software methods. Consequently, Ernst et al. (2018), ILO, p.2) observe that "AI is replacing mental tasks rather than physical ones, which were the target of previous waves of mechanization." However, AI does not always threaten human work. According to the authors, while AI-based applications that are focused on matching tasks (i.e., tasks that imply the matching of supply and demand, especially in markets with a heterogeneous product and services structure) tend to replace human labor, ensuring a more precise and rapid matching of supply and demand, applications involved in classification tasks (e.g., image and text recognition, X-ray image diagnosing, reading and classifying legal documents, analyzing balance sheets, fraud detecting, screening applicants) tend to complement workers performing these tasks, as they help them to concentrate on aspects requiring specific attention, while the more routine, repetitive tasks are left to a machine. Finally, AI-based applications performing process-management tasks (which concern a combination of the two previous sets of tasks, identifying patterns and bringing different suppliers and customers together along a supply chain) expand the number of tasks carried out in an economy, as they perform tasks which, due to their complexity, the human workforce was previously unable to achieve. Therefore, Ernst et al. believe that the effects of AI on labor will depend on the relative importance of these three different classes, and more in general also on the direction that technological change will take in the future under the influence of policies, tax incentives and public and private investment in technological research.

The ability of AI to create new job opportunities is also stressed by Acemoglu and Restrepo (2019a), who assert that AI should not be regarded as a narrow set of technologies with specific, pre-determined applications and functionalities but as a technology platform, which can be used not only to automate tasks but also to restructure the production process in a way that creates many new, high-productivity tasks for labor (in particular in the fields of education, health-care and augmented reality), leading to societal gains both in terms of improved productivity and greater labor demand. The authors also posit, however, that because of the market failures in innovation, recent technological change in the US has been biased towards automation and to what they term "the wrong kind of AI," with insufficient focus on the creation of new tasks where labor can be productively employed.

An alternative classification of the tasks performed by AI has been proposed by Agrawal et al. (2019). Drawing on many examples from the real world, and using the information on several

hundred AI startups collected during their work with the Creative Destruction Lab at the University of Toronto, Agrawal and coauthors argue that AI directly substitutes capital for labor in performing prediction tasks—i.e., tasks based on the ability to using existing data to fill in missing information—and may indirectly affect decision tasks—namely, tasks based on the ability to take an action based on a decision, and the judgment to evaluate the payoffs associated with different outcomes—by increasing or decreasing their relative returns to labor versus capital.

The worries concerning the possible disruptive effects of AI on human work, coupled with the excitement about its great and still partly unknown potential, have fueled a vibrant discussion, inside and outside the academic arena, regarding the labor implications of AI. Nonetheless, there is very little systematic evidence: the rapid advancement in AI is indeed a nascent phenomenon, and accordingly, appropriate tools to measure its impact have not yet been developed, and public datasets on the utilization or adoption of AI are not available (Felten et al., 2019; Seamans & Raj, 2018).

Frey and Osborne (2017) attempt to predict the effect of anticipated advances in technological change, which should be driven by progress in AI, on labor. However, as Felten et al. (2019) remark, they consider the overall impact of automation, which the authors label computerization, without specifying the source (e.g., robots, AI or other types of technology) from which automation stems. Conversely, Brynjolfsson et al. (2018) focus on a subfield of AI, namely machine learning, and measure the “suitability for machine learning” (SML) for labor inputs in the US economy using O*NET data on work activities, tasks, and occupations. The authors’ findings suggest that machine learning technologies can transform many jobs in the economy, but also that few (if any) occupations will soon be fully automated by machine learning. Furthermore, tasks within jobs typically show considerable variability in SML, which can be interpreted as an indicator for the potential reorganization of a job (as the high and low SML tasks within a job can be separated and re-bundled), underlining the need for boosting process reengineering and task reorganization.

While Frey and Osborne (2017) and Brynjolfsson et al. (2018) consider, respectively, overall automation and broad machine learning, both adopt a forward-looking perspective, and primarily focus on the extent to which labor can be displaced, Felten et al. (2019) assess the labor impact of advances in specific functions of AI, such as image recognition, translation, or the ability to play strategic games, on workplace abilities and occupations between 2010 and 2015 (hence, in a backward-looking view). Additionally, unlike the other two previously mentioned studies, they resort to an approach that is agnostic as to the conditions under which AI substitutes or complements human labor, and take a step forward by estimating the implications of AI for some labor outcomes. Specifically, building upon a modified version of the method described by Felten et al. (2018) that links specific applications of AI to different occupation-level abilities, and merging O*Net data with time-varying information on nine AI applications from the Electronic Frontier Foundation, the authors develop a new indicator of the impact of AI on occupations, labelled the AI Occupational Impact (AIOI), which they employ to study how recent advances in AI have affected employment and wages in the US.

Felten et al. (2019) provide evidence that, on average, occupations impacted by AI have experienced a small but positive change in wages, but no change in employment, and that the beneficial effect on wage growth is driven primarily by occupations with higher software skill requirements. Besides, higher-income occupations have a strong positive relationship between their measure of AI and both employment and wages. These findings suggest that, although it may exacerbate labor market polarization and/or income inequality, in recent years AI has mainly complemented, rather than substituted labor. Despite some limitations (e.g., endogeneity concerns), Felten et al. work represents a valuable contribution to the nascent body of literature on the link between AI

and labor, and the authors reckon that the AIOI produced by their methodology may be used by other researchers to further investigate this relevant and interesting topic, for instance, by using a forward-looking perspective, or by studying how the impact varies across occupations, geographies, and backgrounds.

Meanwhile, some useful information on the patterns of origin and adoption of AI technologies and the performance of AI firms have been offered by patent analysis. Martinelli et al. (2021) conduct an exploratory comparative analysis of the technological bases and the emergent patterns of production and use of six major “enabling technologies,” (which, according to the Commission of the European Communities, 2009, can be regarded as technologies that can contribute to innovation and productivity growth in many sectors), namely, AI, Internet of Things (IoT), big data, cloud, robotics and additive manufacturing (also known as 3D printing). As far as AI is concerned, their analysis of 363,803 US patents filed between 1990 and 2014 reveals that: 1.6 % of these patents are related to AI (whereas patents related to the Internet of the Things represent 51.8% of the total number, and has increased over time); the AI field, similarly to those of the other five technologies, shows a relatively stable presence of a large number of smaller size players, coupled with a modest increase in the share of top inventors (whose group displays low stability due to high mobility); technological leaders tend to overlap across the six enabling technologies, probably due to the presence of strong complementarities in use, and IBM is the only company able to maintain the technological leadership in four out of the six technologies (i.e. AI, Big Data, Cloud, and IoT); AI and Cloud attract the largest share of entrants from related technologies, pointing to their key integrating role among the six enabling technologies.

Further information on the emergence, evolution, scale and pervasiveness of AI is provided by Van Roy et al. (2020), who, unlike Martinelli et al., focus specifically on AI patenting activities, which has experienced a tremendous increase since 2013. Interestingly, even though high-tech sectors such as medicine, aeronautics, and vehicles are among the main users of this emerging technology, AI patents seem to grow rapidly in traditionally less technology-intensive fields, such as agriculture, and this trend stresses the nature of AI as a transversally applicable technology. Additionally, the inventors, which are mainly concentrated in China, Japan, South Korea, and the US, display a flourishing economic performance, exhibiting on average positive employment, turnover, and labor productivity growth rates across all global competitive regions.

Patent analysis may also shed light on the degree of potential substitutability between AI and labor. In this regard, Webb (2020) resorts to patents to identify the main tasks that are executed by different types of technology, namely robots, software and AI, and uses the overlap between the text of job task descriptions and the text of patents to construct a task-based measure of the exposure of occupations to automation stemming from these three different classes. Patents describe AI—in this work referring to two kinds of machine learning algorithms, namely supervised learning and reinforcement learning algorithms—as performing tasks such as predicting prognosis and treatment, detecting cancer, identifying damage, and detecting fraud. These tasks, which can be regarded as “mental tasks,” are involved in medical imaging and treatment, insurance adjusting, and fraud analysis -all areas that have been experiencing a high level of R&D in AI-, and relevantly differ from the ones identified for robots and software. Notably, even though some low-skilled jobs are potentially affected to a considerable extent (e.g., production jobs that involve inspection and quality control) as well, AI seems to mainly target high-skilled occupations, such as clinical laboratory technicians, chemical engineers, optometrists, and power plant operators, and individuals with high levels of education.

The key contribution of Webb's study is that AI is qualitatively distinct from software and robots, and consequently it will probably affect different kinds of jobs and people. This result also aligns with the recent findings of Montobbio et al. (2020). The authors, unlike Webb, consider the broader category of robot-related technologies (which also includes the so-called AI-related "intelligent robots," that is, robots that can "sense" and communicate with their environment and operate as mobile, interactive information systems in a wider spectrum of fields, from manufacturing to service sectors) and look specifically at labor-saving innovations. They show that the latter challenge not only manual activities (e.g., in the logistics sector), which are the main target of industrial robots, but also activities entailing social intelligence (e.g., in the healthcare sector) and cognitive skills (e.g., learning and predicting), namely, tasks and skills in which human workforce has had a comparative advantage so far, but which seem to represent the major target of AI. However, Webb notes that his results on the exposure of occupations are purely descriptive, do not refer to the entire universe of AI applications, and do not allow identification of the magnitude and even the sign of the impact on labor.

In conclusion, AI has been rapidly evolving and expanding across countries and sectors. Even though it has the potential to challenge a vast array of occupations, including some in which human labor has traditionally held a comparative advantage, it seems that, so far, it has not caused massive job losses. However, judging from the rapid advances in this field, it is very likely that AI has not unfolded its full potential yet, and, thus, it is difficult to predict how and to what extent AI will affect employment in a near future.

4 | DISCUSSION

The literature presented in Section 3 has been reviewed following two main criteria, namely the proxy of technological change, which guides the structure of the section, and the level of aggregation/unit of analysis, which has been emphasized in the various paragraphs. A summary of the main considerations prompted by the review, together with some further insights, is provided below.

4.1 | Type of technological change and technological input

4.1.1 | R&D and disembodied technological change

The vast academic literature on innovation has identified two broad types of technological change: disembodied technological change, which is mainly related to product innovation and thus fosters product demand and in turn labor demand and job creation, and the technological change embodied in capital inputs, which is mostly associated with process innovation and has a more ambiguous effect on employment. R&D expenditures are regarded as an indicator of disembodied technological change; the empirical literature confirms that R&D and product innovation typically exhibit a labor-friendly nature, even though their positive effect on employment is mainly driven by the more dynamic and innovative sectors and firms, namely, by those that have the "absorptive capacity" to reap the benefits of innovation. Accordingly, governments should strengthen their policies aimed at promoting innovation and R&D investments, targeting, in particular, those industries and companies that lag behind in terms of innovation efforts.

4.1.2 | Computers and ICTs

A considerable number of studies have focused on the side of the adopters of technologies. Starting from the seventies, and especially during the eighties and the nineties, computers and ICTs have experienced great development and diffusion, with significant implications for labor. The introduction of these technologies in many workplaces has penalized the workers whose occupation mainly requires routine tasks that can be performed by software, and individuals with limited computer literacy; at the same time, it has been beneficial for individuals who mainly carry out tasks (e.g., both abstract tasks and complex manual tasks) that computers struggle to perform. Even though it has exerted a significant qualitative effect on labor, and has contributed to the reallocation of workers across occupations and sectors and labor market polarization, on the whole the widespread use of ICT has so far not caused massive technological unemployment, and it has also fostered the creation of new job titles. All in all, ICT has mainly benefited individuals whose tasks are complementary to the ones performed by computer technologies and those who have ICT literacy; accordingly, investments in both formal education and on-the-job training should increase such complementarity and help workers move to other jobs and sectors.

4.1.3 | Robots and new digital technologies

As far as robots are concerned, some empirical analyses, especially at the aggregate level, have found a negative net effect on employment, which is typically mainly borne by more traditional manufacturing sectors and by low/ medium-skilled workers and/or young workers. However, even though “Robots’ capabilities set robots apart from earlier waves of automation and more conventional ICTs, which leave flexible movement in three dimensions firmly in human hands” (Graetz & Michaels, 2018, p.753), this technology mainly challenges occupations that primarily involve manual tasks. Accordingly, there are still several tasks in which human labor holds a comparative advantage, including the tasks necessary to use, run and supervise the new machines. In addition, the adoption of robots is associated with a positive productivity effect which can more than offset the negative displacement effect, especially in firms that successfully adopt these technologies. As a result, a more in-depth understanding of the capabilities and limitations of this complex technology may alleviate the fears about a possible “robocalypse” and shed light on the activities in which workers still have a comparative advantage.

Similar considerations seem to hold for a broader variety of automation technologies, even though empirical evidence is more limited. Nonmachine-based digital technologies typically have, by nature, a more labor-friendly impact compared to complex automation technologies. Besides, since March 2020, the dramatic Covid-19 pandemic has further stressed the importance of investing in digitalization for firms, and the need of mastering those digital tools that have become crucial for the employers required to work from home.

4.1.4 | Artificial Intelligence

Finally, the ongoing digital revolution has been characterized by the rapid development of AI-based technologies, which, unlike computers, robots and other automation technologies, can learn for themselves how to map information about the environment and are mostly directed to

“mental” tasks. Consequently, AI has the potential to challenge a considerable variety of occupations, including service occupations that are typically performed by high-skilled individuals and which have so far been regarded as difficult to automate. However, some AI tasks are still considered complementary to human tasks; moreover, at present AI algorithms still need to “learn” from existing data to improve performance, and software that can entirely think and act on its own does not exist yet. Also, we should keep in mind that AI has been fueling important advances in various scientific fields, including biomedical engineering, which can bring great benefits to humankind.

4.2 | Level of aggregation and unit of analysis

4.2.1 | Firm

A firm represents the main place where employment decisions are made (Harrigan et al., 2020), and firm-level analysis allows a direct and precise firm-level mapping of the innovation activities and the technological inputs. Empirical microeconomic studies tend to find a positive link between R&D/product innovation, since the firms that innovate directly benefit from the increase in market share and product demand, with positive consequences for their employers. Moreover, the gains from innovation are mainly grasped by dynamic and large firms operating in high-tech sectors, and typically do not transfer to non-innovative firms, which, on the contrary, due to the “business-stealing” effect and other competitive dynamics, may be negatively affected and experience a decline in employment.

Similar considerations hold for the adopters of complex technologies, such as robots. Even though these have an intrinsic labor-saving nature, they typically lead to an increase in the firm output, market share and competitiveness, which in turn can lead to job creation. This positive effect of technological change on the adopters can be shared either by various categories of labor (as in Domini et al., 2021) or mainly by high-skilled workers who are able to implement and control these complex new technologies (e.g., Balsmeier & Woerter, 2019). At the same time, business-stealing and negative externalities may hinder the non-adopters, which are typically less dynamic and productive firms, and this may lead to labor reallocation from the non-adopters to adopters. Accordingly, even though investing in R&D and in the adoption of new enabling technologies is generally costly, firms should consider the potential future benefits from such investments.

4.2.2 | Sector

Technological change has contributed to the well-known structural shift of the economy from manufacturing to services, as it has fostered labor reallocation in service occupations that are hard to automate and the creation of new jobs. However, the manufacturing industry still represents an important share of the total economy in several countries, and also includes dynamic, high-tech sectors.

The innovation literature has shown that different sectors, including manufacturing sectors, are characterized by heterogeneous patterns of innovation/technological adoption and employment, and has highlighted the juxtaposition between downstream/adopter sector, where labor-saving ETC often prevails, and upstream/“making,” mainly characterized by labor-friendly disembodied technological change. However, this juxtaposition may be simplistic (for instance, the sectoral classification proposed by Vermeulen et al., 2018, includes not only the adopters and the “making”

sectors, but also complementary sectors and spillover sectors), and may have been challenged by the latest wave of technological progress. Indeed, recent patent analyses have revealed that patent holders of robotics-related technologies comprise not only producers, but also adopters, with Amazon and UPS being two archetypical cases (Montobbio et al., 2020), and that AI patents are rapidly growing in traditionally less technology-intensive fields. Therefore, the opportunities stemming from the adoption of new digital technologies, in particular from those that can be applied to a variety of fields, are not limited to high-tech sectors but can be potentially grasped by the whole economy.

4.2.3 | Occupation

Each occupation comprises a variety of tasks that present different degrees of routinization. In general, technological change has been detrimental for jobs that mainly involve routine tasks that can be easily displaced, whereas it has not hindered, or has even favored occupations that are rich in tasks which machines cannot carry out, or which are complementary to computer and robot applications. According to Autor and Dorn's (2013) classification of US occupations based on the level of their Routine Task Index (RTI), the occupations with the highest degree of routinization are butchers and meat cutters, secretaries and stenographers, and payroll and timekeeping; the list of occupations with the lowest RTI scores comprises both low-skill occupations (e.g., bus drivers, taxi cab drivers and chauffeurs, and waiters) and high-skill occupations (e.g., firefighting, prevention and inspection, police, detectives and public service, and primary school teachers).

Technological change has also led to the creation of new job titles, a phenomenon that has been observed also during previous waves of technical progress and has fostered the growth of occupations that rely on ICT, which in some cases offsets the decline in occupations that are displaced by computerization (see Bessen, 2016).

In recent years, several studies have estimated the risk of automation, or job automatability, for most of the extant occupations, in the US and several other countries. They have also shown that there is significant within-occupation task heterogeneity, and that, when the latter is accounted for, the risk of automation is significantly lower compared to the predictions produced using the so-called occupation-based approach. As suggested by Brynjolfsson et al. (2018), this within-job variability of tasks can be interpreted as an indicator for the potential reorganization of a job, which, if pursued and boosted, may reduce the number of jobs threatened by technical change.

4.2.4 | Individual

Workers differ not only in terms of occupation but also in terms of educational level and demographic characteristics.

High-skilled workers who are able to properly use new digital technologies and can also incentivize the adoption of the latter typically benefit from technological change in terms of employment dynamics. However, as the RBTC hypothesis has stressed, the skill level is often proxied by the amount of formal education (i.e., average years of schooling or educational qualification), which can be an imprecise indicator of the competencies of an individual and the activities implied by his/her job.

The magnitude and the direction of the effect of technological change on labor can be influenced by the worker's age as well. Employment outcomes of older workers are often negatively affected by ICT-induced technological change, since they are generally less familiar with digital technologies. However, some studies (e.g., Biagi et al., 2013; F. Peng et al., 2017; Schleife, 2006) show how high levels of education, and in particular computer literacy and the use of personal computers at work, as well as the presence of solid labor institutions, can alleviate or offset the negative impact of technological change on the older workers' employment. These results emphasize the need to invest in training programs that help workers to stay abreast of technological innovations and that strengthen the complementarity between human labor and machines.

Interestingly, in the case of robot adoption, it seems that younger individuals, especially younger males, are more exposed, as they often perform the so-called "muscle" tasks that can be easily replaced by robots. Dauth et al. (2017) show that the aggregate decline in manufacturing employment in Germany is solely driven by fewer new jobs for the young labor market entrants and suggest that, after the installation of new industrial robots, firms may tend to retain the incumbent workers but to create fewer vacancies that could be filled by young workers. The displacement effect of technological change on the most vulnerable workers may be considerably attenuated by the participation in training programs, which can both improve the technological literacy of individuals and help them transit to new career opportunities. In this respect, Nedelkoska and Quintini (2018) stress the importance of training and re-qualification and their role in reducing the risk of automation.

A few studies covered in this review also assess whether technological change differently affects male and female workers. On examining the polarization of employment in German local labor markets, Senfleben-König and Wielandt (2014) observe that most of the growth in service occupations is explained by the reallocation of female workers. Autor et al. (2015) assert that while losses in routine employment among men in US local labor markets are offset by corresponding gains in occupations with abstract tasks, such offsetting gains are absent for women, thus generating a negative overall impact of technology exposure on female employment. This result may be partly ascribable to the fact that, because of their family duties, female workers can find it more difficult to transition towards a new job.

It is also possible that women tend to differ in terms of skills and tasks, as suggested by Lindley (2012). Brussevich et al. (2019), who conduct a comprehensive analysis of the gender gap in terms of job automatability in a sample of 30 advanced and emerging economies, reporting that women, on average, perform more routine or codifiable tasks than men across all sectors and occupations; at the same time, they perform fewer tasks requiring analytical input or abstract thinking, where technological change can be complementary to human skills and improve labor productivity. This is mainly explained by women's self-selection in certain occupations (e.g., service occupations with a considerable degree of routinization), but also by the fact that, as also highlighted by Nedelkoska and Quintini (2018), women often carry out more automatable tasks than their male counterparts even within the same occupation. As a result, according to Brussevich et al. study, on average female workers are at a significantly higher risk of displacement by automation than male workers. The gender gap varies considerably across countries, however, and in line with growing educational participation, women appear to be increasingly opting into occupations that are relatively more insulated from the risk of automation, and gender differences are substantially lower or even negligible for younger cohorts of women, suggesting that there is room for optimism about the future of work for women.

4.2.5 | Country

Countries differ in terms of economic development, governance, industrial specialization, product market regulations and labor market institutions, which can be relevant moderators of the link between technological change and employment. If labor market laws and institutions are rigid and do not provide sufficient incentives for investment in skill upgrading, technology adoption may lead to job loss (Pissarides & Vallanti, 2004). Similarly, weak governance-specific institutions may motivate managers to adopt productivity-augmenting strategies at the cost of labor demand (Mitra & Sharma, 2020).

Some multi-country studies control for institutional variables (e.g., Breemersch et al., 2019; European Commission, 2014), while others include country fixed effects to account for national specificities (e.g., Marcolin et al., 2016). However, it is difficult to show how these factors vary across countries and, in doing so, how they moderate the technological change-employment nexus.

According to some researchers, the mixed results in terms of the employment impact of robot penetration at the aggregate level observed in different countries (e.g., the US vs. European countries) are partly ascribable to differences in labor market institutions, including the level of employment protection, and also to variations in the exposure to trade (see Section 3.2.2).

Useful information on inter-country heterogeneity comes from some multi-country analyses of the risk of job displacement, even though it should be kept in mind that job automatability does not necessarily reflect the actual replacement of workers by machines. Arntz et al. (2016) show that individuals in the same industry, occupation or even education group perform different tasks in different countries, and attribute this fact to two possible reasons, namely, to differences in the workplace organization (on average, countries which have a stronger focus on communicative tasks in their workplace organization also have a lower share of jobs at high risk) and differences in the adoption of new technologies (the automatability is lower in countries which already invest a lot in ICT).

Similar considerations are prompted by the analysis conducted by Nedelkoska and Quintini (2018) on a larger sample of countries: by means of a shift-share analysis, they show that, contrary to expectations, only 30% of the variation across countries is attributable to differences in the economic structure of economies (i.e., the mix of industries), and more than two-thirds is explained by differences in the way economies organize work within the same economic sectors, that is, their occupational mix within industries and also the job task mix within occupations, which may reflect the extent to which automation has already taken place and jobs have adapted as a result (hence, countries where the adoption of labor-substituting technologies has not yet taken place would show a structure of job tasks that is more prone to automation).

The level of economic development of the country can matter as well. For instance, according to de Vries et al. (2020), the increased use of robots is associated with positive changes in the employment share of non-routine analytic jobs and negative changes in the share of routine manual jobs in developed countries, whereas, in emerging and transition economies, these relations are not significant. However, in recent years some dynamic, fast-growing emerging economies, such as China and India, have rapidly increased their investments in R&D, robot adoption and issue of AI patents, and their performance may deserve further investigation.

Finally, further insights on country-level specificities can be supplemented by field studies (e.g., Krzywdzinski, 2020, documents the evolution of automation and digitalization, and the changes

in the occupational structures that occurred in the automobile industry focusing on Germany, the United States, and Japan).

5 | CONCLUDING REMARKS

The present work attempts to provide a comprehensive picture of the possible implications for employment stemming from a complex and multifaceted phenomenon that has long generated both fear and excitement, namely technological change. From the review of the literature, it emerges that both the selected type/proxy for technical change and the level of aggregation/unit of analysis play an important role in determining the magnitude and the direction of the effect of technical progress on employment.

Despite the fact that the ongoing digital revolution has been displaying unprecedented pace and pervasiveness and has been affecting an increasing number of sectors and occupations, at the moment the “end of work” scenario seems remote. Technical change has contributed to the reallocation of labor across workers, occupations, firms and sectors, and in doing so it has hindered some categories, in particular the most “vulnerable” workers and the more traditional and sluggish sectors and firms that did not catch up with technical progress. However, at the same time it has benefitted the subjects that can properly use and control these new technologies. This comes to bear on policymaking, as the authorities should design interventions aimed at improving the quality of human capital and at producing skills that are complemented, rather than substituted, by technological change. In this respect, the influential work by Goos (2018) identifies a list of possible policy interventions, such as: higher investment in Science, Technology, Engineering and Mathematics (STEM) education, but also in non-routine social, motivational, and interaction skills, which are likely to remain difficult to automate at least in the short term; labor market income redistribution policies that ensure that the benefits of the Digital Revolution are broadly shared; innovation policies that can foster the creation of technologies that are complementary to workers’ skills and help mitigate the impact of technological change on economy-wide inequality. As a result, the central issue is not whether technological change is displacing labor, but how and to what extent policymakers and societies will be able (and willing) to grasp the opportunities and alleviate the potential negative effects of this complex but fascinating phenomenon.

Even though this survey may help achieve a better understanding of the composite link between technological change and employment, it is far from being exhaustive. As an illustration, it touches on some relevant topics which deserve further investigation, such as the role played by institutional factors and in particular by international openness, and the role of organizational innovation and changes in working practices.

Moreover, some recent developments have not been extensively investigated yet. For instance, more attention should be devoted to some high-growth, dynamics developing countries, especially to China, which is one of the countries that have filed the highest number of AI patents between 2000 and 2016. Further, in the last few years digitalization has led to the creation of new job profiles, connected with the new concept of “digital entrepreneur,” that rely heavily on digital technologies and especially on social media. In addition, access to digital tools and assistive technologies can improve and facilitate everyday life quality especially for people with disabilities, favoring their participation in society and increasing their employment opportunities, thus promoting social inclusion. The extant research on this topic mostly belongs to the domain of political science and law, and there is room for more empirical economic research.

On top of that, AI has been experiencing a very rapid development; as an illustration, at the end of 2020 OpenAI launched GPT-3, a powerful algorithm that can create anything that has a language structure and can answer questions, write essays, summarize long texts, translate languages, take memos, and even create computer code. Future research may help to shed light on these issues, and in particular on the opportunities and challenges posed by AI.

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ENDNOTES

- ¹ This work reviews recent studies (published or made available from 2003 onwards) that employ the following proxies of technological change: R&D, computers and ICT (captured by direct or indirect measures), robots, a variety of automation and new digital technologies, and Artificial Intelligence. I also briefly recall some empirical analyses that use specific indicators of product and process innovation as key regressors, but which are out of the scope of this survey (for a comprehensive review of the recent literature on the link between innovation and employment, see Calvino & Virgillito, 2018). In order to identify the selected articles, I first explored the "Economics, Econometrics and Finance" and the "Business, Management and Accounting" sections of the Scopus database; then, in order to include working papers and reports released by international institutions and organizations, I scrutinized some well-known and relevant working paper series (i.e., OECD, IMF, IZA, ILO, and NBER working paper series), and subsequently the "Working Paper" section of the database EconPapers. Finally, I examined the bibliography of a considerable number of articles previously found in order to detect other suitable studies.
- ² Bogliacino & Pianta (2010) classify manufacturing and service sectors according to a revised version of Pawitt's (1984) taxonomy (i.e., Science-based, Specialised Supplier, Scale-Intensive, Information-Intensive Suppliers Dominated) and show that each of the identified sectors mainly pursue one of the two following main innovation strategies (or trajectories): technological competitiveness, which is based on new products and new markets and then is rooted in product innovation, and cost competitiveness, which focuses on increased efficiency and is rooted in process innovation. The types of sector identified by Bogliacino & Pianta (2010) have been classified by Dosi et al. (2021) as either being "upstream" sectors, namely the sectors that produce new machines and equipment (Science-based and Specialised Supplier) or "downstream" sectors (i.e., Scale-Intensive, Information-Intensive and Suppliers Dominated).
- ³ Fernández-Macías & Bisello posit that the presence of human agency and social organization has four main implications for labor and tasks. First, unlike human labor, machines do not have real agency, and therefore some human labor is always required for their functioning. Second, the workers' input into the economic process requires their active cooperation; as a result, the organization of production will not only have to maximize the technical efficiency of labor inputs but also use forms of work organization that ensure the cooperation of employees. Third, work tasks very rarely exist in isolation, but are in the vast majority of cases coherently bundled into jobs, and this affects tasks in ways that are at least partly independent from technical considerations. Finally, tasks are also socially embedded because the structures of production and service provision of any economy necessarily reflect the structures of consumption of society; hence, the change in the contents and types of tasks in production will ultimately reflect how societies change in their tastes and preferences, in their institutions and organizational forms.
- ⁴ Although there is no universal definition, the term ICT generally refers to all the devices, networking components, applications and systems that enable users to access, retrieve, store transmit and manipulate information

in a digital form. As an illustration, the EU-Klems sectoral variable “ICT investment” comprises the tangible assets “computing equipment” and “telecommunications equipment”, and the intangible asset “software”.

- ⁵ Exceptions are represented by the analyses conducted by Marcolin, Miroudot & Squicciarini (2016), Kerr, Maczulskij & Maliranta (2020) and Böckerman, Laaksonen & Vainiomäki (2019), who use direct indicators of ICT capital and study how the latter relate to the employment dynamics of different educational and task groups.
- ⁶ In the last few years, patent analysis has been used to identify the human tasks challenged by different types of technology (e.g., Montobbio et al., 2020; Webb, 2020), as well as to explore the sources and the geographical and historical patterns of adoption of automation and new enabling technologies, including AI (e.g., Montobbio et al., 2020; Van Roy et al., 2020; Martinelli, Mina & Moggi, 2021; Staccioli & Virgillito, 2021a), and to investigate the causal link between the production or adoption of technologies and a labor variable (e.g., Dechezleprêtre et al., 2020; Mann & Püttmann, 2020).

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