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Problems, solutions and new problems with the third wave of technological unemployment

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Abstract

The aim of this paper is to discuss possible solutions to the "third wave" of technological unemployment and their main drawbacks. The process has just started and will only be fully realized in the future, but its main novelty is already well known and concerns robots (and artificial intelligence) entering the production process. Robots do not simply increase labor productivity, in cooperation with humans, but can totally substitute labor, making it possible to produce commodities without the use of human input. This in turn generates technological unemployment. Past "compensation" theories have argued that technological unemployment could be reabsorbed thanks to wage reduction and demand (and production) increase. But these theories have ignored robots. If robots are more productive and less expensive than humans, wage reduction may be insufficient due to the minimum wage subsistence boundary; and, in any case, an increase in demand would only determine an increase in the production of goods by robots alone, without any impact on human employment. Meanwhile, the resulting mass unemployment will require redistributive policies. The paper discusses the most relevant among these policies, emphasizing their drawbacks and their unwanted implications, and proposes an alternative rooted in Tietenberg's tradable permits approach.

JEL code: B12, D21, D30, E24, J64

Key words: Technological unemployment, robots, artificial intelligence, unemployment, redistribution, compensation theory, tradable permits approach

Introduction

The problem of technological unemployment, which, in the remote past, occupied a relevant, albeit controversial, space in theoretical debates, has regained importance in recent years, with the advent of the Fourth Industrial Revolution. According to a number of recent contributions (e.g., Brynjolfsson and McAfee 2011, 2016; Freeman 2015; Ford 2016), the new wave of technological unemployment, which started to affect the economy at the beginning of the 21st century, will be radically different from the old ones. The first wave (1765-1980) mainly relocated workers from one sector to another, while the second (1980-today) lowered wages for unskilled workers and/or

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workers performing routine tasks, thus increasing inequality without a commensurate impact on unemployment. The third wave, however, based on robots and artificial intelligence, is considered capable of virtually reducing human employment to zero in (almost) all industries, irrespective of workers' qualifications.

Albeit conflicting views have always been present in theoretical literature, the old debate had somehow reached the majority conclusion that long-term technological unemployment was actually out of the question, and that technical progress (in particular, process innovation) could cause unemployment, but compensation forces existed, which were able to fully reabsorb it. These conclusions were mainly founded on the condition that wage reduction and (demand and) production increase would have reabsorbed unemployment. Furthermore, the theoretical analysis was confirmed by empirical evidence of employment increases during periods of strong technical progress, even if supporters of the hypothesis of technological unemployment imputed such a result mainly to the simultaneous reduction of per capita working hours.

The contemporary debate radically modifies both the basis and the conclusions of that old debate. Albeit not today, but certainly in the next few years, robots endowed with artificial intelligence will be capable of substituting for both skilled and unskilled workers in (almost) all sectors, as well as workers performing routine and non-routine tasks, so that it will be possible to realize any production without human input. Moreover, robots probably will be more productive and less expensive than workers. This will generate mass unemployment and will make compensation forces ineffective: to reabsorb mass unemployment, wage reductions should be huge, but wages have a subsistence minimum below which they cannot go. Furthermore, an increase in demand for commodities will result in an increase in production and employment, but only for robots, if production can be realized by robots alone. These radical conclusions attracted worldwide attention thanks to a rather popular contribution by Brynjolfsson and McAfee (Brynjolfsson and McAfee 2011).

Curiously enough, few economists are participating in this debate, which is mainly dominated by engineers and computer scientists (Campa 2017, pp. 11-12). The paradoxically limited interest from economists in this new wave of technological unemployment probably depends on theoretical and empirical circumstances. On the theoretical side, economists appear too confident about the conclusions reached during the old debate about the first waves of technological unemployment, failing to understand that, when robots entered the scene, everything changed: the third wave of technological unemployment is not an evolution of the first two waves, it is a completely different phenomenon. The crucial novelty is represented by the circumstance that robots can substitute humans in all the jobs, a substitution that in the past was neither possible nor imaginable. Hence the conclusions of the old debate are irrelevant for discussing the third wave of technological unemployment. On the empirical side, a crucial role may also have been played by the lack of meaningful empirical data for a phenomenon that has essentially just started, since, to date, the full substitution of skilled workers, as well as workers who perform non-routine tasks, with artificially intelligent machines has not yet really begun. Nonetheless, the new circumstance is such that, from today, we know that substituting lawyers, physicians, teachers etc. with robots is technically possible. In the past it was not.

The situation whereby, in some sectors, substitution has yet begun and compensation forces do not work, as shown by Acemoglu and Restrepo (2017), is of little theoretical interest, since, in this paper, the question is far more radical and concerns the future: what are the economic conditions that can lead to the substitution of (almost) all workers with machines? In addition, what can we do to face the problems caused by this substitution of the workforce?

To simplify the analysis, in this article, the assumption is made that two different types of workers exist, i.e., robots and humans. While they can perform the same tasks, robots involve higher productivity, higher precision, higher quality of production and less cost. This assumption requires a relevant change in the theoretical framework used in the past to deal with technological unemployment. The "old" theoretical models were capable of taking into account the "old" process of technological progress, within which machines cooperate with humans in production and increase labor productivity. But these models are incapable of systematizing the new process of technological progress, within which robots can totally substitute for human workers, while neither cooperate with the other nor increase their productivity. In such a framework, mass unemployment, or even full unemployment, will be a realistic outcome, which will require some form of public policy intervention.

Public intervention may take a number of different forms, from redistributive policies (taxing robots, subsidizing unemployed humans, introducing mandatory quotas for human employment etc.) to collectivizing the property of robots or firms; but all these policies come with important drawbacks. The paper focuses on the discussion of these policies and such drawbacks by proposing an alternative solution based on Tietenberg's tradable permits approach. According to this approach, quotas of human employment are assigned to firms, which can in turn buy/sell their quotas to other firms.

The paper is organized as follows. Section 1 offers a brief description of the history of the first two waves of technological unemployment and so-called "compensation theory". Section 2 discusses the main characteristics of the third wave of technological unemployment, which jeopardizes the relevance of compensation theory. Section 3 focuses on "new compensation theory" and possible solutions to the third wave of technological unemployment. Section 4 discusses the problems that the implementation of these solutions might generate. Section 5 proposes an alternative solution rooted in Tietenberg's tradable permits approach. Section 6 concludes the paper.

1. The first two waves of technological unemployment and the "theory of compensation"

The theoretical debate on technological unemployment started with the First Industrial Revolution (roughly 1765-1830), when the development of the steam engine represented a form of technological progress that apparently reduced human employment in a number of sectors. From then on, this debate played a marginal role during the Second Industrial Revolution (roughly 1870-1914), when electric power was the basis of mass production, and during the Third Industrial Revolution (roughly 1969-today), when electronic and ITC automated production, increasing inequality but not unemployment. The theme only regained relevance in the 21st century, when the advent of robots and artificial intelligence seemed possible of opening the way to what Schwab (2016) called the "Fourth Industrial Revolution" and to a world without human employment.[1]

The first three Industrial Revolutions generated two different waves of technological unemployment. During the First and Second Industrial Revolutions, we had the first wave of technological unemployment, involving technical progress that mainly relocated workers from one sector (in the beginning, from agriculture, later from manufacturing) to another (in the beginning, to manufacturing, later to services). Meanwhile, during the Third Industrial Revolution, skill-biased technical change[2] mainly reduced employment for unskilled workers (and/or workers performing routine tasks),[3] as well lowering their wages and increasing the wage of skilled workers (and/or of workers performing non-routine tasks)[4], the skill premium and

[1] For a synthetic but rather complete description of the classical and neoclassical contributions concerning the impact of technological progress on unemployment, and on the different aspects of compensation theory, see Vivarelli (1995, 2007), Feldmann (2013), Abbott and Bogenschneider (2017) and Campa (2017). From an history of economic thought perspective, the concept of technological unemployment gained momentum in orthodox economic theory after Ricardo's contributions, but lost relevance when Wicksell relaunched the neoclassical approach to compensation theory, while theoretical interest was reignited due to Keynes' 1930 work (Campa 2017, p. 7).

[2] According to Violante (2008, p. 2), " 'Skill-Biased Technical Change' (SBTC thereafter) is a shift in the production technology that favors skilled (e.g. more educated, more able, more experienced) labor by increasing its relative productivity and, therefore, its relative demand. Ceteris paribus, SBTC induces a rise in the skill premium – the ratio of skilled to unskilled wages".

[3] According to Violante (2008, p. 6) "information technologies substituted unskilled labor employed on simple and more repetitive tasks – more amenable to computerization and complemented workers endowed with generalized problem-solving, complex communication, and analytical skills".

[4] In general, theoretical contributions studying the rise in technological inequality have mainly focused on skill-biased technical progress (technological innovations that mainly hit low-skilled workers) and on task-biased technical progress (technological innovations that mainly hit workers performing routine tasks). On this point, see Autor et al. (2003, 2006, 2008), Acemoglu and Autor (2011) and Acemoglu and Restrepo (2016).

inequality.[5] However, in both cases, the impact on unemployment was relevant in the short but small in the long term (Campa 2017, p. 5).

To understand the factors that can determine technological unemployment and the causes, which, in the past, drove economists to believe that this problem was of scarce empirical relevance, one should start from a standard neoclassical analysis. Within this context, the choice between hiring labor (workers) or capital (machines) represents a choice of technique problem: given the produced quantities, entrepreneurs will substitute capital for labor if the value of the marginal product of capital, divided by the money price of the service of capital, is greater than the value of the marginal product of labor divided by the money wage rate. Put another way, for a certain quantity to be produced, entrepreneurs will substitute capital for labor if:

1) $$\frac{\bar{p}\frac{\partial Q}{\partial K}}{\bar{w}_K} > \frac{\bar{p}\frac{\partial Q}{\partial L}}{\bar{w}_L}.$$

or if:

2) $$\frac{\bar{w}_L}{\bar{p}\frac{\partial Q}{\partial L}} > \frac{\bar{w}_K}{\bar{p}\frac{\partial Q}{\partial K}}$$

where $\bar{w}_L$ is workers' money wage, $\bar{w}_K$ is the price of the service of capital, $\frac{\partial Q}{\partial L}$ is the marginal productivity of labor, $\frac{\partial Q}{\partial K}$ is the marginal productivity of capital, and $\bar{p}$ is the price of the produced commodity.[6] For a given produced quantity, the profit maximizing equilibrium will be reached when:

3) $$\frac{\bar{w}_L}{\bar{p}\frac{\partial Q}{\partial L}} = \frac{\bar{w}_K}{\bar{p}\frac{\partial Q}{\partial K}}$$

On the contrary, if the produced quantity is variable, the final equilibrium implies:

4) $$\frac{\bar{w}_L}{\bar{p}\frac{\partial Q}{\partial L}} = \frac{\bar{w}_K}{\bar{p}\frac{\partial Q}{\partial K}} = 1.$$

Within such a framework, machines destroy human jobs if: (i) capital productivity increases or the price of the service of capital decreases; (ii) labor productivity decreases or the wage rate increases. Since technological progress impacts both capital and labor productivity and the price of the service of capital, the possibility exists that unemployment rises with technical progress.

It is worth noting that the "old" debate on the impact of technological progress on unemployment gave great relevance to the distinction between process innovation and product

[5] The conclusion, according to which, in recent decades, technological progress increased the polarization of wage income, mainly affecting unskilled workers, was widespread, albeit rather controversial. On this point, see Card and Di Nardo (2002), Autor et al. (2003, 2006, 2008), Violante (2008), Dustmann et al. (2009), Autor and Acemoglu (2011), Freeman (2015), and Acemoglu and Restrepo (2016).

[6] The price of the produced commodity, the wage and the price of the service of capital are considered as given under the (here implicitly assumed) hypothesis of perfect competition.

innovation, concluding that the latter was mainly employment friendly and the former mainly employment unfriendly. Such a distinction was based on the observation that producing new products and/or developing new sectors of activity would in any case increase employment, whereas new processes in many cases displace workers (see e.g. Bessen 2018, Bogliacino and Pianta 2010, Freeman and Soete 1994, Katsoulacos 1984, Pianta 2005, Piva and Vivarelli 2017). As we shall see below the distinction between product and process innovation looses relevance when robots enter the scene, and new products can be produced, and new sectors of activities can be developed, using robots alone, without labor input.

In any case, according to the prevailing view, technological unemployment should reabsorb due to the simultaneous operating of a number of converging mechanisms, which have been described by many different authors and constitute the theoretical approach referred to by Marx as *compensation theory*.[7] These forces can be divided into automatic mechanisms and deliberate intervention mechanisms. Automatic mechanisms are mainly rooted in the neoclassical approach, whereas deliberate mechanisms are mainly rooted in the Keynesian one.[8]

The most important among automatic mechanisms are the following:[9] (i) wage flexibility, which allows wages, in the presence of unemployment, to reduce, so as to increase firms' labor demand and hence regain full employment; (ii) increase in employment in the sector that produces the machines, due to an increase in demand and production of machines; (iii) reduction in production costs and hence prices of commodities produced by the machines, increase in the demand for these commodities, increase in production and increase in employment;[10] (iv) reduction in production costs and hence prices of commodities produced by the machines, increase in real income and hence demand for goods, increase in production and finally increase in employment; (v) reduction in production costs, which, in the presence of price rigidities, increases profits and hence investment, in turn increasing production and employment in the sector that produces investment goods; (vi) reduction in production costs, which, in the presence of price rigidities, increases profits, leading to higher entrepreneurs' demand for goods, and hence increases in production and employment in the sector that produces consumption goods; (vii)

[7] "Indeed, in the first half of the XIX century economists put forward a theory that Marx later called the 'compensation theory' (…) This theory is made up of different market compensation mechanisms which are triggered by technological change itself and which can counterbalance the initial labor-saving impact of process innovation" (Vivarelli 2007, p. 2).

[8] According to Campa (2017, p. 10), "[t]o put it briefly, while marginalist economists keep denying the problem of technological unemployment, Keynesians are sure that the problem exists, but they are also confident that it can be solved with opportune public policies".

[9] For a more thorough description of the different compensation mechanisms briefly listed here, see Vavarelli (2007), Blien and Ludewig (2017), Campa (2017), Peters (2018).

[10] The traditional argument, first discussed by Neisser (1942), is that the impact of technical progress on employment depends upon demand elasticity: "if product demand increases enough there is no unemployment effect of technological progress" (Blien and Ludewig 2017, p. 9). As we shall see below, such an argument becomes ineffective when used with reference to robots and the last wave of technological unemployment.

product innovation, which creates new sectors of activity and employment in these sectors; (viii) increase in the wages of the employed, increase in their demand for commodities, increase in production and employment in these sectors; (ix) transition of employed humans from the primary to the secondary sector when jobs are destroyed in the primary sector, and then from the secondary to the tertiary sector, when jobs are also destroyed in the secondary sector; (x) increase in the marginal productivity of labor caused by an increase in capital accumulation; (xi) decrease in machines' marginal productivity prompted by their increased use, due to capital accumulation, and hence modification of the choice of techniques in favor of labor; (xii) reduction in production costs and hence prices of commodities, increase in the real supply of money, reduction in the interest rate and hence increase in investment and employment in the sector that produces investment goods.

The most important among deliberate intervention mechanisms are the following: (i) increase in public expenditure, which increases aggregate demand, production and hence employment; (ii) public subsidies for education and investment in human capital, which increase labor productivity and hence make workers competitive with machines.

It is certainly true that compensation theory suffers some drawbacks, mainly caused by wage and price rigidity, the absence of a further sector beyond the tertiary one where workers can be displaced, and public debt, which could prevent massive public expenditure.[11] That said, until the end of the 20th century, the majority among theoretical contributors seemed to agree that compensation forces were effective in contrasting technological unemployment, albeit a number of dissenting opinions did persist.[12]

And (at least) until the end of the 20th century, empirical studies seemed to confirm the conclusions reached by majority theoretical analysis. In particular, most contributions confirmed these results for the economic system as a whole in the presence of flexible markets, high demand elasticity for both products and factors and high substitutability between factors (see e.g. Piva and Vivarelli 2017, pp. 11-13). And similar results were obtained also at firm and industry level. For example, Evangelista and Vezzani (2012) found that at firm level in (some selected countries of) the European Union technological and organizational innovation had a positive effect on employment due to the circumstance that they increased the growth of firms, even if in manufacturing firms the contemporary presence of technological innovation and organizational change actually displaced workers. At a sectoral level, Ciriaci et al. (2016) showed the positive

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11 For a detailed analysis, see Vivarelli (2007, pp. 4-7).

12 Dissenting opinions range from those who affirm that technological unemployment exists but is hidden by the historical reduction of per capita working hours (i.e. Vivarelli 1996) to those who maintain that "the economic theory does not have a clear-cut answer about the final employment effect of R&D and innovation" so that "attention should be turned to the empirical analyses" (Piva and Vivarelli 2017, p. 14).

employment effect of small innovative firms in Spain. Bogliacino et al. (2012) found a positive impact on employment of investment made by technological firms but not of investment made by manufacturing firms in general in 677 European companies. Coad and Rao (2011) showed that in the United States high-tech firms employment rose with innovation. Van Reenen (1997) showed that in UK manufacturing firms employment rose with innovation. Partially different were the conclusions of a study by Lachenmaier and Rottmann (2011), that albeit confirming the positive impact of innovation on employment in Germany, found that this impact was positive mainly for process innovation. Piva and Vivarelli (2005) found a similar effect for the case of Italy, with a positive effect on employment by product innovation but no evidence of labor displacement by process innovation. And again Piva and Vivarelli (2018) found that for eleven European Countries R&D innovation had a positive impact on employment mainly in the case of product innovation in medium and high-tech sector. Finally, with reference to imported technological innovations through trade and foreign direct investment, Haile et al. (2017) found a positive effect of technological progress on employment in Ethiopian firms.

The majority view emphasized also the circumstance that, consistently with these results, the global trend of labor productivity and employment showed co-movement.[13] Technological shocks could generate waves of short-term unemployment; but, in the longer run, the trend of employment appeared capable of tracking those of technical progress. Nonetheless, some authors pointed out that the absence of a negative impact of technological progress on employment was mainly a consequence of the huge reduction of per capita working hours that interested the labor market in the last two centuries, hiding in this way the reduction in employment (see e.g. Vivarelli 1996).[14]

We saw a slight change in recent decades, when the empirical debate focused on the fact that, from 1980 onwards, skill-biased technical change reduced unskilled workers' and increased skilled workers' wages (and employment), in turn increasing inequality; but the belief that technical progress (mainly in the sense of process innovation) does not increase long-term unemployment appeared still predominant among economists. At least, it appeared to be predominant up until the end of the 20th century.

[13] See, e.g., Brynjolfsson and McAfee (2014, p. 165).

[14] In particular, according to Vivarelli (1996, p. 26 and 28), technological unemployment would have been successfully contrasted by "the historical tendency towards a continuous decrease in per-capita annual working time; for instance, it has been shown that a manual worker used to work about 3,000 hours at the beginning of this century, whereas the average annual working time ranges nowadays between 1,500 and 1,900 hours".

2. The third wave of technological unemployment and the fall of "traditional" compensation theory

Things began changing with the Fourth Industrial Revolution. While the Third and Fourth Industrial Revolutions were based on an apparently similar technological progress, their impact on wages and/or employment is rather different.

Thanks to the progressive development of artificial intelligence, the possibility currently exists that machines substitute human beings in (almost) all jobs: robots, computers and computer programs have the potential to totally replace doctors, truck drivers, accountants, bank clerks, teachers etc.[15] This circumstance changes everything, since unemployment will affect, in the same way, skilled as well as unskilled workers, independent of whether or not they perform routine tasks, and full unemployment becomes theoretically possible. Up until today it was out of question.

It is worth noting that such a process is only in its very preliminary phases, and one can only find anecdotal evidence of its realization. However, even if an empirical analysis is necessarily inconclusive, and mainly confirms what happened in the last decades of the 20th century (i.e., machines replacing unskilled/routine workers and increasing inequality), a theoretical analysis is perfectly capable of interpreting the new phenomenon (see, e.g., Brynjolfsson and McAfee 2011, 2016; Ford 2015; West 2015), even if economists appear reluctant to deal with this matter. This reluctance likely depends on not giving the correct relevance to the circumstance that a world in which it is possible that robots replace all humans in all jobs is radically different from a world in which full substitution of humans with machines is not possible. The old debate on the theme had as an object a phenomenon completely different from the present day phenomenon, and therefore the old theoretical analyses and empirical studies, together with their conclusions, are irrelevant if referred to the third wave of technological unemployment.

The main novelty concerns the role played by robots. Nowadays, the problem is neither technical progress nor the choice between labor and capital, or even the introduction of machines within the productive process. Rather, the new actors on the scene are robots. Such a change not only simplifies the analysis, but also radically modifies the theoretical framework and hence the theoretical analysis. Capital, such as machines, cooperates with labor in the productive process and may increase human productivity, meaning that unemployment can only rise if demand and production do not sufficiently rise, and compensation theory appears rather effective in

[15] According to Campa (2017, p. 14), "Artificial Intelligence develops exponentially and not only promises to further reduce the workforce in manufacturing, but it will begin to erode the work of specialists in the service sector. In the near future, unemployment could concern economic actors who have attended higher education institutions and invested much time and money to acquire their professional skills, such as journalists, physicians, teachers, lawyers, consultants, managers, etc."

preventing the impact of technological progress on employment.[16] On the contrary, with the Fourth Industrial Revolution, robots substitute humans within the productive process, do not cooperate with them. Thus, commodities can be produced by robots alone, without any contribution from labor, meaning that unemployment may rise independently of demand considerations, with compensation theory becoming ineffective as a result.

Economists seem to misunderstand the crucial difference that exists between robots and capital (see, e.g., Miller and Atkinson 2013) and appear convinced that, in the presence of technological unemployment, automatic mechanisms will sooner or later increase demand, and that this increase in demand will increase production and hence human employment. They understate the situation that, if new production is realized using robots alone, without the need to hire humans, human employment will not vary independently of what happens to demand and production. It is certainly a future outcome, but the claim that this situation is far in the distance does not change the theoretical analysis that has to be used to investigate this "remote" robotic scenario.

According to Freeman (2015, p. 2), "[t]he term 'robots' refers broadly to any sort of machinery, from computer to artificial intelligence programs, that provides a good substitute for work currently performed by humans (…) it does not matter whether a robot/machinery has a humanoid appearance, as long as it can perform human functions".

For the sake of simplicity here, we will only consider the oversimplified scenario within which robots are humanoid programmable machines that can substitute humans in all activities, not merely in the case of manual and/or routine activities. In this scenario, these humanoid machines are capable of performing identical tasks that humans perform, but with a higher productivity and at a lower cost. We can further simplify this scenario by assuming that capitalists own robots and rent them out to entrepreneurs. Meanwhile, entrepreneurs have to decide whether to hire robots or humans for their productive process. A crucial implication of these assumptions is that, since robots are humanoid machines, when their marginal productivity is reduced due to intensive hiring of robots by firms, humans' marginal productivity also declines, and vice versa. [17]

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[16] By definition, $Productivity = \frac{Production}{Employment}$, so that $Employment = \frac{Production}{Productivity}$. In the presence of an increase in productivity, the reduction of employment can be compensated by an increase in production equal to (or greater than) the increase in productivity.

[17] In the opposite scenario, robots are profoundly different from human beings (in the same way that a software is different from a worker) and humans' marginal productivity is independent from that of robots. But problems can all the same arise if investments and plants are robot-specific, i.e., if the set of other factors, which are considered as given when determining the marginal productivity of humans, is different from that of robots. Once the marginal productivity of robots has lowered, it is not possible hiring a human since its productivity will be zero if employed in a firm (a set of other factors) built for robot use. It would be necessary to invest in a different set of given factors. And not only this implies that assuming a human worker could only be feasible in the long run, when the investment in a new set of given factors has been realized. But primarily that if entrepreneurs have to invest in a new set of given factors (a new firm?), they will invest in a new set of factors for exclusive robot use.

Obviously enough, the last hypothesis (where human workers' marginal productivity declines together with that of robots) is important, since it rules out compensation theory adjustments x and xi.

If robots are humanoid machines identical to humans (except for their wage/productivity ratio), according to relation 1 and 2, firms will substitute robots for humans: if, given the same productivity for humans and robots, robots' "wage" (rent price) is lower than humans' wage; if, given the same wage for robots and humans, robots' productivity is higher than humans'; or if the higher (lower) wage of robots (humans) is more than compensated by their higher (lower) productivity.

In our simplified scenario, there exists a crucial difference between humans' and robots' remuneration: humans' wage has a subsistence lower bound, whereas robots' remuneration has a production cost lower bound. The two bounds are different. The monetary subsistence wage depends upon the composition of the subsistence basket and the prices of subsistence goods. No human will work if the wage is below the subsistence level. On the contrary, the monetary lower "wage" for robots is the lowest amount of money that capitalists who own robots will accept when hiring them out to entrepreneurs, which ultimately depends upon robots' production cost.

Now, let us assume that robots' productivity is higher than humans' productivity *and* robots' remuneration is lower than workers' wage for *all the sectors of the economy*. As a result, firms will hire robots and fire humans, thereby increasing human unemployment. If compensation forces do not work, in the end, only robots will be employed.

In the traditional framework, when the substitution of robots for human workers begins, compensation forces start working and drive back employment towards full employment. The problem here is that, in this new framework, traditional compensation theory has limited space, since only few, from among the range of both automatic and deliberate mechanisms, might work, albeit under some rather improbable circumstances.

Indeed, in terms of automatic mechanisms: (i) wage flexibility can play a role if, and only if, the wage lower bound is not reached, i.e., if the level of wage necessary to compensate for humans' lower productivity is not below the subsistence level, which is a very difficult condition to realize; (ii) increase in the demand for robots and the production of robots does not cause an increase in human employment in the sector that produces robots, since robots can be produced by means of robots alone, without a human contribution; (iii) reduction in production costs and hence in prices of commodities produced by robots increases the demand and the production of these commodities, without increasing employment, since these commodities can be produced by means of robots alone, without a human contribution;[18] (iv) reduction in production costs and hence in prices of commodities produced by robots can cause an increase in the real income and hence the demand and production of goods, but employment does not increase, since commodities can be produced by means of robots alone, without a human contribution; (v) reduction in production costs, in the presence of price rigidity, may increase profits and hence investment, but does not increase employment in the sector that produces investment goods, since also investment goods can be produced by means of robots alone; (vi) reduction in production costs, in the presence of price rigidity, may increase profits, entrepreneurs' demand for goods and hence production, without increasing employment in the sector that produces consumption goods, since consumption goods can be produced by means of robots alone; (vii) product innovation can create entirely new sectors of activity but not an increase in employment in these sectors, since, also in these sectors, commodities can be produced by means of robots alone; (viii) an increase in the wage of employed humans is out of question, but, even if it happened, it would result in an increase in demand for the production of robots, and hence would not generate new employment; (ix) at the moment, no new sector of relevance beyond the tertiary sector, which is capable of absorbing human workers, seems to exist; (x) if robots are humanoid, humans' marginal productivity does not rise more than that of robots' with an increase in capital accumulation, meaning that there is no chance that human productivity will rise above that of robots; (xi) if robots are humanoid, the marginal productivity of labor reduces with that of robots and the choice of techniques does not modify in favor of labor; (xii) a reduction in production costs and hence prices of produced commodities increases the real supply of money and reduces the interest rate, and in turn the production of investment goods; but, since investment goods are also produced by robots alone, employment does not rise.

Concerning traditional deliberate intervention mechanisms: (i) an increase in public expenditure has no impact on employment, since any increase in the demand and production of goods generates an increase in the employment of robots, not of human beings; and (ii) public subsidies for education and investments in human capital can hardly increase human productivity above that of robots (incidentally, the skill premium ceases to have a role, and both skilled and unskilled workers are affected in the same way).

The result is that full unemployment is not only a possible, but rather a likely scenario.

[18] If production can be realized by robots alone, without a human contribution, the traditional "elasticity argument" described in fn. 12 does not hold.

3. "New" compensation theory

However, as in the above-described scenario, some deliberate intervention mechanisms, which are alternatives to those depicted in traditional compensation theory, can (and indeed should) be implemented. Were this not the case, not only would demand for the production of robots be insufficient to guarantee the profits of entrepreneurs, but human beings could not acquire their subsistence basket.

We can divide these deliberate intervention mechanisms into two categories: in the first, we find those policies that aim to guarantee employment and hence subsistence for humans and demand for the production of robots; within the second, we find those policies that aim to guarantee subsistence for humans and demand for the production of robots, but not employment for humans. However, as shown below, some important overlapping exists between the different policies.

In order to guarantee employment (and subsistence) for humans (and demand for the production of robots), public policy could implement a number of strategies, the most important of which are as follows:

i. Public policy could reduce the cost of workers for firms, in turn making workers' productivity/wage ratio competitive with that of robots, so that hiring humans becomes a convenient alternative to hiring robots. In order to achieve this result, public policy should subsidize the hiring of humans by paying employment subsidies to firms that hire humans.

ii. Public policy could increase robots' remuneration by taxing the hiring of robots, again with the finality of making workers' productivity/wage ratio competitive with that of robots. Through the taxation of robots, "education and training for workers" and/or "social benefits programs such as a guaranteed minimum income" could be funded (Abbott and Bogenschneider 2017, p. 9).[19]

iii. Since one of the problems that prevents workers from being competitive with robots is the existence of a subsistence lower bound for a human wage, public policy could allow workers to accept wages below the subsistence level by paying an unconditional basic income to all citizens, both employed and unemployed (Campa 2014; Hughes 2014). Once the subsistence basket is obtained, workers can decide whether or not to accept a low

[19] Taxing robots could also simply rebalance the current situation in which machines are taxed less than humans (on this point, see Abbott and Bogenschneider 2017, pp. 19 ff.). For a thorough discussion on the way in which machines can be taxed, and of the consequences of such taxation, see again Abbott and Bogenschneider (2017).

wage for increasing their consumption above the subsistence level or to stay voluntarily unemployed and get the subsistence. [20]

iv. Public policy could increase humans' productivity, so as to make humans competitive with robots. In order to achieve such a result, public policy should boost education and/or professional training, cutting the cost of private investment in human capital or directly offering it for free to humans (Campa 2017, p. 13). A more radical, but future, strategy could be the building of cyborgs, i.e., humans with cybernetic parts.

v. Finally, public policy could impose on firms minimum human employment quotas or maximum robot employment quotas. This policy mimics the immediate (Luddite) reaction of authorities to the displacement of workers caused by the First Industrial Revolution, i.e., "limit the use of the machines" (Campa 2017, p. 3).

In order to guarantee subsistence for humans (and demand for the production of robots) without employment, public policy could implement a number of strategies, the most important of which are as follows:

vi. Public policies could accept full unemployment and subsidize humans with an unconditional basic income.[21] Funds for financing the basic income can be extracted from entrepreneurs by taxing robots and/or generating budget deficits.

vii. Public policies could seek to nationalize firms or assign the property of robots or firms to citizens. In this way, the surplus derived from the production of robots will go to humans displaced by robots.[22]

Before discussing the limits of the above solutions, it should be emphasized that, if technological unemployment happens, i.e., if robots are more efficient than workers across the relevant range of the wage/productivity ratio, the efficient solution would be to only employ robots and then redistribute the profits to compensate unemployed humans. Nonetheless, in this scenario, it may be difficult for humans to possess enough contractual power to obtain an adequate share of profits and, furthermore, for democratic institutions to survive. This is due to the fact that, if humans are unnecessary for production, their contractual power risks falling to zero. However, humans would maintain a residual contractual power if they had a compensation allowance far above the subsistence level. In this latter case, they would enjoy contractual power as consumers rather than as producers: they could take part in a consumption strike and stop consuming

[20] It is worth noting that the basic income is not an unemployment benefit, as humans receive it whether they are employed or unemployed.

[21] As proposed by Hughes (2014), Campa (2014), Colin and Palier (2015), Schiller (2015) and Skidelsky (2015).

[22] Freeman (2015, p. 1) emphasizes the relevance of such a strategy. According to him, "workers could own shares of the firm, hold stock options, or be paid in part from the profits".

certain categories of goods. On the contrary, if their compensation allowance was close to the subsistence level, they could not go on consumption strike and would therefore have no contractual power. In any case, full unemployment could lead to economic, social and ethical consequences that are untenable for a democracy. The question hence would be whether this wave of technological progress, and the resulting technological unemployment, is compatible with democracy.

4. The problems of "new" compensation theory

Apart from the democracy problems deriving from full unemployment, all the above-described solutions involve important drawbacks.

i. Subsiding firms to hire humans is the same as forbidding the hiring of robots (for the substitution of humans) and generates suboptimal results. Wages should (at least) cover subsistence and subsidies should be high enough to guarantee that the hiring of humans is more convenient than the hiring of robots, i.e. subsidies should (at least) cover the difference between the wage/productivity ratio of robots and that of humans. Now, given that, in the long run, public subsidies received by firms can only be financed by taxing the profits of the same firms, firms will ultimately pay the entire amount of workers' wages. The situation where firms pay taxes, without receiving subsidies if they hire robots and not humans, will force entrepreneurs not to hire robots (or at least not to hire robots as substitutes for workers). As a consequence, given the costs, production will be lower than what could be attained by hiring robots. Furthermore, quantifying the subsidies to be paid would be extremely difficult and could cause rent-seeking problems both on workers and firms side.

ii. Taxing the hiring of robots as a disincentive for hiring them and an incentive for hiring humans is the symmetrical solution to subsidizing human employment and bears similar results. Furthermore, in this case, if the tax is high enough to guarantee human full employment, the long-term result is the same as forbidding the hiring of robots (as substitutes for workers).

iii. Guaranteeing to all citizens a public unconditional basic income has even worse consequences for firms and may generate psychological, social and political problems for humans. Inevitably, the basic income should (at least) cover subsistence, such that workers can decide if they prefer to work, and hence earn an income equal to the basic income plus the wage paid by firms (which will be low enough to make workers competitive with robots), or to choose leisure over work, and hence only earn the (subsistence) basic income. Since governments will ultimately finance the basic income by taxing firms' profits, firms will have to pay the basic income *and* the hiring costs of robots if all humans decide not to work. On the contrary, if humans decide to work, firms will have to pay the basic income *and* the wage. For firms, both scenarios are worse than the subsidize/tax scenario. For humans, being unemployed may generate self-esteem-related psychological problems, a lack of objectives in life, a loss of contractual and political power, etc. [23]

iv. Increasing human productivity would be the best solution, but this appears to be the least feasible one. The third wave of technological unemployment is profoundly different from the second, and it is hard to believe that investments in education and/or formation could make humans as productive as robots. Maybe this will happen when cybernetic organisms arrive on the scene.

v. Imposing minimum human employment quotas or maximum robot employment quotas is also inefficient. In the case we are discussing, with robots and humans being identical except in terms of their wage/productivity ratio, firms are forced to hire both robots with lower wage/productivity ratio than workers, and workers, with higher wage/productivity ratio than robots. Furthermore, it will be also inefficient to impose the same human quotas on different industries, or even on different firms. However, this policy can be designed in a way such that there can be positive consequences for the collective as a whole; for this reason, we discuss this matter in more detail in the next section.

vi. As we have already discussed above, introducing a basic income could be either a way for humans to accept lower wages and hence induce firms to hire them, or a way for humans to stay unemployed and survive all the same. In this latter case, there would be greater inefficiency for firms, since, for a given produced quantity, firms would have to pay both robots and humans (for work they do not perform). Furthermore, we should again consider the psychological, social and political problems that derive from a full unemployment situation.

vii. Giving the property of firms to the unemployed has similar effects to introducing an unconditional basic income: humans remain unemployed, but receive an income coming from the profit shares of the firms they own.[24] Since the owners of firms (i.e., the

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[23] According to West (2015, p. 13), "[c]ritics of a basic income generally emphasize two reasons. First, they point out the value that work adds to human worth. Many people define a significant part of their self-esteem through their employment. Even though a large number report they are unhappy in their current position, jobs are vital to many people. Second, people worry about a lack of work incentives in an income guarantee. Proposals must be structured in a way that balances payments with work encouragement. Otherwise, people may stop working and do little to contribute to community goals".

[24] According to Freeman (2015), humans could obtain the property of the means of production and continue to work, but this would be an irrational choice: if workers possess the means of production, and if the production

unemployed) will want to maximize profits, the production will be realized with an efficient technique, i.e., employing only robots, and hence this seems the best solution. However, this presents rather insurmountable policy problems. If, in the past, humans did not have enough contractual power to obtain the property of the means of production, even though they were workers, i.e., they were indispensable and irreplaceable for production, how could they succeed in achieving such a result when they are completely replaceable by robots and hence useless for production? Their contractual power would almost be nil with respect to that of robots (and firms) owners. Put another way, as the contractual power of workers and their wages increased when workers became indispensable to industrial production, and decreased when they became replaceable, it is easy to imagine that their contractual power will fall to zero when they become useless. Furthermore, without contractual power, it is difficult to obtain the property of the means of production possessed by those who retain contractual power.[25]

5. An alternative solution

The above discussion confirms that no simple and uncontroversial solution exists for the new wave of technological unemployment. However, a possible alternative policy, capable of guaranteeing efficiency, profits for firms, less psychological and social problems, employment and the maintenance of contractual power by humans, exists and can be realized by implementing a "cap and trade" criterion. Such a solution mimics Tietenberg's traditional tradable permits approach to environmental economics.[26] In this approach, pollution quotas are allocated among firms, which can either comply with these quotas or sell/buy them.

According to Tietenberg:

> "A principal theorem of environmental economics demonstrates that, under specific conditions, an appropriately defined tradable-permit system can minimize the cost of reaching a predefined environmental target (…) In a perfectly competitive market, permits will flow towards their highest-valued use. Those that would receive lower value from using the permits (owing to lower abatement costs, for example) have an incentive to trade them to someone who would value them more. The trade benefits both parties. The seller reaps more from the sale than s/he could from using the permit and the buyer gets more value from the permit than s/he pays for it." (Tietenberg 2003, p. 401).

and/or surplus can be maximized by hiring only robots, it would be in the interest of workers (who possess the means of production) that firms hire only robots and no workers at all. Thus, workers would cease to work when they obtain the property of firms, whose shares would be held by the unemployed, not by workers.

[25] Freeman's argument, according to which humans would not possess enough contractual power to obtain a relevant share of production without working (as, for instance, in the basic income scenario), unless they own the firms, should be reversed. If humans do not have enough contractual power (and they have not if they are not necessary for production), they cannot obtain the property of firms.

[26] On the tradable-permits approach see Baumol and Oates (1971), Montgomery (1972), Tietenberg (1990 and 2003).

Furthermore:

> "A rather remarkable corollary (…) holds that this theorem is true regardless of how the permits are initially allocated among competing claimants, including whether they are auctioned off or allocated free of charge." (Tietenberg 2003, p. 401).

The same theoretical framework, and the same policy tools, can be used to deal with technological unemployment problems. Moreover, the problems of international competition, which arise when a country unilaterally implements policies against technological unemployment, are quite similar to those that arise when a country unilaterally implements environmental protection policies, and thus can be solved in the same way.

In the case of technological unemployment, governments can decide on the quotas of workers that each firm has to hire, as well as combine this solution with others, such as basic income or taxing robots. Once quotas have been allocated (free of charge, or on the basis of auctions in which firms pay more for smaller quotas), firms can trade them. In this case, sellers pay for selling quotas, and buyers get paid for buying quotas. Firms or industries, for which the hiring of human workers is less profitable, would sell quotas to firms or industries for which the employment of human workers is less disadvantageous. Paraphrasing Tietenberg, quotas will flow towards their lowest-loss use. Those that would suffer a higher loss from being forced to hire humans have an incentive to trade them with someone who suffers lower losses. Such trade benefits both.

It is important to emphasize that, if some firms are forced to hire humans, as in the case of a public intervention mechanism based on quotas, when these firms will have to renew their factories or build new factories they will not build robot-specific plants, but plants compatible with human employment. On the contrary, if firms are free not to hire humans, as in the case of a public intervention mechanism based on the unconditional basic income, they will hire only robots and, when they will have to renew their factories or build new factories, they will build robot-specific plants. As a result, in the first case the long period outcome will see the contemporary presence of robot-specific factories and factories in which humans can work; in the second case we would have only robot-specific factories in which humans cannot work (or can work with a close to zero productivity). Furthermore, in the first case humans will be useful for production in existing plants, and hence will retain contractual power; in the second case humans will be useless for production in existing plants, and will retain no contractual power.

Therefore, implementing the proposed Tietenberg-like solution, given the initial distribution of quotas an efficient solution emerges, humans are hired, full unemployment is avoided, workers retain residual (even if not significant) contractual power, psychological and social problems emerging from full unemployment are mitigated, and firms earn profits since they only pay for the productivity they enjoy. Furthermore, such a solution is suitable, both for the case in which robots and humans are identical, and for the case in which some firms are robot-specific: in the first case, quotas will flow towards firms where humans have the highest ratio between marginal productivity and wage, and, in the second, from robot-specific to human-specific firms.

The main disadvantage of this solution is identical to that concerning environmental protection policies and can be overcome in the same way. Firms lose competitiveness, since they are forced to pay for hiring humans more than they would have paid for hiring robots, or to pay for selling their quotas. As such, if they are exposed to international competition, they may fail. However, traditional comparative advantage theory guarantees that a country could gain from international trade, including when it is less efficient than its trade partners (see, e.g., Freeman 2005, p. 3), while the possibility remains to negotiate international treaties that commit countries to the enforcement of quotas, as in the case of the Kyoto Protocol. Furthermore, the international trade of quotas can be planned.

6. Conclusions

As discussed above, the third wave of technological unemployment has characteristics and implications radically different from the first and the second waves. While the first two waves reduced human employment in specific sectors (agriculture in the beginning, manufacturing later on) or lowered wages and/or employment for unskilled workers and/or workers performing routine tasks, leading to rising inequality, the third wave is eventually capable of destroying (almost) all jobs for humans (both skilled and unskilled, both routine and non-routine) in all the sectors of the economy. This is due to the fact that, while the first two waves of technological unemployment were caused by the development of more productive machines, the third resulted from the introduction of robots in the productive process. Unlike machines, robots do not cooperate with workers, but substitute workers in the productive process. Meanwhile, in the near future, it will be possible to realize all production processes by only using robots. As a result, traditional compensation forces, which, in the past, proved to be capable of preventing the impact of technical progress on employment, will be ineffective: due to the relatively high productivity and low cost of robots, wage reduction should be significant enough to compensate for technological unemployment and guarantee human employment, but may not overcome the limit of the lower subsistence level of the wage. In addition, an increase in demand could result in an increase in the production of commodities produced by robots alone, and hence employment for robots alone.

As the phenomenon is still in its initial stages, empirical proof is scarce. But theoretical analyses are urgently needed on this topic, given that important social problems may emerge during the transition phase, when mass unemployment will begin to rise. Nonetheless, very few contributions to date by theoretical economists have dealt with the problem of future mass technological unemployment and the possible solutions to minimize its impact.

Among the solutions that have (mainly) been proposed by non-economists, taxing robots, subsiding the hiring of humans, collectivizing the property of firms, implementing a basic income and imposing quotas for human (or robot) employment appear the most popular suggestions. Meanwhile, implementing the basic income appears to be the most discussed solution among both economists and non-economists. Despite this endlessly expanding debate, such a solution has the relevant drawback that it will be socially untenable by generating political circularity: implementing a basic income may generate full unemployment and hence reduce the contractual power of humans to zero (since they will become useless for production); but with zero contractual power, humans will not have enough political strength to obtain a basic income or to defend the level of their basic income. Thus, mass poverty would be a possible outcome. Proposing fair solutions is (relatively) simple; but implementing them requires political and social strength that humans only have when they were irreplaceable workers, not when they are replaceable and replaced by robots.

A possible alternative solution, capable of conjugating efficiency and the survival of employment, and hence of the political strength by humans, may consist of implementing a "cap and trade" solution that mimics Tietenberg's traditional tradable permits approach to environmental problems. Governments can decide the quotas of human workers that each firm has to hire; and, once quotas have been allocated, firms can trade quotas. The low level of human contractual power remains; but it is mitigated by the absence of full unemployment

In any case, much more theoretical work on the topic has still to be done, since the problem carries enormous economic and social implications. Furthermore, mainstream economics encounters some difficulties in systematizing it, since elements, such as contractual power on the part of workers, class conflicts, public property of the means of productions, redistribution policies, subsistence wages and basic income appear to make it difficult for them to be dealt with by the traditional approach.

In conclusion, the absence of significant empirical evidence should not be considered as an obstacle to the study of a future possible scenario of full unemployment emanating from the last wave of technological progress. In general, empirical evidence precedes theoretical studies; but, in this case, it would be better to have a thoroughly theoretical analysis, and possibly full consciousness of the policy tools that can be implemented, long before full unemployment becomes an empirical reality.

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