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# Incentives for labour-augmenting innovations in vertical markets: The role of wage rate

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ABSTRACT

This article analyses the link between the wage rate and the incentives to develop and adopt a labour-augmenting innovation in a vertical market. In a model where an upstream monopolist sells the innovation to several downstream manufacturers, I show that the wage rate affects the incentives to innovate in different ways depending on i) the initial level of wage and ii) the timing of the policy's implementation. Moreover, if the policy is introduced when the size and the price of innovation are common knowledge, then the policy-maker can elicit her preferred equilibrium by nudging more firms to adopt the technology. Instead, if the policy is introduced before the investment stage, then the increase of the wage rate generates two opposite effects: a positive cost-reducing effect and a negative output-contraction effect. If and only if the wage level is below a critical threshold, the former dominates the latter. I argue that, under certain conditions, a policy that raises the price of labour may be beneficial for both the incentives to invest in labour-augmenting innovation and the industry outcomes.



## 1. Introduction

In today's economy, two ongoing parallel processes are attracting the attention of scholars and policy-makers. The first one is represented by the ongoing firms' technological transformation and the effects of the so-called Industry 4.0 technologies (I4.0) on the labour market; the other is the rising interest in minimum wage schemes by public opinion and political institutions. This article aims to delve into the interactions of these two separate but parallel trends and, specifically, to analyse how an adjustment in the cost of labour affects the firms' choice of the technological endowment.

The new wave of technological progress is driven by a new set of technologies, such as robotics, internet of things, additive manufacturing, cloud computing, cybersecurity, artificial intelligence, et cetera, usually defined as 'Industry4.0′ technologies. According to many experts, by increasing the level of automation in the assembly lines, some of these technologies are expected to drastically alter the way physical goods are produced, with a major impact on labour demand and possibly

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on labour productivity (OECD, 2019; McKinsey Global Institute, 2017 and Frey and Osborne, 2017). Evidence at the aggregate level is ambiguous in this sense.[2] Using USA data, Acemoglu and Restrepo (2017) estimate a negative effect of automation on labour demand. According to the authors, this result is driven by the joint effect of an increase in substitutability between labour and robots and the higher competitive advantage of robots in performing some of the tasks required to produce the final product. Instead, using EU data, Klenert et al. (2020) find a significant positive correlation between robot use and labour demand between 1995 and 2015. This finding, the authors argue, suggests that '*national industries with a higher robot adoption tend to be more resilient in terms of employment than the rest*' (p. 32, emphasis mine). Although the evidence at the aggregate level is mixed and does not fully clarify the effect of automation on labour productivity, a more detailed picture is drawn from micro-level evidence. Using French firm-level data, Acemoglu et al. (2020) show that, on average, firms that introduced robots in their factories expanded their workforce, although the aggregate trend of employment in that industry was negative. According to the authors, robots make adopting firms more productive and efficient than their labour-intensive rivals. This, in turn, implies a reallocation of production that favours robot-adopting firms, whose market shares expand together with their labour demand. However, as the more labour-intensive firms lose their market shares, the aggregate labour demand shrinks. Using firm-level data of Canadian firms, Dixon et al. (2020) find similar results and suggest that managerial tasks are the most exposed to automation.

The second ongoing trend is the widespread call for minimum wage schemes that would ensure workers a fair living salary.[3] In the last few years, many countries and institutions have discussed or introduced reforms supporting worker earnings, such as adjustments on the minimum wage or the introduction of more generous unemployment benefits.[4] The need for such reforms has been highlighted also by the current President of the European Commission, Ursula von der Leyen. In the presentation of the political guidelines for the 2019–2024 European Commission, von der Leyen stated that 'we will support those in work to earn a decent living, and those out of work as they look to find a job. *Within the first 100 days of my mandate, I will propose a legal instrument to ensure that every worker in our Union has a fair minimum wage.* This should allow for a decent living wherever they work. Minimum wages should be set according to national traditions, through collective agreements or legal provisions' (von der Leyen, 2019, emphasis mine). This statement was formalized in October 2020, when the European Commission proposed 'an EU Directive to ensure that the workers in the Union are protected by adequate minimum wages allowing for a decent living wherever they work'.[5]

Also, in June 2020, Germany announced that its statutory minimum wage will be raised gradually by 12% (from 9.35€ /h to 10.45€ /h) by the end of 2022, with the first adjustment starting in January 2021. Far from being only an EU trend, this renewed interest in socioeconomic issues regarding poor salaries involves other countries as well. In 2019, the US House of Representatives voted for an increase in the federal minimum wage from 7.25$/h to 15$/h. Even if this reform was not voted in by the US Senate, the issue has gathered considerable public support. In fact, several states have already adjusted their minimum wage independently.[6]

This article aims to analyse how the introduction or upward adjustment of a national minimum wage interacts with and alters firms' incentives to adopt and invest in labour-augmenting technologies.

The idea that a more expensive labour input may lead to an adjustment of the labour-capital ratio is not a novel one (Dosi, 1984). However, to the best of my knowledge, this article is the first to look at the effects of a minimum wage policy on firms' strategies regarding the adoption of labour-saving technologies (the 'wage effect') in a market environment where labour cannot directly be substituted with another factor of production.[7] I argue that, if the wage pre-policy and the costs of innovation are sufficiently low, the policy-maker may not only have the capability but also the incentive to raise the minimum wage, to influence the firms' technological endowment and increase production efficiency. In fact, by adjusting the wage rate, the policy-maker makes the labour-augmenting technology incentive-compatible with one or more firms in a competitive framework. The resulting positive shock on the industry output level and, in turn, the negative one on the price of the final goods may benefit the consumers. Moreover, I show that both the incentives to adopt and develop a labour-augmenting innovation are described by an inverse U-shaped function of the cost of labour.

Methodologically, to analyse the strategic behaviour of manufacturers, innovators and policy-makers, I follow an Industrial Organization approach based on a simple model of Cournot competition in a vertical market. A monopolist upstream

[2] Usually, data on robots adoption by industries and firms are used to proxy automation, due to technical difficulties in gathering data on other technologies. See Frank et al. (2019) and Raj and Seamans (2018).

[3] This is relevant also in light of the rise of new types of informal employment agreements such as on-demand workers and gigs. Hara et al. (2018) show that only 4% of the workers on the Amazon MTurk platform earn an hourly wage higher than the U.S. minimum wage. Also, Katz and Krueger (2016) suggest that alternative work agreements increased from 10.7% to 15.8% from 2005 to 2015 in the USA, almost 94% of the net employment increase in the same period. See also De Stefano (2016) and Durward and Blohm (2017).

[4] The Italian Government introduced a minimum income scheme in 2018 that provides unemployed workers with a guaranteed income during their search for a new job. At the EU level, in May 2020, the European Commission registered a new citizens' initiative for the introduction of an unconditional basic income in EU countries.

[5] Advancing the EU social market economy: adequate minimum wages for workers across Member States, available at https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1968

[6] Those states are California, Connecticut, Illinois, Maryland, Massachusetts, New Jersey, New York and Florida. The list is expected to grow in the upcoming months. Furthermore, due to political pressure, in 2018, Amazon decided to raise the minimum wage for its US employees to 15$/h.

[7] Tesla's slowdown of Model 3 production due to excessive automation in 2018 suggests that labour is still a necessary input. See Samuel Gibbs, *The Guardian*, April 16, 2018.

innovator sells a labour-augmenting technology to several downstream manufacturers, who have to decide between adopting a costly superior technology, which is assumed to boost labour productivity or carrying on a standard one, which is of lower quality and freely available in the market.[8] Examples of technologies that improve the productivity of labour abound. Among the I4.0 technologies, robots and cobots are the most established ones.[9] 'Cobots', or collaborative robots, are special machines that operate together with workers and in some cases perceive their movements to intelligently and automatically adjust their routines (Hollinger, 2016). In general, the internet of things, additive manufacturing, cloud computing and Artificial Intelligence may all be listed among the labour-augmenting technologies. However, often a production technology is a combination of two or more components, notably hardware and software. The former defines the boundaries of the range of activities that a machine can physically perform, while the latter defines the pace and precision of the machine during work operations. An example of this may be a robotic arm (technically, a cobot), which is designed to pick an object from the work surface and manipulate it somehow. Keeping it simple, the robotic arm's ability ranges between picking more or fewer items every minute, depending on how sophisticated the installed software is – that is, how precise the arm is in recognizing the item's position on the work surface.[10] There are also less-complex examples, such as exoskeletons in industrial productions, which generally consist of a wearable external support that assists workers dealing with heavy weights.

From a theoretical perspective, this article highlights the economic forces released by an increase in the minimum wage on the incentives to adopt and invest in a labour-augmenting innovation. On one hand, making labour more expensive increases the demand for less labour-intensive technology. As the effect of this technology is to allow firms to reduce their labour intensity, this implies that the higher the wage rate, the larger the benefits for the adopters of the superior technology ('cost-reducing' effect). On the other hand, all else being equal, raising the cost of a fundamental input of production exerts negative pressure on both the manufacturers' output level and the profit margins. In turn, firms employ less labour, and this lowers the potential cost-saving effect of the superior technology ('output-contraction' effect). If and only if the starting level of the wage rate is low enough, I find that the cost-reducing effect dominates the output-contraction effect, and the wage effect is positive.

The article is organised as follows. The second part of this section illustrates this article's contribution to the relevant literature. In Section 2, I outline the set up of the model and present the main assumptions. In Section 3, I analyse the effect of an increase in the wage rate on i) the manufacturers' willingness to pay for the innovation, and ii) the innovator's incentives to invest in the new software package when the price of capital is not affected by the policy. In Section 4, I test the robustness of my results by assuming that the price of capital is affected by the policy. Finally, Section 5 concludes.

### *Literature review*

Methodologically, this article draws from the literature on licensing of a cost-reducing innovation by an outsider innovator (Sen and Tauman, 2018; 2007; Milliou and Pavlou, 2013; Farrell and Shapiro, 2008; Kamien and Tauman, 2002; 1986; Katz and Shapiro, 1985). In particular, the way I model competition in vertical markets is close to Sen and Tauman (2007), although with some relevant differences. First, my paper aims to analyse the underlying forces that determine the effects of a variation in the labour cost on the incentives to adopt and develop a labour-augmenting technology. Instead, Sen and Tauman (2007) delve into the interactions between the market structure – or competition intensity – and the licensing outcomes when the innovator sells the innovation using a particular licensing scheme. Second, the nature and the effect of innovation on the firms' cost functions are different. Sen and Tauman (2007), as it is often assumed in the literature, analyse a standard cost-reducing technology, which consists of subtracting a value which represents the size of innovation from the marginal costs of production. This technology can be easily described as the adoption of a cheaper input of production, or for the sake of comparison with the analysis in this article, as a shock that reduces the worker's wage per unit of product. Instead, I model innovation as a technology that does not affect the price of the input of production, but its productivity, and therefore the intensity of the production function on that input. Thus, the effect of innovation on the marginal costs of production is proportional to the price of the input involved. This strategy creates an interdependence between the effect of innovation on costs and the costs themselves. The more expensive the input, the higher the gain from the adoption of the technology. I argue that this modelling strategy is more appropriate to analyse a labour-augmenting innovation. Finally, from a more technical perspective, the structure of the adopted licensing contract differs across the two articles. Sen and Tauman (2007) model it as an auction with royalties (AR), in which the manufacturers pay a royalty per-unit and then bid for the upfront fee. Instead, I assume that the innovator unilaterally sets a price which maximises the gap between the firms' pre- and post-innovation profits, depending on the desired (profit-maximising) number of contracts they want to sell. Then, firms decide whether to buy the technology at this price or not. This, I argue, is a more conservative assumption, as

[8] The assumption of a vertical market is motivated by the widespread diffusion of new I4.0 products produced in R&D-intensive sectors and adopted as process innovations in more traditional manufacturing sectors.

[9] The stock of industrial robots worldwide has grown by 85% during the 2014–2019 span, according to the International Federation of Robotics (IFR). Of the 2019 new robot-installations, 4.8% were collaborative robots.

[10] Foxconn (Hon Hai Precision Industry) is the main manufacturer for many high-tech industrial sectors. To assemble the final goods, Foxconn makes large use of industrial robots and updates their performance by partnering with software-oriented companies or suppliers, such as the Chinese Megvii, a start-up specialized in image recognition and deep learning technology.

it prevents the manufacturers' willingness to pay for the innovation from increasing excessively as competition increases (in other words, the replacement effect is mitigated).

The analysis in this article adopts a partial equilibrium approach. This notwithstanding, it contributes to the literature on the link between the wage rate and labour productivity. Riley and Rosazza Bondibene (2017) report that in the UK, following the 2011 increase in the national minimum wage, firms affected by the policy did not reduce their workforce but invested in the training of their employees to increase their productivity. Similarly, Kleinknecht et al. (2014) show that flexible labour may be detrimental to innovation. One of the main reasons the authors suggest is that, when short-term contracts are the prevalent form of employment in the market, workers may prefer investing in general skills to increase their employability, rather than acquiring firm-specific skills. Using firm-level data from Belgium, Garnero et al. (2016) show evidence of a negative correlation between cheap, fixed-term contracts and labour productivity. Cirillo and Ricci (2020) confirm these results using Italian data. Davis and Henrekson (2005) show how Swedish centralised wage-setting institutions acted as industrial policy, shifting the distribution of Swedish employment away from industries with a low mean wage. Landini et al. (2020) suggest that the reforms of the labour market that occurred in Italy since the early '90s created strong incentives to exploit labour cost savings as the main driver of competitive advantage.[11] All these papers share the similar conclusion that there is a positive correlation between labour cost and labour productivity (boosted by investments, training and market dynamics), which is consistent with the direct technological change argument (Acemoglu, 2002). These results also suggest that manipulation of the cost of labour may alter the strategic behaviour of firms, modifying their incentives to invest to increase the productivity of their workforce. This article offers a theoretical framework that supports this view. Moreover, I show that, by adjusting the wage rate, a PM can i) elicit her preferred equilibrium in the adoption game and ii) improve the Consumer Surplus under some conditions. Thus, from a policy perspective, this article suggests that the introduction of a minimum wage may be an adequate tool to improve the level of investments in innovative activities.

Finally, the role of wage on the incentives to innovate has been the subject of a vast amount of literature, with a special focus on rent-sharing mechanisms and the unionisation structure (Grout, 1984; Calabuig and Gonzalez-Maestre, 2002; Haucap and Wey, 2004; Petrakis and Vlassis, 2004; Manasakis and Petrakis, 2009, and Mukherjee and Pennings, 2011). Lommerud and Straume (2012) show how flexicurity – defined as smaller employment protection and a higher reservation wage for workers – unambiguously increases firms' incentives to invest in labour-saving innovations. Although I do not directly address the role of unionisation structure and wage bargaining, this article contributes to this literature as it analyses the reaction of the incentive structure of firms and innovators to an increase in the reservation wage of workers.

## 2. The model

Consider an industry made of an upstream and a downstream sector. The downstream segment is populated by $n \geq 2$ identical firms (or *manufacturers*) that compete *a lá* Cournot for a homogeneous good and face a linear inverse demand function $P(Q) = \delta - Q$, with $Q = \sum_{i=1}^{n} q_i$ being the total industry output. To produce one unit of the final product, the downstream firms employ low-skilled labour ($L$) and capital ($K$) inputs in fixed proportions. Moreover, the quality of capital ($A$) determines how many units of labour must be employed with one unit of capital to produce one unit of the final product. As an example, the capital input can be viewed as a composite device, made of a hardware device and a software package, similar to a computer. The quality of the software package, represented by $A$, enables workers to complete their tasks at a faster pace, or to waste less time moving from one workstation to another. This improvement allows the manufacturers to employ less labour per unit of goods produced. Formally, the production function of the manufacturers can be written as:

$$q_i = \min\left\{\frac{L}{1-A}; K\right\}$$

where $A = \{0, \alpha\}$. Capital is produced in the upstream segment and sold to manufacturers as an input of production. There are two types of capital available to downstream firms: a *standard* capital input, and a *high quality* one. I normalise to zero the quality of the set of *standard* software, while the quality of the *high quality* software package is indicated by $\alpha \in (0, 1)$, and represents the amount of labour per unit of product that the firms would save by adopting it.

For simplicity's sake, I assume that the hardware component is produced competitively employing labour ($K = L$) and that it is already endowed with the *standard* software package which represents current state-of-the-art technology. Competition drives the price of the hardware down to its marginal cost of production, which is the minimum wage paid to workers in the upstream sector, $r$. Instead, the new software package is developed ex-ante by the monopolist innovator, who invests $I(\alpha)$ and brings it to the market at the fixed fee $f(\alpha)$, with $f(0) = 0$ and $f'_\alpha > 0$. I assume that the innovator has the full bargaining power to determine the level of surplus extraction through $f(\alpha)$, and that the new software package is compatible with all the hardware devices of the adopting firms. Formally, the investment of the upstream supplier is represented by the convex cost function $I(\alpha) = \gamma\,\alpha^2$, where $\gamma$ represents the cost of the specific high-tech equipment that is necessary to the development of the software (including, for instance, high-skill labour). Therefore, the objective function

[11] Raitano and Fana (2019) show that young cohorts of workers who entered the Italian job market after the Italian labour market reform of 2001 had worse economic conditions than colleagues that had entered the market before the reform.

of the innovator supplier can be written as follows:

$$\pi_u = m\,f(\alpha) - \gamma\,\alpha^2 \quad (1)$$

with $m \leq n$ representing the number of manufacturers that adopt the innovative capital input and pay the fee $f(\alpha)$. The subscript $u$ indicates the *upstream* innovator.

To produce the final goods, the downstream manufacturers purchase one hardware device and hire $\frac{1}{1-A}$ units of labour, depending on the software package installed – i.e., the quality of capital. The price of labour in the downstream sector is set at the national minimum wage $w$.[12] Thus, the profit function of the downstream firms is:

$$\pi_d = \begin{cases} q_i(\delta - w - r - q_i - Q_{j\neq i}) & \text{if} \quad A = 0 \\ q_i(\delta - w(1-\alpha) - r - q_i - Q_{j\neq i}) - f(\alpha) & \text{if} \quad A = \alpha \end{cases} \quad (2)$$

where the subscript $d$ indicates the *downstream* manufacturers.

I aim to investigate the effect of an increase in the minimum wage rate $w$ by the policy-maker (PM) on the incentives of the innovator to invest in the labour-augmenting technology – i.e., the software package of quality $\alpha$ – and on the incentives of the manufacturers to adopt it. I examine two scenarios: first, I assume that the price of upstream labour ($r$) is not affected by the adjustment in the minimum wage. This is the case, for instance, when the supply chain is developed across several countries, or when the minimum wage is defined within a single sector of the industry. Then, I test the robustness of my results by assuming $r = w$ – that is, there are no differences between upstream and downstream labour markets. This represents a more conservative assumption, as it implies that a minimum wage increase makes both labour and capital inputs more expensive - the hardware device is produced employing labour - while the manufacturers can only increase the productivity of labour. The timing of the game is as follows: at time $t = 0$, the upstream innovator decides the optimal size of $\alpha$ by investing $I(\alpha)$. At time $t = 1$, they set the price $f(\alpha)$ according to the number of contracts $m$ they want to sell. Finally, at time $t = 2$, the manufacturers observe the price and the size of the innovation, choose their production technology and compete on quantities. The PM may intervene with an adjustment in the wage rate either before the game starts, or before manufacturers move. In the first case, the PM mainly influences the investment decision of the monopolist innovator by altering the characteristics of the market they are about to enter with their innovation. In the second case, the innovator alters only the strategic decisions of the manufacturers, by modifying the payoffs they are facing. As I am interested in the Subgame Perfect Nash Equilibrium, the game is solved by backward induction. Hereafter, I will refer to the upstream innovator using the male pronoun (he) and to the downstream firms and the PM using the female pronoun (she).

## 3. Results - exogenous price of capital

### *3.1. Duopoly*

To present the results as clearly and simply as possible, I first present the downstream duopoly case $n = 2$, and generalise to the $n$-oligopoly at a second stage. To comprehensively describe the effect of a rise in the minimum wage on the incentives to adopt and invest in labour-augmenting innovation, I first analyse the downstream subgame in isolation. Here, the manufacturers take the size and the price of innovation as given and decide whether to adopt it or not. If the PM introduces the minimum wage policy at the beginning of this stage, I show that she can elicit her preferred equilibrium in the adoption subgame and, as a result, influence the efficiency of the production in equilibrium. Afterwards, by backward induction, I analyse the innovator's problem and show that if the policy is enforced before the investment stage, the PM influences the investment decision of the innovator, but she is no longer able to nudge the adoption strategy of the downstream manufacturers. However, the PM can still influence the efficiency at the production level by altering the equilibrium size of labour-augmenting innovation.

*Incentives to adopt the innovation*

The downstream subgame is represented by a standard 2x2 matrix where the two firms observe a pair $(\alpha, f)$ and choose either to pay the observed fee and adopt the innovation (strategy A) or to keep producing with the standard technology without paying any fee (strategy B). The payoff matrices are shown in Table 1 (if the innovation is non-drastic) and in Table 2 (if the innovation is drastic). Following Arrow (1962), a drastic innovation is defined as a technology that, in case of asymmetric adoption, forces the rivals out of the market and generates a monopoly. In other words, innovation is drastic if its adoption by just one firm implies that the non-adopting rival is no longer able to produce any positive level of output (her best reply function collapses to zero). From Table 1, it is possible to derive the value of $\alpha$ above which the payoff of playing strategy B when the rival chooses A is non-positive. Standard calculations show that this is so when $\alpha \geq \frac{\delta - r - w}{w} \equiv \bar{\alpha}$. When this condition is satisfied, the outcomes (A,B) and (B,A) imply a change in the market structure from a duopoly to a monopoly (Table 2).

Given the size of $\alpha$ and $f$, the adoption of the technology may be profitable for both firms ($m = 2$), for only one firm ($m = 1$), or may not be profitable for any of them ($m = 0$). Using the payoff matrices, it is possible to define firm $i$'s incentives to

[12] The two versions of the capital input are perfect substitutes. They can be thought of as two vertically differentiated products. Moreover, once a manufacturer has paid the fixed fee, they are entitled to install the software on all their hardware devices.

**Table 1**
The downstream subgame in the duopoly scenario with $\alpha < \bar{\alpha}$. Payoffs of firm 1 (firm 2) are displayed on the left (right) of each cell.

| | | Firm 2 | |
|---|---|---|---|
| | | $A$ | $B$ |
| Firm 1 | $A$ | $\frac{(\delta-r-(1-\alpha)w)^2}{9}-f,\ \frac{(\delta-r-(1-\alpha)w)^2}{9}-f$ | $\frac{(\delta-r-(1-2\alpha)w)^2}{9}-f,\ \frac{(\delta-r-w(1+\alpha))^2}{9}$ |
| | $B$ | $\frac{(\delta-r-w(1+\alpha))^2}{9},\ \frac{(\delta-r-(1-2\alpha)w)^2}{9}-f$ | $\frac{(\delta-r-w)^2}{9},\ \frac{(\delta-r-w)^2}{9}$ |

**Table 2**
The downstream subgame in the duopoly scenario with $\alpha \geq \bar{\alpha}$. Payoffs of firm 1 (firm 2) are displayed on the left (right) of each cell.

| | | Firm 2 | |
|---|---|---|---|
| | | $A$ | $B$ |
| Firm 1 | $A$ | $\frac{(\delta-r-(1-\alpha)w)^2}{9}-f,\ \frac{(\delta-r-(1-\alpha)w)^2}{9}-f$ | $\frac{(\delta-r-(1-\alpha)w)^2}{4}-f,\ 0$ |
| | $B$ | $0,\ \frac{(\delta-r-(1-\alpha)w)^2}{4}-f$ | $\frac{(\delta-r-w)^2}{9},\ \frac{(\delta-r-w)^2}{9}$ |

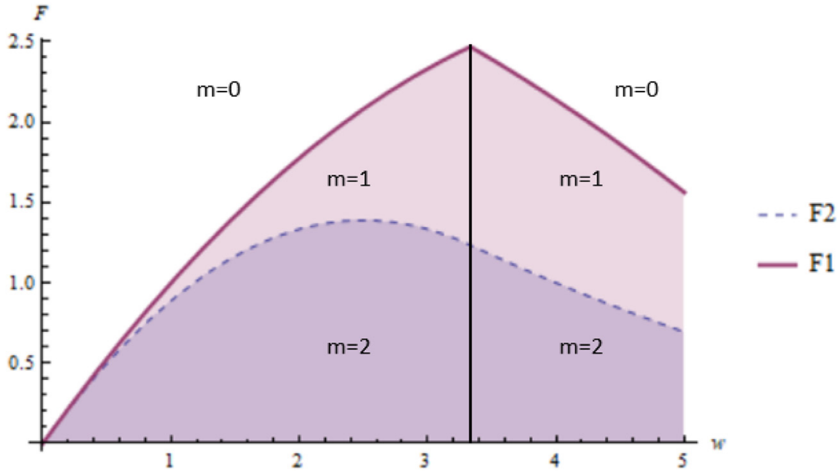


**Fig. 1.** The incentive to adopt the innovation, measured in terms of the firms' willingness to pay a fee $f$ as a function of the wage rate $w$. In order to produce this graph, I set $\alpha = 0.5$ and $\delta - r = 5$. The vertical line identifies $w = \frac{\delta-r}{1+\alpha}$.

adopt the innovation - i.e., playing strategy A - as the maximum fee that she is willing to pay when i) firm $j$ plays A, and ii) when firm $j$ plays B, with $i, j = \{1, 2\}$ and $i \neq j$. Moreover, I define $F_2$ as the maximum fee that the two firms are willing to pay to adopt the innovation simultaneously (A,A) and $F_1$ as the maximum fee that a firm is willing to pay to adopt the innovation when the rival does not ((A,B) or (B,A)).

As $F_1$ and $F_2$ represents the firms' willingness to pay for the new technology, they also mirror their incentives to adopt the innovation, which are non-monotonic in the value of the cost of labour $w$, as shown in Fig. 1. It follows that:

**Proposition 1.** *Assume the downstream market is a duopoly ($n = 2$). The effect of the wage rate on the firms' incentives to adopt an innovation provided by an outside innovator is non-monotonic, with an interior maximum. Moreover, there exist two critical values of the wage rate $\breve{w}_1$ and $\breve{w}_2$, such that $\frac{\partial F_1}{\partial w}$ ($\frac{\partial F_2}{\partial w}$) is positive if $w < \breve{w}_1$ ($w < \breve{w}_2$), and negative otherwise.*

**Proof.** See the mathematical appendix. □

Proposition 1 has important policy implications as it suggests that a policy-maker may, in some circumstances, influence the firms' strategy by adjusting the wage rate and, therefore, elicit her preferred equilibrium. Moreover, the policy-maker may have the incentive to influence that choice when the wage rate is sufficiently low. As the price of the final good depends on the number of adopters, to elicit one or two firms to buy the innovative technology may lower the price of the final good as shown in Fig. 2.

In other words, if $w$ is sufficiently low, the policy-maker may introduce an upward adjustment in the minimum wage rate as a tool to *nudge* the manufacturers to adopt the labour-augmenting innovation. In the example shown in Fig. 2, to raise the wage rate from about $w = 1$ to $w = 1.2$ elicits the adoption of the innovation by both firms – formally, the equilibrium changes from no adoption (B,B) to the symmetric adoption (A,A) of the technology. Consequently, the production of the final goods becomes more efficient and the industry output expands, with a negative effect on market price (and a positive one on

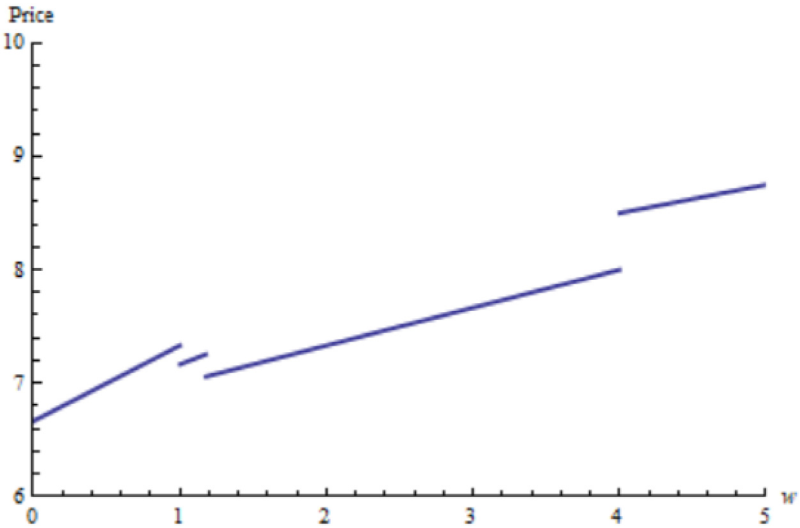


**Fig. 2.** The effect of the wage rate on the product market price, considering the firms' choice of the technological endowment. To produce this graph, and for comparison purposes with Fig. 1, I set $\alpha = 0.5$, $f = 1$ and $\delta - r = 5$.

Consumer Surplus). Instead, raising the wage rate when it is already high may have a severe impact on consumers' welfare, as it may hamper the incentives to adopt the innovation by both firms simultaneously (see Fig. 1).[13] In fact, focusing on the right-end values of $w$, to increase the wage rate above $w = 4$ is sufficient to switch the equilibrium from the symmetric equilibrium (A,A) to the asymmetric ones (A,B), (B,A). As the innovation is drastic for these values of $w$, the non-adopting firm is forced out of the market and the production is allocated entirely to the efficient adopter. Nevertheless, the increased market concentration generates a loss from the Consumer Surplus perspective.

*Incentives to invest in innovation*

As shown in the subsection above, the downstream firms' adoption choice depends on the values of $\alpha$ and $f$. Here, I present the innovator's problem and analyse the effect of the minimum wage policy introduced by the PM before the game starts on those two variables. Following the timing of the game, by backward induction, I analyse i) the price of the innovation $f$ and ii) the size of the cost-reducing effect $\alpha$. At time $t = 1$, the innovator chooses the price to maximise the revenues from licensing and considers the cost of innovation as sunk. Therefore, he sets a price that maximises his revenue flow, anticipating the choice of the downstream firms. More particularly, he anticipates that when $f \le F_2$, both firms pay the fee ($m = 2$) and obtain the technology, while when $F_1 \ge f > F_2$, only one firm does so.[14] The innovator sets either $f = F_1$ or $f = F_2$ depending on the optimal number of adopters he wants to elicit. This represents somehow the participation constraint of the innovator's maximisation problem, as any price $f > F_2$ is not compatible with $m = 2$, while any price above $f > F_1$ is not compatible with $m = 1$. Furthermore, there is no valid reason to set a price $f < F_2$ for an innovator that wants to sell his innovation to $m = 2$ firms, as this pricing strategy would imply lower revenues. Similarly, if the profit-maximising number of contracts is $m = 1$, then no fee below $f = F_1$ should be taken into consideration.[15] Standard calculations reveal that the innovator's revenues are maximised under $m = 2$ when $w < \frac{\delta - r}{1+\alpha}$ – that is, the innovation is non-drastic - and under $m = 1$ otherwise – that is, the innovation is drastic. Going backwards, at time $t = 0$, the innovator invests in innovation and sets $\alpha$ to maximise his profits. Specifically, the innovator maximises the difference between the manufacturers' pre- and post-adoption payoffs. Intuitively, the size of innovation is regulated by the cost parameters $\gamma$, on the innovator's side, and $w$, on the manufacturers' side. As I have shown in the previous section, the effect of the wage rate $w$ on $F_1$ and $F_2$ – i.e., the firms' incentives to adopt the innovation – is inversely U-shaped (Proposition 1). Instead, the cost parameter $\gamma$, which signals how costly the R&D process is, represents the pure cost for the innovator. All these forces are internalised in the equilibrium size of innovation $\alpha(w, \gamma)$ - the inventor's incentives to invest in innovation. As derived in the previous

[13] This is so because the profit margins are already very thin and a cost increase would generate a loss which is not compensated by the increase in labour productivity.

[14] Jehiel and Moldovanu (2000) use a different condition. Assuming the manufacturers bid in an auction for the innovation licensed by an upstream innovator, they consider that the exit option of the manufacturers is affected by the expectation of the adoption of the high-quality technology by rivals. Similarly, Sen and Tauman (2007) adopt a similar structure, with firms paying a royalty per unit of output and bidding for the upfront fees (auction with royalties). In my case, this would imply that, for asymmetric adoption, firms compare payoffs on the secondary diagonal of Tables 1 and 2. However, I believe that the current pricing strategy represents a more conservative solution, as it mitigates the replacement effect when the competition is more intense.

[15] Note also that an innovator who wants to sell $m = 1$ contracts would not set a price $f < F_2$, as this would not be compatible with the incentives of the downstream manufacturers.

subsection, the PM can improve the efficiency of the market by introducing a minimum wage rate, when the initial wage rate is low. For consistency's sake, I focus on the scenario in which the innovation is non-drastic – that is, when the initial level of the wage rate is low.[16]

$$\alpha^*(w,\gamma) = \min\left\{\frac{4w(\delta - r - w)}{9\gamma}, 1\right\} \tag{3}$$

One can see that, as the maximum value of $\alpha^*(w,\gamma)$ is reached in $w = \frac{\delta - r}{2}$, it follows that the necessary condition for $\alpha^*(w,\gamma) < 1$ is $\gamma > \frac{(\delta - r)^2}{9}$. Eq. 3 is helpful to detail the effect of the wage rate on the incentives to invest in labour-augmenting innovation. In fact, after a simple manipulation, it is possible to rewrite:

$$\alpha^*(w,\gamma) = \frac{2(\delta - r - w)}{3}\,\frac{2w}{3\gamma} \equiv Q^c(w)\,\eta(w,\gamma) \tag{4}$$

where $Q^c(w)$ represents the benchmark Cournot industry output in absence of innovation, while $\eta(w)$ is a positive multiplier that depends exclusively on cost parameters. Following these notations, it is possible to decompose the effect of the wage rate on the size of innovation (the wage effect) as follows:

$$\frac{\partial\,\alpha^*(w,\gamma)}{\partial\,w} = Q^c(w)\,\eta'_w + \eta(w,\gamma)\,Q^{c'}_w \tag{5}$$

The first term of Eq. 5 represents the positive 'cost-reducing' effect, while the second term, which is negative, is the 'output-contraction' effect. The former is because as the wage rate increases (and labour becomes more expensive), the firm's reservation value for a less labour-intensive technology rises. In contrast, the latter is due to the fact that an increase in the wage rate affects the firm's output level negatively, as production is more expensive. Everything else being equal, this reduces the demand for the input in equilibrium and hampers the gains of replacing the old technology with a more efficient one. The dominance of one of these two forces determines the sign of the wage effect.

**Proposition 2.** *Assume that the downstream market is a duopoly (n=2). The equilibrium level of investment $\alpha^*(w,\gamma)$ undertaken by the upstream innovator depends on the wage rate. There exists a critical value $w^*$ such that ${\alpha^*}'_w > 0$ for $w < w^*$ and ${\alpha^*}'_w < 0$ otherwise. Moreover, $\alpha^*(0,\gamma) = 0$.*

**Proof.** See the mathematical appendix. □

*Consumer Surplus*

The analysis above shows that the innovator spontaneously chooses to cover the market in equilibrium, and he does so by offering the new technology at a price which is compatible with the participation constraint of the manufacturers. Thus, increasing the national minimum wage before the investment stage at $t = 0$ does not influence the equilibrium in the adoption stage. However, the PM can nudge the equilibrium size of innovation $\alpha(w,\gamma)$. By doing so, the PM alters the effect of the innovation on the industry output:

$$Q^*(w,\gamma) = \frac{2(\delta - r - w)}{3}\,\frac{9\gamma + 4w^2}{9\gamma} = Q^c(w)\,\psi(w,\gamma)$$

where it is easy to observe that $\psi(w,\gamma) > 1\ \forall\, w$.

Standard calculations show that the first derivative of the total industry output is:

$$\frac{\partial\,Q^*(w,\gamma)}{\partial\,w} = \begin{cases} > 0 & \text{if} \quad w \in (w_{min}, w_{max}) \\ \leq 0 & \text{otherwise} \end{cases} \tag{6}$$

where $w_{\min} = \frac{\left(8(\delta - r) - \sqrt{64(\delta - r)^2 - 432\gamma}\right)}{24}$ and $w_{\max} = \frac{\left(8(\delta - r) + \sqrt{64(\delta - r)^2 - 432\gamma}\right)}{24}$. It follows that:

**Proposition 3.** *Assume that the downstream market is a duopoly (n=2) and let $\gamma \in \left(\frac{(\delta - r)^2}{9}, \frac{4(\delta - r)^2}{27}\right)$ holds. The equilibrium output level $Q^*(w,\gamma)$ produced by the manufacturers with the labour-augmenting technology depends on the wage rate. Moreover, there exists a range of values $W = [w_{\min}, w_{\max}]$ such that $Q^{*'}_w > 0$ if $w \in W$, and $Q^{*'}_w < 0$ otherwise.*

**Proof.** By looking at $w_{\min}$ and $w_{\max}$, one can see that those are real numbers as long as the cost of innovation parameter satisfies $\gamma < \frac{4(\delta - r)^2}{27}$ (see Fig. 3). □

In a model with linear demand function, the Consumer Surplus is a simple monotonic transformation of the industry output. Thus, Proposition 3 applies also to Consumer Surplus under the same conditions.

Let me summarise the results in this section. The PM can influence the equilibrium of the game by adjusting the wage rate. First, consider the case in which the minimum wage rate is introduced just before the downstream subgame starts

[16] In the mathematical appendix, I show that the necessary condition for the innovation to be non-drastic is $w < \sqrt{2\gamma}$. The analysis of the scenario in which the innovation is drastic does not add relevant information to the analysis and it is therefore omitted here.

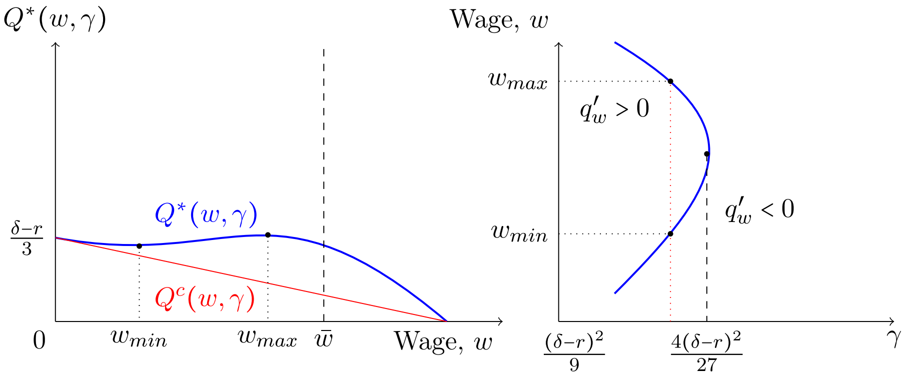


**Fig. 3.** In the left panel, the equilibrium output $Q^*(w, \gamma)$, depending on the wage rate $w$. In the right panel, the range of values $W = [w_{\min}, w_{\max}]$ within which an increase in the wage rate has a positive effect on $Q^*(w, \gamma)$, as a function of the cost parameter $\gamma$. Notice that, when $w > \bar{w}$, the innovation becomes drastic.

(between $t = 1$ and $t = 2$). Then, the PM cannot alter the choice of the innovator, but she can influence the manufacturers' outcomes. In particular, the PM can change their technology-adoption strategy. Furthermore, as the output levels in the different equilibria are different, by nudging the firms into the most efficient one (A,A), the PM can increase the level of production and improve the Consumer Surplus.

Instead, if the policy is introduced before the investment stage (before $t = 0$), the PM directly affects the choice of the innovator. Moreover, by changing the market environment, an adjustment in the minimum wage rate may foster the innovator's investment in the size of the labour-augmenting technology. Under some conditions, this policy has a positive effect on the output level and Consumer Surplus. However, as the simultaneous adoption of the innovation by the two manufacturers is the profit-maximising choice for the innovator, an adjustment in the minimum wage is not required to reach the most efficient equilibrium in the downstream subgame.

### *3.2. Oligopoly*

*Incentives to adopt the innovation*

The results derived in the previous subsection can be extended to the more general case of an oligopolistic downstream segment of the market. In the following section, I introduce competition in the market by assuming that the number of manufacturers is $n \geq 2$. The major difference between this scenario and the duopoly one is that the size of the negative externalities exerted on non-adopting firms by the adopting ones depends on the number of the latter. As I consider an innovation whose ultimate effect is a reduction of the marginal cost of production, the adopting firms gain a competitive advantage in the production of the final good compared with the non-adopting one. Thus, the more firms that adopt the innovation, the stronger the negative effect on non-adopters' profitability. Eventually, when a sufficiently large number of firms adopt an innovation of a given size $\alpha$, the consequent negative externalities push the profits of non-adopters into negative territory, forcing them to leave the market.[17] This feature of the oligopoly model has an important effect on the incentive structure of the innovator and his choice of the size and the price of the innovation. Instead, it does not modify the effect of an increase in the minimum wage on the manufacturers' incentives to adopt the innovation. It is possible to generalise the result in Proposition 1 as follows:

**Proposition 4.** *Assume that the downstream segment of the market is a n-oligopoly. There exists a critical value of the wage rate* $\check{w}_m$ *such that* $\frac{\partial F_m}{\partial w} > 0$ *if* $w < \check{w}_m$*, while it is negative otherwise.*

**Proof.** See the mathematical appendix. □

*Incentives to invest in innovation*

In addition to the complete adoption of the non-drastic innovation and the partial adoption of the drastic one (with the non-adopters' exit), in an oligopolistic framework, the adoption of a non-drastic innovation by a limited number of firms is a possible outcome. Thus, at stage $t = 1$, the innovator must choose the price of the innovation to elicit the profit maximising number of adopters among the manufacturers. Because $m$ is a discrete number, deriving it from the first-order condition would not be very rigorous, especially when the competition is not very intense – that is, for low values of $n$. Nevertheless, it may be helpful to analyse the relationship between the level of competition and the adoption rate.[18] As a

[17] Sen and Tauman [2007] define these large innovations as *k-drastic*. According to their definition, an innovation is *k-drastic* if $k$ is the minimum number such that, if at least $k$ firms adopt the innovation, the non-adopting rivals are forced out of the market and a natural $k$-oligopoly is created.

[18] See the mathematical appendix.

reference value, this helps insofar as it shows clearly that $1 > m_n' > 0$. Thus, if competition becomes tougher, the number of contracts that the innovator wants to sell increases, but at a slower pace. In other words, by defining the rate of adoption as $\mu(\alpha, n) = \frac{m(\alpha,n)}{n}$, one can see that $\mu_n' < 0$, which means that partial adoption becomes more likely the more intense the competition is. However, as already mentioned, this way of computing the number of adopters by considering it as a continuous variable does not yield the most accurate result, especially when the number of active firms in the market $n$ is low. For this reason, in the remainder of this subsection, I estimate the optimal number of contracts using a standard comparison of the payoffs of the innovator in the different scenarios. For consistency's sake, I will focus only on non-drastic innovations.

*3.2.1. Complete adoption $m = n$*

The analysis of the case with complete adoption yields a set of results which represent a generalisation of the equivalent ones derived in the duopoly case. The innovator wants to sell the innovation to all the manufacturers when the following condition is satisfied:

$$n\,f(\alpha, n) \geq (n-1)\,f(\alpha, n-1) \qquad \text{if} \quad \alpha \leq \frac{2(\delta - r - w)}{(3n-4)w} \text{C.1} \tag{*}$$

meaning that the flow of revenues is maximised when $n$ adopters pay the price $f(\alpha, n)$.

**Proposition 5.** *Assume that the downstream segment of the market is a n-oligopoly and that condition C.1 is satisfied. There exists a critical value $w_n^*$ such that $\alpha_w^{*'} > 0$ for $w < w_n^*$ and $\alpha_w^{*'} < 0$ otherwise.*

**Proof.** See the mathematical appendix. □

*3.2.2. Partial adoption $m < n$*

Instead, if Condition C.1 does not hold, the innovator prefers eliciting the adoption by a limited number of downstream firms. In this case, the maximisation process leads to the innovator's optimal investment level:

$$\alpha(w, \gamma, m) = \frac{m\,n\,w(\delta - r - w)}{\gamma(n+1)^2 - mn(n - 2(m-1))w^2}$$

which has an interior maximum.[19] It is complex to isolate the wage effect on the incentives to invest in the general oligopoly case; in fact, to alter $w$ may affect the number of downstream adopters ($m_w' < 0$), which would, in turn, influence the equilibrium size of innovation. To overcome this problem and offer the most rigorous and accurate analysis of the wage effect possible, I now consider the particular case of a downstream triopoly $n = 3$.

To restrict the analysis to the partial adoption scenario, I define the conditions for it to be an equilibrium.

**Lemma 1.** *Assume that the downstream market is a triopoly ($n = 3$), and that $w \in (w_1, \min\{\tilde{w}, w_2\})$, with $\tilde{w} > w_1$ and $w_2 > w_1$. In equilibrium, the innovator sells $m = 2$ contracts and invests $\alpha^* = \frac{3w(\delta - r - w)}{8\gamma - 3w^2}$.*

**Proof.** See the mathematical appendix. □

One can see that, in a market as the one described in Lemma 1, Proposition 2 holds. Moreover:

**Proposition 6.** *Assume Lemma 1 holds. There exists a critical value $w_3^*$ such that $\alpha_w' > 0$ for $w < w_3^*$ and $\alpha_w' < 0$ otherwise. Moreover, $w_3^* \in (w_1, \min\{\tilde{w}, w_2\})$ if $\gamma \in \left(\frac{(\delta-r)^2}{2}, \frac{243(\delta-r)^2}{448}\right)$.*

**Proof.** See the mathematical appendix. □

Fig. 4 represents Proposition 6 graphically.

*Consumer Surplus*

The analysis above adds some relevant insights to the results obtained in the duopoly case. Specifically, it shows that a minimum wage policy introduced before the investment stage at $t = 0$ can influence the adoption strategy of the downstream firms. If we consider the triopoly example, to increase the wage rate from below $w < w_1$ to $w' \in (w_1, w_2)$ has the effect of reducing the optimal number of contracts from the innovator's perspective.

The generalisation of Proposition 3 is complicated by the large number of variables involved. However, using a numerical example, it is possible to see that Proposition 3 can be generalised for $n > 2$. In fact, assuming that $m = n = 3$, $\delta - r = 5$, and $\gamma = 1.8 > \frac{n^2(\delta-r)^2}{4(n-1)(n+1)^2}$ s.t. $\alpha < 1$, it is possible to observe that:

$$Q(w, \gamma, n) \Rightarrow \quad Q^*(w) = \frac{1.5\left(w^2 + 1.6\right)(5 - w)}{w^2 + 3.2}$$

[19] Notice that, in order to ensure an interior solution ($\alpha < 1$), it must be that $\gamma > \frac{(\delta-r)^2 mn}{(n+1)^2(8m-4(n+1))}$. One can see that when $m = n = 2$, the condition on the cost parameter $\gamma$ boils down to the duopoly condition $\gamma > \frac{(\delta-r)^2}{9}$.

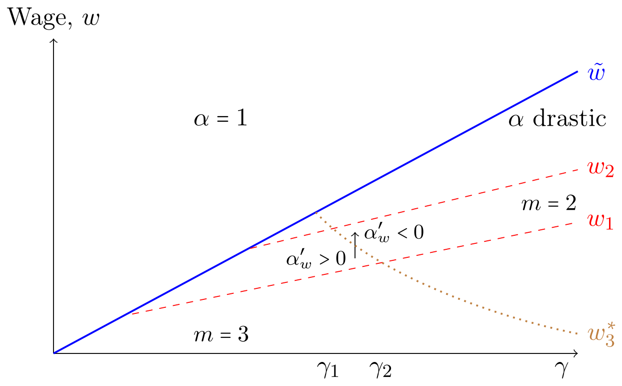


**Fig. 4.** The wage effect $\alpha'_w$ with partial adoption of the superior technology. Notice that $\gamma_1 = \frac{(\delta-r)^2}{2}$ and $\gamma_2 = \frac{243(\delta-r)^2}{448}$, and that $w_1$ and $w_2$ are parallel, positive concave functions, which are represented as straight lines for simplicity's sake.

Taking into consideration that the innovation is drastic when $w > 1.78$, we can see that $Q_w^{*'} > 0$ when $w \in (0.403, 1.245)$ and is negative otherwise.[20] Consistently with Proposition 3, with a high value of the cost parameter - i.e., $\gamma = 3$ - the wage effect on the industry output level is monotonically negative. This example suggests that the results in Proposition 3 are robust to an increase of competition in the downstream segment of the market.

## 4. Extension: Endogenous price of capital

In this section, I briefly test the robustness of Propositions 1 to 3 when the minimum wage policy affects not only the price of labour in the downstream sector but also the price of the hardware component (produced employing labour) of the capital input. To do this, I assume that the labour input employed to produce the hardware component is the same as the one employed to produce the final goods, so that $r = w$. This extension aims to link the I.O. topic on incentives of innovation to the labour-oriented literature on minimum wage. More specifically, while not abandoning the partial equilibrium model, this assumption enables me to offer a more general view on how incentives to adopt and invest in labour-augmenting innovation are driven by adjustments in the cost of labour. Intuitively, when $r = w$, the output-contraction effect is stronger, as increasing the wage rate makes both labour and capital more expensive, while firms can only increase labour productivity. For simplicity's sake, I focus only on the duopoly case ($n = 2$) with non-drastic innovations, but the analysis can be easily extended to the more general $n$-oligopoly case.

The main results on the manufacturers' and the innovator's incentives, as stated in Propositions 1 and 2, remain true when the price of capital depends on the price of labour.

**Proposition 7.** *Assume that the price of the capital input is $r = w$ and the downstream segment of the market is a duopoly. There exist two critical values of the wage rate $\check{\check{w}}_1$ and $\check{\check{w}}_1$, such that $\frac{\partial F_1}{\partial w}$ ($\frac{\partial F_2}{\partial w}$) is positive if $w < \check{\check{w}}_1$ ($w < \check{\check{w}}_2$), and negative otherwise.*

**Proposition 8.** *Assume that the price of the capital input is $r = w$ and the downstream segment of the market is a duopoly. Also, assume the innovation is non-drastic ($w < \sqrt{2\gamma}$). There exists a critical value $\check{\check{w}}_2$ such that the wage effect on a non-drastic innovation ($\alpha'_w$) is positive for $w < \check{\check{w}}_2$ and negative otherwise.*

**Proof.** The proof stems from the same procedure as for Propositions 1 and 2. See the mathematical appendix. □

*Consumer Surplus*

Finally, I analyse the effect of an increase in the wage rate before $t = 0$ on the level of output in equilibrium. As already shown, the PM does not alter the equilibrium in the downstream subgame, as the innovator already has the incentives to serve all manufacturers. However, the PM can nudge the equilibrium size of innovation $\alpha(w)$. By doing so, she alters the effect of the innovation on the industry output:

$$Q^* = \frac{2(\delta - 2w)}{3}\,\frac{(9\gamma + 4w^2)}{9\gamma} = Q^c(w)\,\psi(w,\gamma)$$

[20] Moreover, notice that when $w > 1.17$ condition C.1 stops holding. However, it is easy to observe that in case of partial adoption ($m = 2$ and $n = 3$), the first derivative of the total output function is positive for $w > 0.723$. This is easily explained by the fact that in case of partial adoption, an increase in the minimum wage exerts a stronger pressure on the less efficient firms who cannot adjust their productivity level. Thus, the production is reallocated towards the most efficient ones.

where it is apparent that $\psi(w, \gamma) > 1 \ \forall w$. Standard calculations show that the first derivative of the total industry output is:

$$\frac{\partial Q^*}{\partial w} = \begin{cases} > 0 & \text{if} \quad w \in (\tilde{w}_{min}, \tilde{w}_{max}) \\ \leq 0 & \text{otherwise} \end{cases} \tag{7}$$

where $\tilde{w}_{\min} = \frac{(\delta - \sqrt{\delta^2 - 27\gamma})}{6}$ and $\tilde{w}_{\max} = \frac{(\delta + \sqrt{\delta^2 - 27\gamma})}{6}$. One can see that $\tilde{w}_{\min}$ and $\tilde{w}_{\max}$ exist if and only if $\gamma < \frac{\delta^2}{27}$. However, since the problem requires $\gamma > \frac{\delta^2}{18}$ to have an interior solution, it is possible to state that under no conditions can the PM improve the output level by adjusting the wage rate before the innovation stage. In other words, Proposition 3 does not hold under the stricter assumption of a wage-based price of capital. This is because when the PM increases $w$, she is raising the cost of both labour and capital, exerting a negative pressure on firm profitability which is not compensated by the increase in productivity of the mere labour input.

## 5. Final remarks

During the last few years, we have been witnessing the rise of new technologies which are meant to change the way physical goods are produced. Those technologies are expected to reduce the amount of labour input that a firm must combine with capital to produce the final goods. In other words, they are expected to give a boost to labour productivity. At the same time, the calls for adjustments in the minimum wage paid to workers are becoming more frequent and pressing as this technological transformation progresses. This article analyses the effect of these policies on the incentives of firms to invest in innovation. This effect, I argue, is non-monotonic and inversely U-shaped. On the one hand, to make labour more expensive increases the demand for less labour-intensive technology. As the effect of this technology is to allow firms to reduce their labour intensity, this implies that the higher the wage rate, the larger the benefits for the adopters of the superior technology ('cost-reducing' effect). On the other hand, all else being equal, raising the cost of a fundamental input of production exerts negative pressure on both the manufacturers' output level and the profit margins. In turn, firms employ less labour, and this lowers the potential cost-saving effect of the superior technology ('output-contraction' effect). If and only if the starting level of the wage rate is low enough, I find that the cost-reducing effect dominates the output-contraction effect, and the wage effect is positive.

Moreover, I show that the policy-maker can influence the choice of the firms with respect to either the adoption of or the investments in labour-augmenting innovation. When the wage rate is sufficiently low, by adjusting it after the innovation has been developed and priced and before the manufacturers choose their technological endowment, the PM can elicit her preferred equilibrium (full adoption) by altering the manufacturers' incentives. This, of course, is interesting *if the market is not able to achieve it spontaneously*. Instead, if the policy is introduced before the innovation has been developed, the policy-maker can nudge the innovator to invest more in labour-augmenting technology, so that in equilibrium, the efficiency of the production is higher despite the higher wage rate. This result is possible if the effect of the minimum wage rate on the manufacturers' costs is modest. In fact, by assuming that the policy raises both labour and the capital inputs' prices, I show that the positive effect on the Consumer Surplus abates. However, the non-monotonic relation between wage and the size of innovation is confirmed. From a policy perspective, this article suggests that the introduction of a minimum wage may be an adequate tool to improve the level of investments in innovative activities.

## Appendix A. Mathematical Appendix

*Proof of Proposition 1*

**Proof.** When $\alpha < \bar{\alpha}$, the innovation is non-drastic – that is, in case of asymmetric adoption, the non-adopting firm can profitably compete in the market producing with the standard technology. Using the payoffs in Table 1, it is possible to show that both firms adopt the technology if:

$$f \leq f_2 \equiv \frac{(\delta - r - (1-\alpha)w)^2}{9} - \frac{(\delta - r - w(1+\alpha))^2}{9}$$

while only one firm adopts it if:

$$f_2 < f \leq f_1 \equiv \frac{(\delta - r - (1-2\alpha)w)^2}{9} - \frac{(\delta - r - w)^2}{9}$$

Finally, both firms decide not to adopt the new technology if $f > f_1$, as the new technology is simply too expensive, given the market characteristics.[21]

Instead, when $\alpha \geq \bar{\alpha}$, the innovation is drastic, meaning that the adoption of the new technology by just one firm implies the exit of the non-adopting rival from the market. The result is that, in the case of asymmetric adoption, the downstream

[21] The numerical subscripts used to define the thresholds $f_1$ and $f_2$ refer to the maximum number of firms that find the simultaneous adoption of the innovative software profitable when the fee is lower than these values.

market becomes a monopoly in which only the adopter produces the final goods. In this case, using the payoffs in Table 2, one can see that both firms adopt the innovation if:

$$f \leq \bar{f}_2 \equiv \frac{(\delta - r - (1-\alpha)w)^2}{9}$$

while only one firm adopts it if:

$$\bar{f}_2 < f \leq \bar{f}_1 \equiv \frac{(\delta - r - (1-\alpha)w)^2}{4} - \frac{(\delta - r - w)^2}{9}$$

Finally, both firms decide not to adopt the new technology if $f > \bar{f}_1$.

To sum up, the number of licensees is i) $m = 2$ if $f \leq f_2$ with $\alpha < \bar{\alpha}$, and if $f < \bar{f}_2$ otherwise; ii) $m = 1$ if $f \in (f_2, f_1]$ with $\alpha < \bar{\alpha}$, and if $f \in (\bar{f}_2, \bar{f}_1]$ otherwise; finally, iii) $m = 0$ if $f > f_1$ with $\alpha < \bar{\alpha}$, and if $f > \bar{f}_1$ otherwise. The condition for an innovation to be drastic ($\alpha \geq \bar{\alpha} \equiv \frac{\delta - r - w}{w}$) can be rearranged as $w \geq \frac{\delta - r}{1+\alpha}$. Exploiting the fact that when $w = \frac{\delta - r}{1+\alpha}$, then $f_1 = \bar{f}_1$ and $f_2 = \bar{f}_2$, it is possible to rewrite the thresholds as follows:

$$F_1 = \begin{cases} f_1 & \text{if} \quad w < \frac{\delta - r}{1+\alpha} \\ \bar{f}_1 & \text{if} \quad w \geq \frac{\delta - r}{1+\alpha} \end{cases} \qquad F_2 = \begin{cases} f_2 & \text{if} \quad w < \frac{\delta - r}{1+\alpha} \\ \bar{f}_2 & \text{if} \quad w \geq \frac{\delta - r}{1+\alpha} \end{cases}$$

The proof of Proposition 1 is easily derived by looking at the first derivative of equations $F_1$ and $F_2$. First, I focus on $F_2$, i.e., firm $i$'s maximum willingness to pay for the innovation (strategy B), when firm $j$ chooses to adopt it as well (strategy A).

$$\frac{\partial F_2}{\partial w} = \begin{cases} \frac{4(\delta - r - 2w)}{9} \begin{cases} > 0 & \text{if} \quad w < \frac{\delta - r}{2} \\ < 0 & \text{if} \quad w > \frac{\delta - r}{2} \end{cases} & \text{if} \quad w < \frac{\delta - r}{1+\alpha} \\ \frac{2(1-\alpha)(\delta - r - (1-\alpha)w)}{9} < 0 & \text{if} \quad w > \frac{\delta - r}{1+\alpha} \end{cases}$$

Since $\frac{\delta - r}{2} \leq \frac{\delta - r}{1+\alpha}$ $\forall \alpha \leq 1$, and $f_1 = \bar{f}_1$ when $w = \frac{\delta - r}{1+\alpha}$, it is easy to prove that $F_2$ reaches a maximum in $\breve{w}_2 = \frac{\delta - r}{2}$.

Now, I focus on $F_1$, which is firm $i$'s maximum willingness to pay for the innovation (strategy A), when firm $j$ chooses the standard technology (strategy B).

$$\frac{\partial F_1}{\partial w} = \begin{cases} \frac{4(\delta - r - 2(1-\alpha)w)}{9} & \begin{cases} > 0 & \text{if} \quad w < \frac{\delta - r}{2(1-\alpha)} \\ < 0 & \text{if} \quad w > \frac{\delta - r}{2(1-\alpha)} \end{cases} & \text{if} \quad w < \frac{\delta - r}{1+\alpha} \\ \frac{(\delta - r)(9\alpha - 5) + w(5-3\alpha)(1-3\alpha)}{18} & \begin{cases} > 0 & \text{if} \quad w < \frac{(\delta - r)(5-9\alpha)}{(5-3\alpha)(1-3\alpha)} \\ < 0 & \text{if} \quad w > \frac{(\delta - r)(5-9\alpha)}{(5-3\alpha)(1-3\alpha)} \end{cases} & \text{if} \quad w > \frac{\delta - r}{1+\alpha} \end{cases}$$

One can see that $\frac{\delta - r}{2(1-\alpha)} < \frac{\delta - r}{1+\alpha}$ if $\alpha < \frac{1}{3}$ and $\frac{(\delta - r)(5-9\alpha)}{(5-3\alpha)(1-3\alpha)} > \frac{\delta - r}{1+\alpha}$ when $\alpha > \frac{7}{9}$. Building on these results, we can state that $F_1$ reaches its maximum in $w = \breve{w}_1 \equiv \min\left\{\frac{\delta - r}{2(1-\alpha)}, \max\left\{\frac{\delta - r}{1+\alpha}, \frac{(\delta - r)(5-9\alpha)}{(5-3\alpha)(1-3\alpha)}\right\}\right\}$. Depending on $\alpha$, the maximum is reached before, at or after the 'drasticity' level of $w$. Moreover, $\breve{w}_1 = \frac{\delta - r}{2(1-\alpha)}$ if $\alpha < \frac{1}{3}$, $\breve{w}_1 = \frac{\delta - r}{1+\alpha}$ if $\alpha \in \left[\frac{1}{3}, \frac{7}{9}\right)$, and $\breve{w}_1 = \frac{(\delta - r)(5-9\alpha)}{(5-3\alpha)(1-3\alpha)}$ if $\alpha \geq \frac{7}{9}$ and the second part of Proposition 1 is proven. □

*Proof of Proposition 2*

**Proof.** Looking at the innovator objective function, it is possible to prove that, when the innovation is non-drastic, full adoption is more profitable than partial adoption from the innovator's perspective, while the opposite is true when the innovation is drastic.

$$2f_2 = \frac{8\alpha w(\delta - r - w)}{9} > \frac{4\alpha w(\delta - r - w(1-\alpha))}{9} = f_1 \qquad w < \frac{\delta - r}{1+\alpha}$$

$$2\bar{f}_2 = \frac{2(\delta - r - (1-\alpha)w)^2}{9} < \frac{(\delta - r - (1-\alpha)w)^2}{4} - \frac{(\delta - r - w)^2}{9} = \bar{f}_1 \qquad w > \frac{\delta - r}{1+\alpha}$$

Thus, the profit-maximising level of innovation when the innovator develops a non-drastic innovation, and when he develops a drastic one, can be written as:

$$\alpha^* = \begin{cases} \frac{4(\delta - r - w)w}{9\gamma} & \text{if} \quad w < \frac{\delta - r}{1+\alpha^*} \\ \frac{(\delta - r - w)w}{4\gamma - w^2} & \text{if} \quad w \geq \frac{\delta - r}{1+\alpha^*} \end{cases}$$

The innovator is better off when the innovation is drastic. Therefore, in order to rule out this scenario, we must look at the region of parameters $\gamma$ and $w$ such that it is not feasible for the innovator to develop a drastic innovation. Substituting the drastic level of $\alpha^*$ in the condition $w \geq \frac{\delta - r}{1+\alpha^*}$, one can see that:

$$w \geq \frac{\delta - r}{1+\alpha^*} = \frac{\delta - r}{1 + \left(\frac{(\delta - r - w)w}{4\gamma - w^2}\right)} \Rightarrow w \geq \sqrt{2\gamma}$$

At the same time, the non-drastic innovation satisfies $w < \frac{\delta - r}{1+\alpha^*}$ if

$$w < \frac{\delta - r}{1+\alpha^*} = \frac{\delta - r}{1 + \left(\frac{4(\delta - r - w)w}{9\gamma}\right)} \Rightarrow w < \frac{3\sqrt{\gamma}}{2}.$$

Since $\frac{3\sqrt{\gamma}}{2} > \sqrt{2\gamma}$, it implies that $w < \sqrt{2\gamma}$ is a sufficient and necessary condition for the innovator to elicit full adoption and develop a non-drastic innovation.

From here, standard calculations show that:

$$\frac{\partial \alpha^*}{\partial w} = \frac{4(\delta - r - 2w)}{9\gamma} > 0 \quad \text{if} \quad w < \frac{\delta - r}{2}$$

Keeping in mind that a non-drastic innovation requires $w < \sqrt{2\gamma}$ and that $\gamma > \frac{(\delta - r)^2}{9}$, one can see that $\frac{\delta - r}{2}$ is a maximum when $\gamma > \frac{(\delta - r)^2}{8}$. Instead, if $\gamma \in \left(\frac{(\delta - r)^2}{9}, \frac{(\delta - r)^2}{8}\right]$, the sign of $\alpha'_w$ is always positive. □

*Proof of Proposition 4*

**Proof.** Proposition 4 is a generalization of Proposition 1. Therefore, the proof stems from the same logic. Moreover, one can see that $\bar{\bar{w}}(n=2, m=2) = \frac{\delta - r}{2}$, $\bar{\bar{w}}(n=2, m=1) = \frac{(5-9\alpha)(\delta - r)}{(5-3\alpha)(1-3\alpha)}$, which are the same values as those in Proposition 1. The downstream subgame has $n$ players and two strategies. Each firm must decide which technology to use for the production of the final goods. As in the duopoly case, they observe the pair $(\alpha, f)$ and decide which technology to adopt in order to produce the final good between the superior one (strategy A) and the standard one (strategy B). If the innovation is non-drastic, the payoffs of the $m \le n$ firms that adopt the innovative technology can be written as:

$$\pi_d(\alpha, m) = \frac{(\delta - r - w(1 - \alpha(n - m + 1)))^2}{(n+1)^2} - f$$

while the payoffs of the $n - m$ firms that carry out the production with the standard technology can be written as:

$$\pi_d(0, m) = \frac{(\delta - r - w(1 + \alpha m))^2}{(n+1)^2}$$

from which it is easy to show that the innovation has drastic effects on competition when $\alpha > \frac{\delta - r - w}{m w} \equiv \bar{\alpha}(m)$. When this threshold is exceeded and the number of adopters is smaller than the total number of manufacturers ($m < n$), then all non-adopters are simultaneously forced to exit the market, as they are no longer able to compete profitably against their more efficient rivals. When $\alpha > \bar{\alpha}(m)$, the payoffs of the $m$ adopters can be rewritten as:

$$\bar{\pi}_d(\alpha, m) = \frac{(\delta - r - w(1 - \alpha))^2}{(m+1)^2} - f$$

Instead, the payoff of the non-adopting firms is zero, as they exit the market.

In any case, the maximum willingness to pay for the innovation is estimated for each firm from the comparison of the payoff she obtains with the new technology and the payoff she earns by keeping the standard one. Specifically, a manufacturer is willing to adopt the innovation if:

$$f \quad \text{s.t.} \begin{cases} \pi_d(\alpha, m) \ge \pi_d(0, m-1) & \text{if} \quad \alpha < \bar{\alpha}(m) \\ \bar{\pi}_d(\alpha, m) \ge \pi_d(0, m-1) & \text{if} \quad \alpha \in [\bar{\alpha}(m), \bar{\alpha}(m-1)) \\ \bar{\pi}_d(\alpha, m) \ge 0 & \text{if} \quad \alpha > \bar{\alpha}(m-1) \end{cases}$$

In other words, a firm pays the fee $f$ if and only if the fact of being an adopter guarantees her higher returns than operating with the standard technology, all else being equal. Considering that $\alpha > \bar{\alpha}(m)$ can be rearranged as $w < \frac{\delta - r}{1+m\alpha} \equiv \bar{w}$, it is possible to use the payoffs introduced above to update the manufacturers' willingness to pay for the innovation, depending on the number of simultaneous adoptions:

$$F_m = \frac{\alpha n w(2(\delta - r - w) + \alpha w(n - 2(m-1)))}{(n+1)^2}$$

As in the duopoly case, the incentives to adopt the innovation display a non-monotonic relation with the wage rate. Moreover, standard calculations reveal that $\frac{\partial F_m}{\partial w} = 0$ if $w = \check{w}_m = \min\left\{\bar{w}, \bar{\bar{w}}\right\}$ with, $\bar{\bar{w}} = \frac{\left(m\left(\alpha\left(m^2+m-1\right)+m+2\right)-(1-\alpha)n(n+2)\right)(\delta - r)}{\left(\alpha\left(m^2-n-2\right)+m+n+2\right)\left(\alpha m^2-(1-\alpha)n+m\right)}$ and $\bar{w} = \frac{\delta - r}{1+m\alpha}$.

Thus, Proposition 1 holds also in the more general case of downstream $n$-oligopoly. □

*Proof of Proposition 5*

**Proof.** Proposition 5 is a generalization of Proposition 2. Therefore, the proof stems from the same logic.

From the definition of $F_m$, it is possible to derive the number of adopters that maximises the innovator's revenues:

$$\frac{\partial\, m\, F_m}{\partial\, m} = 0 \quad \Rightarrow \quad m(\alpha, w, n) = \frac{n+2}{4} + \frac{\delta - r - w}{2\,\alpha\, w}$$

Notice that $0 < m'_n < 1$. As the number of adopters cannot exceed the number of active manufacturers, it is possible to write $m = \min\{m(\alpha, w, n), n\}$.

The equilibrium level of investment in the full adoption scenario is:

$$\alpha^*(w, \gamma, n) = \frac{n^2(\delta - r - w)w}{\gamma(n+1)^2 + n^2(n-2)w^2}$$

From which, it is easy to observe that:

$$\frac{\partial\, \alpha^*(w, \gamma, n)}{\partial\, w} = \frac{n^2\big((\delta - r)(\gamma(n+1)^2 - (n-2)n^2w^2) - 2\gamma(n+1)^2w\big)}{\big(\gamma(n+1)^2 + (n-2)n^2w^2\big)^2} = 0 \qquad \text{if} \quad w < w_n^*$$

with $w_n^* = \frac{\sqrt{\gamma(n+1)^2\left((n-2)n^2(\delta-r)^2+\gamma(n+1)^2\right)}-\gamma(n+1)^2}{(n-2)n^2(\delta-r)} < (\delta - r)\ \forall\, \gamma > 0$.

It is possible to see that, when $n = 2 \quad \Rightarrow \quad \alpha^*(w, \gamma, 2) = \frac{4w(\delta-r-w)}{9\gamma}$, which is the same as in the duopoly scenario. If this is the case, then Proposition 2 holds. □

*Proofs of Lemma 1 and Proposition 6*

**Proof.** The proof to the first part of Proposition 6 stems from the same logic as the proof to Proposition 2 and 5. Assuming $n = 3$, it is possible to derive the payoffs of the innovator if $m = 1$, $m = 2$ and $m = 3$, and determine by comparison what scenario yields higher returns:

$$\pi_u = -I(\alpha) + \begin{cases} \frac{3\alpha\, w(2(\delta-r-w)+3\alpha\, w)}{16} & \text{if} \quad m = 1 \\ \frac{6\alpha\, w(2(\delta-r-w)+\alpha\, w)}{16} & \text{if} \quad m = 2 \\ \frac{9\alpha\, w(2(\delta-r-w)-\alpha\, w)}{16} & \text{if} \quad m = 3 \end{cases}$$

Focusing on non-drastic innovations only, it is possible to observe that $m = 3$ if $\alpha < \frac{2(\delta-r-w)}{5w}$ and $m = 2$ if $\alpha \in \left[\frac{2(\delta-r-w)}{5w}, \frac{(\delta-r-w)}{2w}\right)$. Thus, the equilibrium size of the labour-augmenting innovation at time $t = 0$ can be written as:

$$\alpha^*(\gamma, w) = \begin{cases} \frac{3w(\delta-r-w)}{8\gamma-3w^2} & \text{if} \quad w \in (w_1,\, w_2) \\ \frac{9w(\delta-r-w)}{16\gamma+9w^2} & \text{if} \quad w \le w_1 \end{cases}$$

with $w_1 = \frac{4\sqrt{\gamma}}{\sqrt{21}}$, and $w_2 = \frac{2\sqrt{2\gamma}}{3}$. Notice that, when $w > w_2$, the innovation is drastic. The first line of the equation represents the equilibrium investment that elicits $m = 2$ contracts. This equilibrium exists if the condition $w \in (w_1,\, w_2)$ is satisfied. Instead, the second line is the equilibrium level of investment that fosters $m = 3$. Therefore, keeping in mind that $\alpha < 1$ when $w < \tilde{w} \equiv \frac{8\gamma}{3(\delta-r)}$, Proposition 6 is easily proved by taking the first derivative of the equilibrium level of innovation with $m = 2$ which is equal to zero when $w = w_3^* \equiv \frac{2\left(4\gamma-\sqrt{16\gamma^2-6(\delta-r)^2\gamma}\right)}{3(\delta-r)}$. Moreover, it is straightforward to see that $w_1 < w_3^*$ if $\gamma < \frac{243(\delta-r)^2}{248}$ and $w_2 > w_3^*$ if $\gamma > \frac{(\delta-r)^2}{2}$. Moreover, $\tilde{w} > w_3^*$ if $\gamma > \frac{3(\delta-r)^2}{8}$. Since $\tilde{w} > w_2$ if $\gamma > \frac{(\delta-r)^2}{8}$ and $\frac{(\delta-r)^2}{2} > \frac{3(\delta-r)^2}{8} > \frac{(\delta-r)^2}{8}$, the condition for $w_3^* \in (w_1, \min\{\tilde{w}, w_2\})$ is as described in the second part of Proposition 6. □

*Proofs of Corollary 7 and 8*

**Proof.** When the innovation is non-drastic - i.e., when $\alpha < \bar{\alpha}$ - both firms adopt the technology if:

$$f \le f_2 \equiv \frac{(\delta - (2-\alpha)w)^2}{9} - \frac{(\delta - w(2+\alpha))^2}{9}$$

while only one firm does it if:

$$f_2 < f \le f_1 \equiv \frac{(\delta - 2(1-\alpha)w)^2}{9} - \frac{(\delta - 2w)^2}{9}$$

Finally, both firms decide not to adopt the new technology if $f > f_1$. Instead, when the innovation is drastic - i.e., $\alpha \geq \tilde{\alpha}$ - both firms adopt the innovation if:

$$f \leq \tilde{f}_2 \equiv \frac{(\delta - (2-\alpha)w)^2}{9}$$

while only one firm does it if:

$$\tilde{f}_2 < f \leq \tilde{f}_1 \equiv \frac{(\delta - (2-\alpha)w)^2}{4} - \frac{(\delta - 2w)^2}{9}$$

Finally, both firms decide not to adopt the new technology if $f > \tilde{f}_1$. It is possible to rewrite the thresholds as follows:

$$F_1 = \begin{cases} f_1 & \text{if} \quad w < \frac{\delta}{2+\alpha} \\ \tilde{f}_1 & \text{if} \quad w \geq \frac{\delta}{2+\alpha} \end{cases} \qquad F_2 = \begin{cases} f_2 & \text{if} \quad w < \frac{\delta}{2+\alpha} \\ \tilde{f}_2 & \text{if} \quad w \geq \frac{\delta}{2+\alpha} \end{cases}$$

From which it is easy to derive that $\frac{\partial F_1}{\partial w}$ is positive if $w < \check{\tilde{w}}_1 \equiv \min\{\frac{\delta}{2(2-a)}, \frac{\delta}{2+\alpha}\}$, and negative otherwise; also, $\frac{\partial F_2}{\partial w}$ is positive if $w < \check{\tilde{w}}_2 \equiv \frac{\delta}{4}$. This proves Proposition 7.

The equilibrium size of innovation can be written as:

$$\alpha^*(w, \gamma) = \min\left\{\frac{4w(\delta - 2w)}{9\gamma}, 1\right\}$$

As $\alpha$ reaches its maximum at $w = \frac{\delta}{4}$, it is straightforward to demonstrate that $\alpha^*(w, \gamma) < 1$ if $\gamma > \frac{\delta^2}{18}$. This proves Proposition 8. □

## Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijindorg.2021.102715.

## CRediT authorship contribution statement

**Luca Sandrini:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.

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