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From wages to widgets: how minimum wage hikes fuel automation

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This study considers the relationship between the recent technological advancements in robotics and three key economic factors which arguably define labour market well-being: wages, productivity, and labour share. Given these advancements, many forecasts have been made regarding the repercussions of technological adoption for the labour market. However, we rely on empirical evidence to examine these phenomena and project the future trajectory. By developing a theoretical model and using data on robot adoption from six European economies that implemented minimum wage in the 21st century, this study analyses the effects of minimum wage policies on robot adoption and, in turn, the impact of robot adoption on productivity and labour share. Our findings suggest that the implementation of minimum wage policies is associated with an increase in robot installations, which, subsequently results in higher productivity and a greater labour share of income.

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Introduction

Robots have for decades been a core component of manufacturing processes, but their application in the modern world extends far beyond only manufacturing. The use of these industrial robots is attributed to factors such as the need to increase productivity and reduce costs. The reduction of costs, particularly labour costs, is more relevant in high-income countries, including those with minimum wage laws, as the savings from robot adoption are greater in these economies compared to low-wage countries. Therefore, scholars increasingly argue that robots in industrialised economies are responsible for the shrinking labour share, an issue that is projected to be exacerbated in the coming years (Heer et al., 2023; Brambilla et al., 2023). These forecasts persist despite empirical evidence suggesting that productivity is increasing due to the use of robots (Liu et al., 2024; Ballestar et al., 2020), which may have important implications for the labour share. Thus, it is more pertinent to ask whether the rise of robots in recent years has exacerbated these trends? Can the labour market seamlessly adapt to the shifting technological landscape? Do robots also affect productivity, and does that play any role in affecting labour share? Will the compensation mechanisms from this technology help completely re-equilibrate the job market?

Wages can significantly impact both automation and the labour market. According to Brummund and Strain (2020), firms may be hesitant to alter their production processes or their workforce in response to minimum wage hikes due to the high transition costs involved. However, if businesses believe that the wage increases are permanent and may continue in perpetuity, they might be more inclined to modify their operations and workforce accordingly. Although adopting and maintaining a new technology can be costly for some firms, they may find this option more attractive if wages are expected to increase significantly, thereby narrowing the gap between labour cost and automation cost.

Most studies in this field either consider the overall labour market influences of minimum wage or focus on specific employment groups (e.g., Bassanini and Duval, 2006; Addison and Ozturk, 2012; Sturn, 2018). Likewise, several studies examine the effect of wages and robots on employment (see Sharfaei, 2024), with some even investigating the role of minimum wage hikes in the adoption of labour-saving devices such as touch screen technologies (e.g., Ashenfelter and Jurajda, 2022). However, no study has yet explored how an increase in the minimum wage might affect robot adoption by firms in order to cut labour costs. This is particularly relevant given that jobs which are easier to automate, such as those typically earning minimum wage, might react more strongly to wage increases compared to other types of jobs.

This study extends the literature by investigating the effects of minimum wage laws on robotisation from three perspectives. First, we develop a model to show how firms in a competitive market decide between labour and robots for production. In this model, when the minimum wage increases, the cost of hiring rises, pushing firms toward automation. This improves productivity and lowers costs, resulting in lower prices or higher demand. Consequently, while initial automation lowers labour demand, higher output can later increase the demand for labour, which could compensate the initial displacement, with implications for labour's share of income.

Second, we empirically test these dynamics in six European economies. More specifically, we explore whether low-skilled workers are being replaced by robots as a direct consequence of minimum wage increases. We also examine the effects of robotisation on productivity and labour share. We begin with the premise that an increase in wages incentivises firms to automate certain jobs. As a result, the productivity of the remaining workforce rises as robots complement their work. The ultimate impact of these influences on labour share will crucially depend on whether the increased productivity leads to more demand for labour through compensation mechanisms. Third, using the theoretical framework of the compensation mechanisms, we explain both theoretically and empirically how new technologies impact labour demand, and we make the case for adding a seventh category, compensation mechanism from a reduction in costs.

There have been numerous studies that have examined robot adoption's influence on productivity (Antonietti et al., 2023; Sharfaei and Bittner, 2024). The focus on productivity in economics is not surprising, especially since it has been observed that total factor productivity has fallen from 1.5% to 1.0% annually over the last five decades (Crafts and Mills, 2017). Since the late 1990s, and particularly following the global financial crisis, nearly all countries in the Organisation for Economic Co-operation and Development (OECD) have suffered a deceleration in worker productivity growth. This deceleration can also be observed in developing countries, which experienced a wave of productivity growth early in the millennium but then peaked around the time of the global financial crisis (Syverson, 2017). Many efforts have been undertaken to understand the reasons behind this decline, particularly because of the apparent paradox it creates between the promised benefits of a technologically advanced future and the present economic stagnation. This phenomenon is often known to as the Solow (1987). Exploring the impact of robotisation on productivity and labour share might shed some light on the issue.

Our paper is related to studies that investigate the causal effects of higher wages on automation and labour share. For instance, Hémous and Olsen (2022) develop a model demonstrating that low-skilled wages rise due to horizontal innovation, which motivates more automation. Initially, this can depress low-skill wages and reduce overall labour share. Eventually, the economy reaches an equilibrium with a stable proportion of automation-driven innovation. During this phase, low-skill incomes increase, but at a less rapid pace relative to the high-skilled and overall GDP growth. More closely related to our study, however, is Zeira (1998). It posits that productivity gains are associated with higher wages, which in turn incentivise capital investment, thereby driving wage growth.

Different from these models, ours integrates both productivity and labour share into the framework. Moreover, while in these models the catalyst for higher wages is horizontal innovation (Hémous and Olsen, 2022) and increases in total factor productivity (Zeira, 1998), in our case, it is minimum wage policies. However, in all these frameworks, including ours, higher wages incentivise automation. In our model, as minimum wages are implemented (or raised), the incentive to automate increases. More automation may lead to short-term declines in labour share; however, as labour becomes more productive with the use of robots, the initial job losses are *compensated*, leading to a higher share of labour.

Background and related work

New technologies can either directly or indirectly create jobs which outpace the job replacements. Without this property, we would witness human workers being confined to an ever-shrinking job market, particularly given the increasing rate of technological advances in the past two centuries. The compensation mechanisms explain both the direct and indirect ways in which labour-saving devices lead to more job creation (Freeman et al., 1982; Vivarelli, 1995, 2014). These mechanisms have been classified into six categories, namely, compensation mechanism via new machines, new products, decrease in wages, decrease in prices, new investment of extra profits, and increase in income. The last three mechanisms require a reduction in costs as a precondition.

Compensation mechanism from a decrease in prices: New technologies result in productivity gains, which lower production costs. In a free market, this effect pushes down unit prices, thereby increasing quantity demanded, which results in higher employment in jobs that have not been mechanised. Moreover, the lower prices in the industries that have been mechanised can also lead to more demand for goods and services in unmechanised sectors as well, since consumers will be left with more disposable income. Importantly, this mechanism assumes that the new technologies first cause a reduction in costs. Only after the costs are lowered does compensation via decrease in prices manifest. Therefore, we believe that the compensation mechanism from decrease in costs is a precursor to compensation mechanism from decrease in prices.

Compensation mechanism from new investments of extra profits: This mechanism involves taking advantage of the extra-profits made between the time the costs are saved from the new technology, and the resulting reduction in prices. During this time, the extra profits can be invested by entrepreneurs to grow the productive capacity, and as a result, create new jobs. A reduction in costs is also a key precondition for this mechanism to occur.

Compensation mechanism from an increase in incomes: Based on this compensation mechanism, a share of the cost savings from the new technology and increased productivity can materialise in the form of higher wages for workers, as well as more consumption and expenditure. As a result, the rise in demand stimulates employment, which could counterbalance any job losses (Pasinetti, 1981). This mechanism also requires a reduction in costs.

It is curious that reduction in costs has not been included in the classification of the compensation theory given its key role in three of the mechanisms. Therefore, we propose the addition of "compensation mechanism from a reduction in costs" as the seventh mechanism of the compensation theory.

The compensation theory is an important framework explaining how new technologies both destroy and create jobs. Nevertheless, it does not tell us which effect is greater. For that reason, empirical investigation is paramount to understand whether a technology creates or destroys more jobs in the aggregate. This is particularly pertinent since the conventional economic outlook regarding technology's positive impact on productivity and jobs, exemplified in the compensation mechanisms, has diminished as technologies have improved.

There are several reasons for this shift, one is the argument about the different characteristics that the newer technologies, such as robots and AI, have relative to the technologies of yesteryear. Furthermore, just as automation can reduce costs, the inverse can also be true. In effect, rising wages can induce more automation, and this automation may or may not create jobs through compensation mechanisms. Since wages are one of the primary costs faced by any business, an increase or a decrease in wages can have important consequences for the compensation mechanism, from a reduction in costs. In particular, an increase in minimum wage can itself become a catalyst for more automation since higher wages may create a more pressing need for a reduction in costs through technology adoption.

Minimum wage and robots. Minimum wage is one of the most discussed areas in labour economics, justified by its significance to policy and its vital role in evaluating various labour market models. Despite much research on this topic, economists have continued to expand the body of knowledge by addressing important issues with new empirical methods (Rycx and Kampelmann, 2013; Neumark et al., 2014; Clemens and Strain, 2018; Clemens and Wither, 2019), and exploring new aspects of the minimum wage discussion (Hirsch et al., 2015; Horn et al., 2017; Brummund and Strain, 2020; Sabia et al., 2019). This study extends the current body of work by examining the heterogeneity throughout the minimum wage policy level. It investigates whether increasing or introducing a minimum wage impacts the adoption of robots by firms, thereby adding complexity to the implications for the workforce. The study investigates how these policies may drive firms to automate, thus reshaping labour share and productivity in different industries.

There have been a number of studies that uncovered a fairly large negative impact of the minimum wage on the labour force (Totty, 2017; Martínez and Martínez, 2020; Jardim et al., 2022). Increases in minimum wage can also have different impacts on different skill groups. For instance, the minimum wage can lead to lower employment in automatable jobs, pushing low-skilled workers either into unemployment or worse jobs, but potentially leading to better employment opportunities for higher-skilled individuals (Lordan and Neumark, 2018). These negative effects of the minimum wage found in many studies over the past decades prompted Neumark and Wascher (2004) to proclaim that there is a consensus view that the minimum wage reduces employment among unskilled workers.

Since then, there have been a number of studies that tested this consensus view and found insignificant or no minimum wage effects on the labour market (Dube et al., 2016; Sturn, 2018; Nadler et al., 2019; Cengiz et al., 2021). Studies conducted in Germany, which instituted a minimum wage in 2015, also showed no negative employment effects (Dustmann et al., 2021). The same can be said about Czechia and the Slovak Republic, which experienced large increases in their minimum wage in the early 2000s (Eriksson and Pytlikova, 2004). It should be noted that the minimum wage could have heterogeneous impacts on aggregate employment and on the employment of different groups. Despite this distinction, the literature on the effects of the minimum wage on labour market outcomes has yielded contradictory results. Therefore, it is important to explore other explanations for the possible effects of minimum wage on employment and labour share.

A vast corpus of research suggests that an increase in wages can encourage more mechanisation, a concept first explored by Habakkuk in 1962. This effect is particularly relevant for low-skilled workers (Dechezleprêtre et al., 2021). According to studies on the employment impacts of technology, unskilled workers, who are often minimum wage earners, are among the most affected by technological advancements (e.g., Nota et al., 2016; Brambilla et al., 2022). Relatedly, some studies have found that minimum wage increases can indirectly influence the labour market by incentivising robot adoption (Fan et al., 2021). As a result, it stands to reason that a rise in minimum wage may not only incentivise companies to automate routine and low-skilled tasks but could affect labour share as well. Thus, this study examines whether a firm's decision to adopt labour-saving devices as a replacement for workers is influenced by a rise in minimum wage, potentially impacting labour share.

Robots and labour share. The compensation mechanisms imply that when old work is mechanised by a productivity-enhancing technology, new jobs can also be created, however, it does not determine which effect ultimately prevails in the aggregate (i.e., whether the new jobs can fully or partially compensate for the job losses). If the compensation mechanisms do not have a dominant role on employment, then the total return on capital would increase. Consequently, there will be an increase in share of capital income and a simultaneous fall in the relative share of labour. Hence, robot adoption could cause a deepening of capital. However, if the compensation mechanisms prevail, robots may not result in higher capital intensity since more jobs would be created. Nevertheless, it is reasonable to assume that, so far, the job creation effect has been stronger, otherwise, the progression of technology would have increasingly limited the range of tasks available to workers.

The studies investigating labour share have mainly found negative results. For example, Koch et al. (2021) suggest that robotisation lowers the labour cost share by 5 to 7%, however, they do not observe a commensurate effect on average wages within firms. A possible explanation for this could be the creation of new jobs through the compensation mechanisms. Therefore, the reduction in labour cost share may not translate into a lower labour share. In contrast, Dauth et al. (2021) observed that increased robot use led to a drop in the total labour share of income. Similarly, Acemoglu et al. (2020) found that investment in robotics results in a lower share of labour as well as a decrease in the share of manufacturing workers in France. This trend is not primarily because growing companies had reduced labour shares, rather because firms that embrace automation technologies, such as robots, tend to be large and continue to grow following robot adoption. Consequently, the relative labour share declines. It is therefore important to distinguish between a decline in the absolute labour share and a relative decline. If the latter is the case, then the increase in capital intensity does not come at the expense of labour. Instead, it is just a function of capital share increasing faster than the labour share.

Fu et al. (2020) investigate labour share by segregating the developed and developing countries. They determined that industrial robots have a negligible effect on labour share in advanced economies. Nevertheless, their results suggest that, unlike in advanced economies, robot use is associated with a lower labour income share in developing countries. Therefore, developing economies may experience a higher capital share when they increase robotic process automation. This could be, at least in part, because the compensation mechanism via new machines does not apply to developing countries if robots are produced in developed economies. In advanced countries, where robots are developed, new jobs are created in their robot-producing sector, which would lead to a higher labour share in their economies. In contrast, countries outside these robot-producing nations would not attain the benefits from the compensation mechanism via new machine.

There are other factors, such as industry concentration, that may have an impact on labour share as well, and there is evidence that robots are reinforcing these factors. According to Autor et al. (2020), superstar firms have the largest declines in labour share. Therefore, when the prevalence of these highly productive firms arises, the overall labour share may decline. Stiebale et al. (2020) claim that robots are aiding this process. They find that robot adoption favours superstar firms within a sector, leading to a movement in the income share from labour to capital.

Labour share can also be determined based on the balance between routine and non-routine workers in an economy. If the routine-task automation is to be considered, robots are biased towards replacing workers who perform routine tasks, but complement workers performing non-routine tasks. Since non-routine workers typically receive higher wages than routine workers (Vannutelli et al., 2022), robots may, in fact, lead to higher labour share of income by replacing routine workers and complementing the non-routine workforce. Therefore, by tilting the balance in favour of non-routine workers, robot adoption can lead to an overall increase in labour share.

The same pattern may exist between skilled and unskilled workers, too. Investment in robots can increase the wage disparity between unskilled industry workers and their skilled counterparts, further contributing to income inequality (Stemmler, 2019). Nevertheless, despite the change in the distribution of income between the unskilled and skilled, the overall labour share may not change. It is even conceivable that the outcome from robot adoption could be a higher labour share as automation complements the high-skilled workers and potentially increases their wages substantially. The labour share could even increase more if robots complement low-skilled workers. Aghion et al. (2021) claim that the effects of technologies could lead to an increase in relative demand for low-paid/low-skilled workers because of increased complementarity among the low-skilled and high-skilled workforce in robot-intensive firms. Therefore, irrespective of whether robots automate tasks based on their repetitiveness (i.e., routine tasks) or the level of skills, robot adoption may positively impact a certain faction of workers.

Overall, the field of study concerning the effects of robots on labour share remains under-researched. The disparity between developed and developing countries provides some insight into the issue. However, the reasons behind this dichotomy in effects are unclear and warrant further investigation. Some studies have found that the labour share has been declining in recent decades (Karabarbounis and Neiman, 2014; Autor et al., 2020; Takahashi and Riche, 2021). Nonetheless, the challenge with measuring capital and labour share is the assumption that a declining labour share is inherently negative for workers. In reality, workers may be better off even as the labour share declines. This is because the decline in labour share may not correspond to a decline in income for workers but rather to an increase in returns from capital. This would result in an increase in capital share relative to labour, but this relative increase is not necessarily at the expense of workers. In fact, both capital share and workers' income could increase simultaneously, with the latter growing at a slower pace relative to the former. In this case, the labour share would decline even as labour income grows. These nuances are typically not considered in the methodological approaches to this topic, which is particularly relevant with negative results.

The main contributions on the relationships between labour share and robot adoption, and between labour productivity and robot adoption are presented in Tables 1 and 2, respectively. Whether robot adoption leads to a higher or lower share of labour may depend on its impact on productivity. If productivity increases due to robotisation, it could result in the creation of more jobs, which may compensate for the initial job destruction, and thus lead to a higher labour share.

Robots and productivity. Published literature generally documents that robot adoption may stimulate labour productivity (see Table 2), as robots perform tasks more efficiently and with higher quality than human workers (Graetz and Michaels, 2018; Koch et al., 2021; Sharfaei and Bittner, 2024). Thus, industrial robots can complement workers by enhancing their efficiency. This is consistent with the long-standing economic doctrine regarding the positive effects of advanced technologies on productivity.

Graetz and Michaels (2018) analyse the use of robots in production across industries in 17 developed economies. They suggest that an increase in robot use significantly improves labour productivity, leading to a decrease in the price of goods and an

Table 1 Effects of robots on labour share.

	Approach	Findings
Dauth et al. (2021)	Local labour market shift-share model.	Increased robot use causes a drop in the total labour share of income.
Graetz and Michaels (2018)	Cross-country/cross-industry panel data analysis on industrial robots with instrumental variables that estimates robots' ability to automate specific tasks.	An increase in robot density is generally due to decreases in robot prices, which indicates that increased robot use may not lead to a more deepening of capital.
Acemoglu et al. (2020)	They use French data from 2010 to 2015 to examine firm-level changes following industrial robot use.	At the firm-level, the introduction of robots aligns with reductions in labour shares.
Fu et al. (2020)	Cross-country panel regression of 74 countries between 2004 and 2016.	Industrial robots do not have a significant effect on labour share in advanced economies, however, they are associated with lower labour income share of GDP in developing countries.
Autor et al. (2020)	Panel data analysis with information from the U.S Economic Census since 1982, which relies on a framework that considers technological or institutional dynamics that favour superstar companies.	Superstar firms have the largest declines in labour share.
Stiebale et al., (2020)	The analysis combines sector-level data of robot adoption with firm-level balance sheet data for 6 economies in Europe for the 2004–2013 period.	Robot adoption benefits the superstar firms to a much higher extent and contributes to the shrinking labour income share relative to capital.
Koch et al. (2021)	The study uses a monopolistic competition model and a task-based framework where workers and robotics are considered perfect substitutes in a series of simple tasks.	Robots lower the labour share by about 6 percent, however, there are no impacts on average wages within firms.
Hémous and Olsen (2022)	An endogenous growth model where low-skilled workers are replaced by technologies, while simultaneously new products are being created.	The share of automation innovations grows and labour share falls.
Vannutelli et al. (2022)	Using survey data, they estimate wage distribution among routine and non-routine labour through a semi-parametric decomposition method.	Workers in non-routine roles in Italy command substantially higher wages compared to those in routine positions.
Heer et al. (2023)	The study combines cointegration analysis and a neoclassical growth model.	Robot adoption driven by tax policies reduces the labour share by substituting workers.

Table 2 Effects of robots on productivity.

	Methodology	Findings
Jäger et al. (2016)	A multivariate regression model which relies on data from a subset sample of the EMS 2009 survey of manufacturing firms in 7 European countries.	Firms increase labour productivity by using robots.
Graetz and Michaels (2018)	Cross-sector/cross-country panel data analysis with instrumental variables.	Widespread robot use in production significantly improves labour productivity.
Bessen (2020)	By developing a model of demand satiation, the study analyses the variations in the elasticity of demand.	The elasticity of demand determines the labour market impacts of new technologies.
Acemoglu et al. (2020)	They develop a theoretical framework and use French data from 2010 to 2015 to examine firm-level changes following industrial robot use.	Firm-level robot investments are associated with a growth in productivity.
Stiebale et al. (2020)	The analysis combines sector-level data of robot adoption with firm-level balance sheet data for 6 economies in Europe.	Robot adoption leads to increases in productivity as well as profits for large firms but causing a decline for smaller companies.
Christofzik et al. (2021)	They develop a quarterly time series for utilisation-adjusted total factor productivity measure for Germany.	Advancements in the information and communication technology producing sector is associated with net employment growth, but its influences on productivity is minor.
Dauth et al. (2021)	Local labour market shift-share model.	Increased robot use results in higher labour productivity.
Fu et al. (2020)	Cross-country panel regression of 74 countries between 2004 and 2016.	Robot adoption is associated with significant positive effect on the productivity of workers only in developed countries.
Koch et al. (2021)	The study combines a monopolistic competition model where robots and workers are perfect substitutes in a series of tasks.	Robot use leads to higher labour productivity. Furthermore, non-adopters of robots account for the majority of the drop in productivity.
Antonietti et al. (2023)	A two-step analysis based on data across 15 sectors in Italy.	Robot adoption has no impact on overall labour productivity.
Liu et al. (2024)	Using the O*NET Content Model, they assessed 16 jobs based on work context, skills, and constraints.	Collaborative robots have enhanced productivity in manufacturing and reduced idle times.

increase in output. Jäger et al. (2016), using a sample which covered 2848 manufacturing firms, found that firms increase labour productivity by using robots. Similarly, Dauth et al. (2021) found that increased robot use leads to a productivity effect. Koch et al. (2021) arrived at comparable conclusions. These studies provide evidence in support of the productivity effect argument. Additionally, robots can also allow for specialisation in high-skill activities.

Whether these productivity improvements lead to an increase or a decrease in employment appears to hinge on the elasticity of demand (Bessen, 2020). Bessen (2020) argues that productivity-augmenting technologies, initially, stimulated employment in some industries due to demand being elastic. However, as demand became saturated, there was eventually some contraction in the workforce.

An important issue to highlight here is that once demand becomes satiated in the exposed industry, it can shift to other sectors. Essentially, when the robot-exposed sector reduces costs and hence prices, it leads to an increase in demand. However, once demand in this sector becomes saturated, consumers can use their disposable incomes on other products, thereby growing demand elsewhere as a consequence of the cost reduction in the initial automated industry. Therefore, the impact on aggregate employment might differ from the impact on employment in specific sectors due to the mechanisms resulting via lower prices. Bessen (2020) did not explore these mechanisms in detail as he mainly focused on demand in three industries: textile, primary steel, and automotive.

The impact of industrial robots may have different effects in developed and developing countries. According to Sharfaei and Bittner (2024), despite the insignificant effect in developing economies, robot use leads to a positive effect on labour productivity in developed countries, which also adopt robots more intensively. This logic seems to hold at the firm level as well, mainly for large companies. Acemoglu et al. (2020) argue that firm-level robot investments are associated with higher productivity. Additionally, Stiebale et al. (2020) exploit data from six European countries and find that industry-level robot automation leads to increases in productivity as well as profits for large firms, but smaller companies see a decline. Additionally, as demonstrated by Graetz and Michaels (2018), widespread robot use is the main component leading to substantial improvements in productivity. This perspective is supported by Koch et al. (2021), who found that non-adopters of robots accounted for the bulk of the drop in productivity prior to the global financial crisis.

Model

This section introduces a simple model for understanding firms' decisions with regards to using robotics. The model forms the foundation for our empirical approach. We consider a scenario where firms can choose between workers and robots in order to produce. Production function is represented as $Y = F\ (L,\ R)$, where Y signifies output, L represents labour, and R stands for robotics. The production function exhibits diminishing returns to both inputs but is also complementary, implying that labour productivity improves as firms adopt robots.

The cost structure comprises of a fixed cost for robots and variable costs (i.e., labour costs and robot maintenance), with the minimum wage influencing the variable cost of labour. The labour market balances based on supply and demand, and the minimum wage acts as a floor on wages. Consequently, a rise in the minimum wage increases the labour cost of firms, which will prompt firms to move towards capital-intensive production such as robotics.

Let $Wmin$ denote the minimum wage, and W indicate the wage rate. A minimum wage hike can be stated as:

$$W = \max (W\min, W0) \quad (1)$$

where $W0$ is the initial wage rate prior to the increase. The effect on labour cost (CL) given labour (L) can be expressed as:

$$CL = W \times L \quad (2)$$

The decision of firms to automate depends on the relative price of labour compared to the relative cost of automation. When firms automate using robot technologies, they incur upfront fixed costs but gain in the long run due to reduced variable costs.

Let CR denote the total cost of robots, which encompasses both fixed costs (FCR) and variable costs of robots (VCR). The total cost of robotics can therefore be expressed as the following:

$$CR = FCR + VCR \times R \quad (3)$$

Companies choose to use robotics if the present value of future cost savings from robot adoption is higher than the present value of labour costs. Robots likewise improve the productivity of the remaining workforce, as tasks are divided into robot-efficient and human-efficient activities. Consequently, higher productivity and possibly reduced costs of production result in compensation mechanism via lower costs. Basically, the lower costs lead to lower prices, higher output, or both, thereby leading to higher demand for the product.

The production function with labour and robots, taking into account productivity (A), can be expressed as follows:

$$Y = A\,(L, R) \times (L\alpha \times R\beta) \quad (4)$$

where $0 < \alpha,\ \beta < 1$ and $\alpha + \beta$ can be <, =, or >1, which reflects different returns to scale.

The higher demand for products can spur higher demand for labour, not just in the robotised sector but also in other sectors due to higher economic activity and compensation mechanisms. Essentially, the demand for the product (D) can be affected by output (Y):

$$D = f(Y) \quad (5)$$

And the labour demand (LD) will then adjust because of the improved productivity and output:

$$LD = f(Y, A(L, R)) \quad (6)$$

Enhanced productivity and potentially higher wages lead to higher disposable income for consumers, spurring demand across industries. This creates new jobs, possibly compensating the initial job displacement caused by robotisation.

Higher overall economic activity and demand for workers in different industries can be represented by a multiplier effect (Γ), which reflects the growth in total employment and wages:

$$E = \Gamma \times (LD + R) \quad (7)$$

where E signifies employment across the economy.

This model illustrates how initially, robot adoption may decrease the demand for labour, resulting in unemployment or underemployment. Nonetheless, as the economy adjusts over time, the enhanced productivity and reduced costs can result in more employment opportunities through the compensation mechanism from a reduction in costs, thus impacting labour share.

Methodology and data

Data description. This study is done based on data from six European economies. The six countries include Czech Republic, France, Germany, Ireland, Netherlands, and the United Kingdom (UK). The specific adjustments to minimum wages vary across these economies, but they are typically done with government decree. For example, in Czech Republic and the Netherlands, the minimum wage is set by the government and consider the changes in wages and consumer prices. The national minimum wage in UK and Ireland is also determined by the government and its based on recommendations from independent commissions. In Germany, which introduced a statutory minimum wage in 2015, the policy is reviewed and adjusted by the Minimum Wage Commission. Finally, France's minimum wage is determined annually based on the inflation rate and the average salaries of the blue-collar workforce. If the inflation rate surpasses 2% during the year, an automatic increase is triggered.

Our study combines the minimum wage data with robot installation data from the International Federation of Robotics (IFR), a widely used source in this field (see Sharfaei, 2024). While IFR data has been used in previous research, we are the first to utilise this dataset to investigate the effects of minimum wage on robot adoption. To ensure a robust analysis, we compiled a comprehensive dataset encompassing robot data from IFR, alongside productivity and labour share metrics, and other relevant control variables. These data were sourced from International Labour Organization (ILO), the World Bank (2021), and the Penn World Table 10.0 (Feenstra et al., 2015).

Methods. Using data from six European nations, we conduct an econometric analysis which aims to investigate whether the implementation of minimum wage has any effect on robot adoption. To ensure robustness, we employ a panel data model that incorporates country and time fixed effects, controlling for unobserved time-invariant factors, such as national institutions and global economic shifts:

$$Robo_{it} = \alpha + \beta \ln(MW_{it}) + \sum_{j=1}^{n} \gamma_j Z_j + \delta_i + \delta_t + \epsilon_{it} \qquad (8)$$

Robo represents robot adoption (i.e., the number of operational robots per thousand workers), and MW denotes minimum wage implementation in Euros, treated as a continuous variable. To address potential heteroscedasticity, we use the logarithm for minimum wage in our analysis. The control variables for country i and time t, represented as Z, include the logarithm of population (country size). Other control variables consist of the logarithm of the working-age population share (15–64) in percentage, and the percentage change in annual GDP. Furthermore, we include lagged minimum wage values to reduce the likelihood of reverse causality.

Additionally, we use event studies as a robustness check. The event study methodology allows for a precise analysis of the temporal effects associated with the minimum wage adjustments by examining the changes in robot use within a defined time window around the event. This approach strengthens the reliability of the results and provides deeper understanding into the immediate and delayed impacts of minimum wage changes on robotisation.

Beyond examining the effects of minimum wage on robot adoption, we also aim to determine how robotisation itself impacts labour share and productivity in our sample economies for the 1993 to 2019 period. We use the following panel data model to address this question:

$$S_{it} = \alpha + \beta(Robo_{it}) + \sum_{j=1}^{n} \gamma_j Z_j + \delta_i + \delta_t + \epsilon_{it} \qquad (9)$$

where S represents one of our two outcome variables: labour share and productivity. We measure productivity using the log values of output per worker to analyse its relationship with robot adoption. The analysis also controls for the log of total population, the logged percentage of the working-age population, exports as a percentage of GDP (i.e., economic openness), and annual percentage change in GDP. Additionally, we use lagged values of robot stocks.

The fall in labour share in the past decades has been extensively researched (e.g., Bergholt et al., 2022; Moreira, 2022; Heer et al., 2023); however, the impact of robot use on this variable requires further investigation. In this model, the share of total labour compensation in GDP is considered as the dependent variable. Therefore, we investigate whether increased robot use has shifted income from labour to capital. The controls include proportion of imports as a percentage of GDP and export levels as a percentage of GDP.

In addition to the ordinary least squares (OLS) method, the study uses the two-stage least squares (2SLS) approach to address endogeneity issues. In the 2SLS approach, we use country minimum wage as an instrument to analyse the effects of robot adoption on productivity and labour share.

Table 3 Minimum wage model estimates.

Panel least squares		
	Model 1	**Model 2**
VARIABLES	**Robot stock**	**Robot stock**
Minimum wage (log)	1.054*** (0.160)	
Lagged minimum wage (log)		0.908*** (0.181)
Population (log)	−2.849*** (0.809)	−3.129*** (0.856)
Growth	−0.005 (0.009)	−0.002 (0.009)
Working-age population (log)	−4.344*** (1.934)	−4.552*** (1.955)
Constant	35.149*** (2.784)	36.099*** (2.986)
Cross-section fixed	Yes	Yes
Period fixed	Yes	Yes
R-squared	0.978	0.973
Observations	106	101

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Results and discussion

Minimum wage and robot adoption. Table 3 reports the results of the effects of minimum wage on robot adoption. The findings show significant and positive results, indicating that implementing a minimum wage leads to more robot adoption. Model (2) presents the results for the lagged values of minimum wage. The estimates corroborate the significant impact of minimum wage on robot adoption.

Next, we present the results of the event studies for our six sampled economies in order to observe the medium-term effects of minimum wage adjustments on robot installations. Figure 1 displays the trend in robotisation both before and after minimum wage changes for Czech Republic, France, Germany, Ireland, the Netherlands, and the UK using a 3-year event window. Although there is variability across different economies, the plots present a clear overview of the trends surrounding each minimum wage event over an extended period.

As Fig. 1 indicates, there is a rise in operational robots following minimum wage changes. The results imply that the effects of minimum wage on robotisation becomes more apparent over time. We can also observe from the event studies that there are some differences in the minimum wage effects across countries.

Germany sees the greatest difference following the implementation of a minimum wage in 2015. The results exhibit variability, as some years experience a sizeable rise in robot stocks, while others show a more modest growth. But overall, the trend shows an increase in robot installations after minimum wage increases. Ireland, on the other hand, experienced the smallest difference from minimum wage effects between the sampled countries. The findings indicate a slight average decline in robot installations following the changes.

France, Czechia, and the Netherlands also experienced substantial increases in robotisation following minimum wage adjustments, although to a lesser extent than Germany. In the UK, the detailed results show a combination of decreases and moderate increases in robot installations in the years following

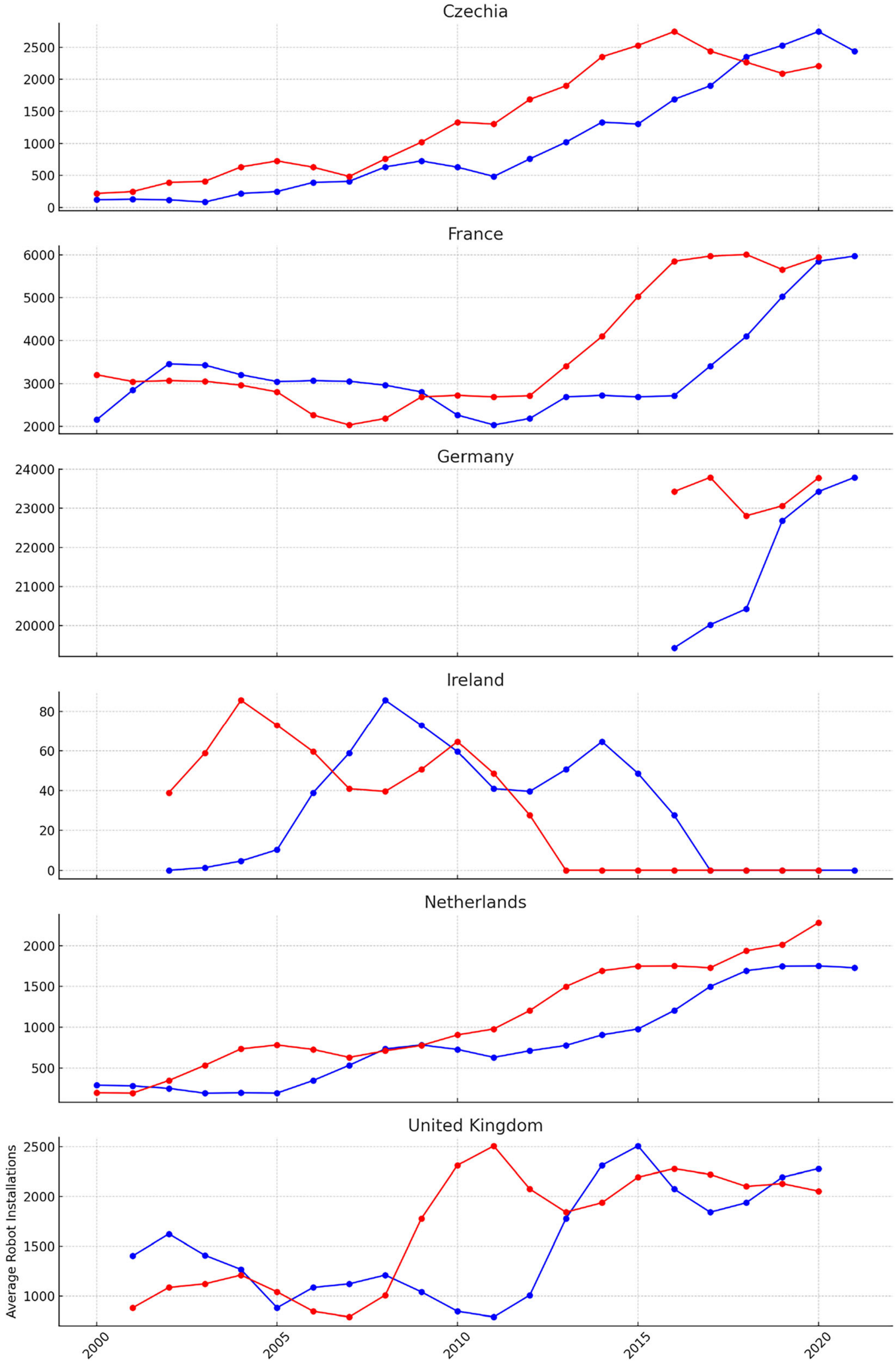

Fig. 1 Robot installations before and after minimum wage changes. Blue line is the average number of robot installations in the years before and the red line is for the years after a minimum wage adjustment.

minimum wage adjustments, which contrasts with the positive average increases. The difference indicates that although some post-event periods experienced a fall in robot installations, the broader trend across all events still reflects a slight growth when averaged out.

Overall, the calculated average difference across all countries suggests a general movement toward a rise in robotisation following minimum wage increases, which confirms the result of our panel least squares analysis. The results suggest that higher labour costs incentivise more firms to automate in order to save

Table 4 Robot stocks and productivity (OLS estimates).

Panel least squares

VARIABLES	Model 1 Productivity (log)	Model 2 Productivity (log)
Robot stock	0.004 (0.015)	
Lagged robot stock		−0.015 (0.016)
Exports	0.008*** (0.001)	0.008*** (0.001)
Population (log)	0.655*** (0.250)	0.471* (0.246)
Growth	0.004** (0.002)	0.004* (0.002)
Working-age population (log)	1.849*** (0.421)	1.264*** (0.435)
Constant	1.067 (2.269)	4.151* (2.291)
Cross-section fixed	Yes	Yes
Period fixed	Yes	Yes
R-squared	0.977	0.977
Observations	153	148

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 5 Robot stocks and productivity (2SLS model estimates).

Variable	Productivity (log)
Robot stock	0.087*** (0.028)
Constant	11.387*** (0.033)
Cross-section fixed	Yes
Period fixed	Yes
R-squared	0.895
F-test statistic	36.456***
Observations	118

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, Instruments: Minimum wage (log).

Table 6 Labour share model estimates.

Panel least squares

VARIABLES	Model 1 Labour share	Model 2 Labour share
Robot stock	0.026*** (0.004)	
Lagged robot stock		0.026*** (0.005)
Imports	0.001 (0.001)	0.001 (0.001)
Exports	−0.005*** (0.001)	−0.004*** (0.001)
Constant	0.715*** (0.017)	0.717*** (0.0185)
Cross-section fixed	Yes	Yes
Period fixed	Yes	Yes
R-squared	0.908	0.906
Observations	162	156

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 7 Labour share model estimates.

Variable	Productivity (log)
Robot stock	0.027** (0.013)
Constant	0.534*** (0.013)
Cross-section fixed	Yes
Period fixed	Yes
R-squared	0.871
F-test statistic	19.540***
Observations	107

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, instruments: Minimum wage (log).

on the increased labour costs. However, the remaining workers are likely to enjoy higher productivity with the helping hand of a robot.

Robot effects on productivity. Table 4 presents the OLS results on the impact of robotisation on labour productivity in the six sampled countries. The findings show that robot adoption does not have a significant effect on productivity. However, to account for endogeneity, we also use the two-stage least squares (2SLS) approach.

We use the 2SLS approach with minimum wage as an instrument. The estimates reported in Table 5, show that the effect of robots on productivity in these regions is positive. The contrasting results indicate that there might have been endogeneity or omitted variable bias in the initial regression, thus, the insignificant effect could be spurious. The 2SLS method with minimum wage as an instrument attempts to address this issue. The 2SLS result suggests that robot adoption in the six economies might have a positive impact on productivity once endogeneity is properly accounted for. These results align with previous studies (e.g., Liu et al., 2024).

The aggregate improvements in productivity found in this study indicate that robots are probably not the reason for the deceleration of growth in productivity seen in the past few decades. In fact, there is ample evidence to suggest that robot adoption aids in enhancing productivity. Hence, we argue that the Solow Paradox is not applicable to robots, as they do not seem to contribute to the slowdown in productivity. On the contrary, robots increase productivity according to our findings.

Theoretically, the results also indicate the presence of a productivity effect. Increased productivity in these countries leads to a compensation mechanism via lower costs and raised output, which, in turn, results in lower prices. Consequently, the compensation mechanism via a reduction in prices stimulates demand for goods and services, eventually leading to higher demand for workers. To shed more light on these dynamics, we present the results of the analysis on the effects of robot adoption on labour share next.

Robot effects on labour share. In order to investigate further, we need to analyse the effects of robot adoption on labour share. A negative effect would suggest a replacement of labour by capital, possibly to save on the increased wages. Table 6 presents the results of the impact of robot adoption on the labour share of compensation in GDP from 1993 to 2019. The findings suggest a significantly positive effect of robotisation on labour share, confirmed by the lagged results as well.

Table 7 reports the 2SLS findings with minimum wage as an instrument. Similar to the OLS results, the estimates indicate that robots lead to a higher labour share of income.

The results show that robotisation does not lead to a lower labour share; on the contrary, labour share increases due to robot adoption. The positive effects of robots on labour share are also consistent with our result on the impact of robots on labour productivity. Evidently, a more productive labour force leads to compensation mechanisms, which, in turn, leads to more demand for workers, resulting in a higher labour share. Without these compensation mechanisms, we would expect to observe rising unemployment with each technological breakthrough and, consequently, a constant reduction in labour share. However, as noted by Autor et al. (2022), there is no strong evidence from past or present to indicate that productivity-enhancing technologies lead to widespread job losses. Instead, they predict that industrialised economies will experience a labour shortage over the coming decades. This suggests that the compensation mechanisms from automation lead to more job creation than destruction, as confirmed by the findings of this study with respect to robots.

Conclusion

In this paper, we analysed the effects of minimum wage laws on robot adoption in six European economies. We examined whether the implementation of minimum wage can encourage more firms to adopt robots and how robotisation, in turn, can affect labour share and productivity. Using OLS and event studies, we first show that minimum wage has an impact on robot adoption in our sampled economies, however, the effects are heterogeneous across these countries. Although this may suggest that minimum wage increases could possibly incentivise more firms to automate in order to cut on labour costs, it does not necessarily suggest causality.

In order to investigate further, we analysed the effects of robot adoption on labour share and found positive results, which contradict the common assumption that automation reduces labour share and causes job losses. There are two possible reasons for these findings. First, the robot adoption was not motivated by an increase in minimum wages and the replacement of workers, hence, it did not have a negative effect on labour share. The second explanation is that initially, robot adoption was a response to the implementation of minimum wage to cut rising labour costs. However, the compensation mechanisms triggered by automation compensated for the initial job losses and eventually led to higher labour share. Our 2SLS analysis with minimum wage as an instrument provided some clarity by showing that increased robot use has a positive effect on labour share, suggesting that the second explanation is more plausible. In addition, the positive effect of robot adoption on productivity also indicates that the compensation mechanisms led to job creation through higher productivity, which can reduce costs, prices, etc.

Although the positive effects of robotisation on labour share are contrary to the findings of the majority of past studies, the results are consistent with the studies that have found a positive effect of robot adoption on employment (Chung and Lee, 2023; Sharfaei and Bittner, 2024). The findings thus provide a basis for asserting that automation could co-exist with labour market well-being.

Relatedly, the paper extends compensation theory by adding a seventh mechanism—compensation mechanism from a reduction in costs—based on its crucial role in the technology-employment relationship. This acknowledges that cost savings from automation are an essential factor that can potentially lead to the creation of jobs and increase the labour share. Embedding this mechanism within compensation theory allows for a broader explanation of how technological changes interact with economic factors in the labour market.

The findings on the effects of robot adoption on productivity also help explain the heterogeneous effects of minimum wage across economies. Okudaira et al. (2019) showed that markets with higher productivity were less negatively affected by minimum wage increases. Our findings imply that this could be due to productivity-enhancing technologies such as robots. In other words, if minimum wage hikes lead to robotisation and, in turn, higher productivity, it can result in compensation mechanisms which help counter the negative effects of minimum wage laws. Furthermore, since our results show that robot adoption is associated with higher productivity, we contend that the Solow paradox does not apply to robotics.

The findings have several implications at the policy level. The result of this research can help policymakers in making decisions on policies which may affect the job market. Policies such as the introduction of, or increases in, minimum wages to support workers should take into account the specific characteristics of the job market, as well as technological capabilities. Specifically, the adoption of robots should be carefully evaluated when examining the consequences of minimum wage on the labour market. Therefore, it is crucial to understand the effects of minimum wage policies and the adoption of these labour-saving devices on employment and labour share. Importantly, the initial displacement of minimum wage workers by machines needs to be considered when designing a minimum wage policy. Although the results show that robot adoption does not negatively impact labour share due to compensation mechanisms in the sampled countries, this may not necessarily apply to all countries, as the compensation mechanism could manifest at different degrees across economies. For instance, the compensation mechanism from new machines might apply in advanced countries such as Europe that developed these technologies, but not in developing countries. Indeed, research has found that robot adoption leads to employment growth in developed economies, whereas the positive effects are not seen in developing countries (Fu et al., 2020).

Furthermore, many scholars and public intellectuals believe that AI and robots will replace a significant number of current workers. As a result, they put forth programs such as universal basic income to counter the expected mass unemployment that they believe is on the horizon. However, the positive effect on labour share indicates that these proposed policy responses are premature in the age of robots. Importantly, the job-creating effects of the different compensation mechanisms should be considered.

Although the study did not directly address the effects of wage laws on workers based on their skills, it is implied that minimum wage earners, who typically occupy the lower end of the wage distribution, may also be those with the least skills. Consequently, the minimum wage laws affect low-skilled workers by increasing the likelihood that their jobs will be automated by robots. Nevertheless, future studies can provide support for this argument by examining these dynamics directly based on workers' specific tasks. These dynamics can be considered in other newer technologies as well, including AI and large language models.

Data availability

The raw data supporting the findings of this study were retrieved from the International Labour Organization, the World Bank, the Penn World Table, and the International Federation of Robotics (IFR).

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Shahab Sharfaei: Conceptualisation, Methodology, Formal analysis, Validation, Investigation, Writing—Original Draft, Writing—Review and Editing. Jakkrit Thavorn: Conceptualisation, Methodology, Formal analysis, Writing—Review and Editing.

Competing interests
The authors declare no competing interests.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
Informed consent was not required as the study did not involve human participants.

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