

Master Thesis

*Exploring consequences of robotics for the labour market:
A microeconomic approach*

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Abstract

The purpose of this study is to examine the consequences of new developments in robotization for the labour market. We do this by performing a microeconomic analysis, and using the Ricardian labour model of Acemoglu and Autor (2011) as a basis for this analysis. The possibilities and applications of technology are changing rapidly in this era. This has important consequences for the production process and therefore also for the task allocation and wages of the workers. In this research, the workers will be divided into three groups: low-skilled, medium-skilled and high-skilled workers. Further, we will distinguish two types of technology. Technology can lead to increased productivity for a specific type of workers, and technology can replace workers of certain type by performing the tasks these workers performed before. We find that technology influences the task allocation between the three worker types and the corresponding wages. Technology can also lead to unemployment of one or more worker groups, depending on the rigidity of wages. Policy recommendations for firms and government are given to improve the adaptation of organizations to technology developments.

Key words: *technology, robotization, labour market, task allocation*

Chapter 1 - Introduction

The level of technology in our lives determines for an important part how we live our lives. This is already captured in the definition of technology by Oxford Dictionaries (2016): “the application of scientific knowledge for practical purposes, especially in industry”. Technology has not only influenced our daily lives with all the tools that make our lives more comfortable, also the organization of work has changed substantially, both within an organization and in the labour market as a whole.

At first, the development went moderately and mostly affected the industrial sector (Davidow & Malone, 2014). Quite a number of studies examined what the consequences of this industrialization were for the organization of work. The common finding in these studies is that especially the low-skilled jobs were replaced by machinery (e.g. Benders, 1995; Ebel, 1987; Edler and Ribakova, 1994).

Today however, progress is made at a much higher rate because of the development of intelligent robots, automobiles and drones. This technology can be applied to and implemented in a much broader range of sectors. Technology can be programmed in such a way that it sometimes is even smarter than humans, so there might be a real possibility that this technology replaces higher-skilled workers as well. In this research we want to examine what the consequences of robotics nowadays are for the organization of work by performing a literature study and a microeconomic analysis. Two possible ways in which technology influences the production process differently in sectors will be distinguished. First, technology can lead to increased productivity for a specific type of workers and secondly, technology can replace workers of a certain type by performing the tasks these workers performed before. Special attention will be given to the role of the organization of work including the (downward) rigidity of wages and the interchangeability of workers across tasks.

There are two ways to look at the development of robotics. On the one hand, it brings new opportunities, as robots can replace particular employees at a much lower cost. Examples of benefits are that robots can work 24 hours a day and seven days a week, that they are never ill or go on strike and in addition they do not demand wage rise (Est and Kool, 2015). On the other hand, one can wonder what this will do to the jobs. Questions that arise are what jobs are on the line and what new jobs are created. As described, the debate affects both companies and citizens. Therefore, also on policy level it is a topical issue, as the labour market might need a transformation to become more ready for the further development of robotics in which both government and firms play a role. This research therefore satisfies in a need of having a clearer view of what the actual consequences of robotization are for the labour market. This can improve the societal debate and be of help in

preparing the labour market for the increasing robotization. Some researches about the impact of industrial robots also included recommendations which we will return to in chapter 6. For example, Edler and Ribakova (1994) recommend government-sponsored training both within firms and through agencies, which is important for a smooth transition. In addition to give recommendations for government labour market policy, we also want to give firm policy recommendations, as the firm plays an important role in the labour market.

From industrial robot to current technology

Most research dated before 2000 examines the industrial robot, replacing mainly workers with repetitive industrial tasks. In this subsection, we will discuss part of the literature to draw a rough picture on which we will elaborate in chapter 2. An example is the study of Edler and Ribakova (1994), showing the long-term impact of industrial robots on level and structure of employment in Germany. They find that the new technology of industrial robots has a significant impact on the occupational structure of the economy. Mainly low-skilled jobs suffer from the development, whereas high-skilled jobs with specific qualification requirements may even gain. Ebel (1987) confirms that unskilled jobs are replaced by robots and can therefore reduce employment in a firm. Workers might become more socially isolated, but on the other hand working conditions might be improved.

In their empirical study, Hollon and Rogol (1985) discover that firms that implement robot technology expect non-automating firms to create far more chronic unemployment, as these firms cannot compete in the world market and therefore disappear. Respondents in this research assign the individual and the firm more responsibility in retraining than education and the government. Most researches do not include quantitative results and accurate predictions of how big the consequences would be and how many workers would be replaced. Howell (1985) defined six possible scenarios and drew rough indications from them. His results show that both job displacement and job creation happen as a consequence of industrial robots, but the displacement effect is 4.5 to 6.2 times greater. The results also confirm that blue-collar and low-skilled jobs disappear and white-collar and high-skilled jobs grow, e.g. engineers. The job creation mainly stems from the production and development of robots. Another important result from this research is that the impact on the labour market is concentrated in a few industries, especially the electronics and metalworking industries.

A research that investigates the global impact of robotization on the economy is the study of Kinoshita and Yamada (1989). In Japan and Korea robotization stimulates economic growth, whereas in the US it has a negative impact. A possible explanation might be that this research focused on the

machinery industry, in which Japan has a comparative advantage over the US. The difference in impact of technological development for different sectors is therefore included in the microeconomic analysis.

Until now, we mostly focused on the impact of industrial robots. However, the development of technology changes over time and therefore the impact might be different now. Rumberger (1984) already points out this change. Whereas in the past especially low-skilled physical labour was displaced, technologies based on microelectronics will displace higher-skilled mental labour. Another difference is that new technology will affect all sectors of the economy instead of affecting only a few sectors as before. An example is robotization in the service sector. Robots can already take over the basic caring tasks from nursing employees. The question arises whether the increased productivity that comes along with the increasing technology can offset the negative consequences. Evidence from the United States suggests that the jobs created by the high-technology industries will not supply many new jobs (Rumberger and Levin, 1985). Especially service and clerical jobs will increase. Technology therefore affects the number of jobs, the kind of jobs and the skill requirements of jobs in the future. Important to investigate is how the allocation of tasks changes and what the impact of this change is for wages and employment per skill group. This is crucial in determining the effect of robotization on the labour market.

There is not much empirical evidence yet of the consequences of current technology developments. However, we can draw parallels from related subjects in the globalization literature. Parallels can be drawn to the immigration and trade literature. Increasing trade leads to a trade in tasks with the foreign labour market, whereas with increasing robotization robots take over tasks. Therefore, the trade literature can help to identify some factors that should be included in the microeconomic analysis. Also immigration puts a stamp on the economy and the labour market. Borjas et al. (1997) show that immigrants in the US are mostly low-skilled workers and therefore the low-skilled US workers encounter a negative economic impact. In chapter 2 we will discuss the corresponding literature in more detail.

Scope of this research

In order to find out how robotics is changing the labour market, we will first look deeper into the influence industrial robots had in the past. This historical perspective is the starting point from which we can proceed towards the current impact. When examining the current influence of technology on the labour market, we will look at skill level jobs that might become unnecessary and other jobs experiencing an increase in importance. This will be done by developing a literature-based

microeconomic analysis. In this analysis we also address what happens when wages are (downward) rigid or when workers are not interchangeable across tasks of different skill levels. Lastly, we will discuss where the current labour market can improve to be better able to adapt to the changes that come along with robotization by giving policy recommendations for organizational and governmental labour market policy.

Research question and research goal

The explored literature leads us to the following research question: *What are the consequences of increases in robotics for the labour market?* As many research is already done about what the consequences of industrial robots are for the labour market, in this research we want to focus on the more current and future consequences of new technologies. A review of historical studies is necessary to develop an analysis, but cannot forecast the future consequences.

In order to answer the above research question the following sub questions need to be addressed in the research.

1. *What were consequences of new technologies in the past for employment?*

From the literature, we will explore the consequences of more advanced technology in the past, focussing thereby on the industrialization. We want to look here at empirical evidence of some specific cases in the past century to get a general picture of what the impact of technology on the labour market is.

2. *What are the consequences of robotization for the labour market?*

Then the focus will be moved to robotization. How will it change the labour market? What skill level jobs are removed and how will it affect the wages? What are the different consequences when robots are complementary to human workers and when they are substitutes?

3. *How can the labour market be improved in adapting to the changes of increasing technology?*

Following from the previous question, we can now ask what can be done to prepare the labour market and employees for this change. Once we know for which employees robotization causes the most problems, we want to find out how to prevent or reduce these problems. Is it possible for employees to retrain for other jobs? Or will robotization make employees of a certain skill level redundant? In these recommendations will be addressed what firms and governments can do to improve the adaptation of firms to robotization.

The main contribution of the research is the analysis of what the consequences of current and future technologies are for the labour market. Consequences of past technological developments can be

found in the literature, but a gap exists concerning current developments. We want to analyze this by taking a macro perspective in the literature and provide this with a microeconomic foundation. This combination makes the research more strong and its outcomes more valid. The expectations are that increasing technology influences the number of jobs and the skills required for the available jobs. To extend the scope of the research different scenarios concerning wage rigidity and interchangeability of workers will be included. Also recommendations will be given about how the labour market can be prepared for these changes. These recommendations are based on the results and the literature, which makes them valuable for both government and firm policymakers and gives them societal relevance.

Method & structure

The literature review will help to answer above questions from a macro perspective. This review will be provided with a microeconomic foundation, investigating how the different aspects of robotization affect the labour market. This microeconomic analysis is helpful as a foundation to the macroeconomic perspective that is taken in the literature review. Note that the model does not predict what the technological developments will be. The literature has to point to the developments in robotics that are expected. Then the model can predict what the expected consequences of these technological developments are. Variables that seem to be important from the literature will be included in this analysis, for example the distinction between different worker groups. The analysis will lead to qualitative findings, which are helpful in pointing out what direction current and future policy should go. Performing an empirical analysis is difficult in this context, as consequences of current technological developments are difficult to measure on a short term. An additional difficulty in empirical studies is to distinguish the effects from technology from other factors and developments (Rumberger, 1984).

In the subsequent chapter, an analysis will be made of the existing literature, discussing the relevant literature on the first two sub questions. Then in chapter 3 the Ricardian labour model is explained and discussed. The theoretical analysis is covered in the chapters 4 and 5, in which the model is applied to this research and the outcomes are presented. From both the literature review and the microeconomic analysis a conclusion will follow, in which the main findings will be presented to answer the main and sub questions. This sixth chapter also includes a discussion part, in which the limitations of this research are discussed and suggestions for further research will be done. The thesis finishes with policy recommendations about how the labour market can be improved to become more suitable for the development in robotics.

Chapter 2 - Literature

In this chapter we will review the relevant literature concerning the influence of the robotization development on the labour market. We will look at the historical development, and the chances and challenges for the current and future labour market.

Lessons from the past: effect of the industrial robot on labour

From the literature, we will explore the consequences of increasing technology in the past, regarding the labour market. As there is not much literature yet concerning current robotic impact, past consequences can indicate what the relevant aspects are to look at. The aim of this research is to show how the direction and/or size of the consequences might differ. The consequences will be ordered, hence the different aspects can easily be recognized and included in the analysis.

A first consequence of the introduction of the robot in industries is the impact on the occupational structure of the economy. The labour market can be divided into different skill levels of the workers. In this research, three levels will be distinguished: low-, medium- and high-skilled workers. These three levels are the most essential, and including more levels makes the analysis unnecessary complex. We will come back to this in the next chapter. Edler and Ribakova (1994) found evidence in Germany for a long-term impact on the structure of employment. Low-skilled jobs are the most affected, because the robots especially replace the tasks performed by low-skilled workers (Ebel, 1987). The consequence of this is that employment decreases. This decrease might in some cases (partly) be offset by an increase in higher-skilled jobs with specific requirements (Edler and Ribakova, 1994). An example of such a job is a mechanic with specific knowledge and skills regarding the employed industrial robots in a firm. Edler and Ribakova (1994) only expect an increase at the beginning of the diffusion process due to the production of robots. Bartel and Lichtenberg (1987) empirically confirm that higher-skilled workers have an advantage over the lower-skilled, because these workers are more capable to adjust to and implement new technologies. In their research they also pay attention to the development over time on firm-level. After some time, when the technology becomes older, the consequences alter as the demand for higher-skilled workers declines. Especially in industries which are R&D-intensive, these effects will be stronger. From this we can learn that often technology is biased towards a certain skill level, so that the relations between the different worker types will change.

Except for the occupational structure also the sectoral structure of employment changes as a consequence of industrial robots (Edler and Ribakova, 1994). An illustration of a change in industries

is the motor vehicle sector. From 1985 onwards, when this sector exploits approximately 60% of all robots, it experiences a continuous decrease in share of robots, whereas other sectors get a bigger share of economic growth during the diffusion process. The decrease of robots in the motor vehicle sector is thus only a relative decrease, not an absolute decrease. Together with this shift the employment effects will therefore also change and probably spread over a broader range of sectors.

The organization of work also changes as the importance of technology on the working floor increases (Ebel, 1987). This implies for instance that the working conditions might be improved, as the unskilled, hazardous jobs are now performed by robots. This change might also lead to employees becoming more socially isolated. The study of Benders (1995) stresses this contrast between the image created by suppliers, namely that robots improve bad working conditions e.g. because they do the monotonous work, and the fact that low-skilled workers lose their jobs. For this research we will focus more on working conditions in a narrow sense. This includes whether and how the production process and corresponding demand for skills will change and also whether or to what extent wages will adjust. That the flexibility of wages may make an important difference is for example shown by the research of Drèze and Sneessens (1997), which also studied the consequences of technological development, but specific in low wage countries. They point out that the government should be aware of the rigidity of wages because it increases unemployment. The study of Bresnahan, Brynjolfsson and Hitt (1999) provides some useful insights into the adaptability of organizations. They performed an empirical firm-level study, showing that after an adjustment period reorganized firms are associated with higher output. In this study also came forward that especially skilled labour is complementary to changes and developments in (information) technology. This implies that this technological change biased towards high-skilled labour increases demand for this labour and also increases high-skill wages. In the analysis we will check whether this can be confirmed.

The above three aspects that prevail from the literature will be included in the analysis. So, the different skill level jobs, the differences in sectoral impact and the change in organization of work are important issues in this research.

Recent developments concerning robotization

Before jumping to the current consequences of robotization, first a short overview of the recent development of robotization will be given. Edler and Ribakova (1994) simulated the diffusion process of industrial robots from 1985-2000 by among others interviewing technical and marketing experts. Their forecast is that the quantity of robots increases significantly over time, and also the

composition of the different application types changes over time and by sectors. The absolute number of robots increases at an exponential rate. These simulations are compared with the actual data for the years 1980 to 1990 and they show similarity, which makes the predictions reliable. However, Ebel (1987) states that the rate of diffusion of industrial robots is not as high as expected. The reason is that social barriers need to be overcome. Examples of social barriers are the displacement of workers, the change in certain working methods and the deskilling of operations. Especially the changing working methods and how this affects the occupational structure are barriers that we will deal with in the policy recommendations. That these negative consequences also restrict the diffusion of robots is a unique perspective that Ebel (1987) takes in his research. Concerning the service sector, and then especially health care and elderly care, the lack of funding is slowing down the development of new robots (Engelhardt and Edwards, 1992). Another aspect that hampers the use of robotics in the service sector is the fear that people have, because they cannot control robots and therefore do not feel comfortable. The current frontrunners in such technology are the US, France and Japan. At least in the US also government regulation of the industry is an important driver of the technology development (Pellerin, 1991). Knod et al. (1984) mention the concern that labour costs will rise, whereas technological advances reduce the costs of exploiting robots. This might also plea for an increasing use of robots. The expectation is that in future also in the labour-intensive service sectors robotization will play a bigger role. We further expect that different types of technology in the different sectors also have different consequences.

Current consequences of robotization for the labour market

The recent developments in technology and robotics also suggest a difference in the related consequences of technology for the labour market. We want to explore this further in the theoretical analysis, and the literature in this section is relevant in providing a starting point for this analysis. In this section, first will be examined what the literature says about what skill level jobs become unnecessary and what other jobs increase in importance. Related to that we deal with the question in what ways comparative advantage plays a role when discussing robotization. Then a parallel to the trade literature is made to discover what can be learned from the developments in this field.

Already in 1984, Rumberger suggested that in future also higher-skilled mental labour might be displaced due to the development of robotics. He also mentioned that a broader range of sectors would be affected, which is in accordance with the forecast of Ebel (1987) that the diffusion of industrial robots would spread over all sectors. Also Blum (2008) confirms the changing sectoral impact of increasing capital. In his model, he assumes that capital is complementary and not substitutable to labour. The main result of the study is that capital shifts from manufacturing sectors,

where it was complementary to low-skilled workers, to sectors where capital is complementary to higher-skilled workers, for example service and retail sectors. So, the consequences will not only become more severe, they will also have a different impact on workers in skilled and unskilled jobs. When labour is substituted for capital this may even lead to a surplus of workers (Rumberger, 1984). It was already mentioned that the job loss was partly offset by an increase in higher-skilled jobs. Murphy, Riddell and Romer (1998), studying the labour market in the US and Canada, also expect that future technological change will increase the demand for high-skilled labour. Rumberger and Levin (1985) on the other hand highly doubts that high-tech industries and occupations will supply many new jobs in the future. Instead they expect that only the service jobs and clerical jobs benefit from job growth. With this they mean jobs that require only little or no schooling after secondary school, so they are classified as low-skilled jobs. Possible explanations for this diversity in results are that different sectors are studied and/or no clear distinction is made between substitutable and complementary technology. Therefore, we expect from the analysis that in the future technology will have consequences for a broader range of sectors. We also expect that the centre of gravity will shift from the low-skilled workers, as seen in the past, towards the medium and high-skilled workers and that it influences the demand for different types of labour.

The concept of comparative advantage was already introduced in the first chapter regarding the different sectors. There is also a comparative advantage between different worker types, which becomes relevant when discussing the model. Acemoglu and Autor (2011) define it as follows: a group of workers has a comparative advantage for a task when the relative price of producing the concerning tasks is the lowest for that group of workers. This relative price is depending on their relative wage and their productivity for performing the task. Within the topic of robotization also the comparative advantage between human workers and robots can be distinguished. This advantage differs per task and is determined by which of the two can perform the task for the lowest price. However, there is something more to take into account. One could think of tasks in which a robot has a comparative advantage, but human workers still perform the tasks, for example caring tasks. From a psychological or social point of view, however, one might prefer a human worker to perform the tasks. Related to this is the earlier mentioned consequence that in the service sector less funding for robotic development is available. In the analysis we will return to this when comparing the different types of technology in sectors.

In the introduction, the link with trade and immigration literature was already pointed out. The similarity is that both increasing trade and increasing robotization lead to a trade in tasks, respectively with the foreign labour market and with robots. Regarding the consequences of this, we

saw in the historical literature that also increasing trade leads to less demand for low-skilled and higher demand for high-skilled workers in advanced countries (Slaughter, 1998). However, Slaughter suggests that the aggregate gains for society are positive of both increasing trade and technology. Concerning increasing robotics not all studies share this suggestion, especially the gains for the labour market are disputable. A clear illustration is the earlier mentioned study of Rumberger (1984), which indicates that future job loss might be much more widespread than in the past, as all types of work will be affected instead of only low-skilled labour, as we saw before.

Baldwin and Cain (1997) also connect the two strands of literature and view trade and technology as two separate factors that influence the labour market and the relative wages of different skill level groups. His research focuses on the wage levels and showed that technical progress has a bigger influence in increasing the wage gap between low- and high-skilled work than increasing trade has. This is important to take into account as changes in wage levels clearly have an impact on demand for the different worker types. This is confirmed by the study of Murphy, Riddell and Romer (1998), which shows that the demand for a type of labour is influenced by the relative price of labour. The role of wage will therefore be an essential part of the theoretical model as it is associated with the allocation of tasks. The importance of wage also becomes visible when we turn to some specific influences trade and immigration can have on the labour market. An increase of low-skilled supply of workers in the US due to immigration causes a decline in these wages. The influence of immigration on wages is even more substantial than the impact from increased trade with low-wage countries (Borjas et al., 1997). Borjas (2003) confirms the effect of immigration with numbers: a supply increase of 10% causes a decline in wages of 3 or 4%. However, Borjas also finds evidence for a small positive cross effect, meaning that low-skill immigration increases high-skill wages and vice versa. We expect that the effect of task-replacing technology on wages is more or less to the effect of immigration, as in both cases workers of a certain skill level are replaced.

Besides wage effects there are also other factors that are affected. Grossman and Rossi-Hansberg (2008) found three effects by modelling the trade of tasks between countries when production is offshored. The first effect is a productivity effect, resulting from cost-saving when firms can easily offshore some of the tasks of the production process. The offshored tasks can now be performed by the world supply instead of only the country, which reduces the relative price of the task. This second effect, called the relative-price effect, is therefore directly related to the wage effect discussed before. The third effect that arises from the model is a labour-supply effect in the home country. This effect is derived from the re-employment of the workers that performed tasks that are now offshored. From the analysis of Grossman and Rossi-Hansberg (2008) we learn that at first mainly

low-skilled labour is replaced and therefore the negative labour supply effect is much stronger for low-skilled workers. Dependent on the rigidity of wages, this will also contribute to a decline in their wages. However, there can also be gains for the low-skilled workers when the technological improvements benefit the productivity of low-skilled workers more than of high-skilled workers. In that case, the wage effects from technology increasing productivity are different from the technology replacing tasks. The analysis will have to prove whether this is true. From the trade and immigration literature we conclude that the factors wage, productivity, relative price and labour supply are essential to include in the analysis.

Conclusion towards modelling the labour market

As most of previous empirical research studies the industrial robot, it is important to indicate how future and current consequences might differ from earlier consequences. Above summary of literature gives a good indication towards the outcome of our analysis concerning the consequences of more recent developments in robotics. The first aspect to observe is that as the developments in robotics continue, the consequences will shift from affecting mainly low-skilled workers towards affecting the medium and high-skilled workers. Another expectation is that the development of robotics will include a broader range of sectors, for example also involving the service sector whereas now mainly industrial sectors are affected. When the development and implementation of new technologies focused on industries, the impact is logically the highest in the engineering and related sectors. Thirdly, as the technology developments often will be biased towards a certain skill level, this will also influence the relative wages and the effects on unemployment.

Before the analysis is set up, first should be clarified what is necessary in the model to be able to answer the research question. A first feature should be that at least three different skill levels of workers should be distinguished as the impact on the skill levels will probably differ (Edler and Ribakova, 1994; Ebel, 1987). Secondly, the impact of robotization on job displacement and wages should be measured by the model (Hollon and Rogol, 1985; Howell, 1985). Howell (1985) also points towards the difference in impact between the industries, which adds to the question where jobs are displaced and where created. Therefore, in the application of the model a distinction between the different sectors will be made. The consequences robotization has for a sector where technology is productivity increasing and a sector where technology is task-replacing will be compared, as countries often have a comparative advantage in certain sectors (Kinoshita and Yamada, 1989). The model should thus show whether tasks robots can perform are substitutable or complementary to the tasks of employees. Lastly, we should be able to draw different scenarios from the model concerning the organization of work. This includes the rigidity of wages and whether the different

worker types are interchangeable in performing tasks. These criteria are met in the Ricardian labour model of Acemoglu and Autor (2011).

The research of Acemoglu and Autor (2011) is highly related to the current research, because it also deals with the question how increasing technology has impact on employment. Acemoglu and Autor use both the canonical model and the Ricardian labour model to study changes in employment due to interaction among different skills, tasks, evolving technologies and changing trade opportunities. The canonical model provides a framework for analyzing how the interactions between workers, wages, skills, technology and trade shape the labour market, with as main outcome the price of skills. The model is therefore part of the literature of changes in earnings distribution. However, this model suffers from quite a few restrictions that make the model less reliable (Acemoglu and Autor, 2011). A first restriction is that it does not distinguish between tasks and skills, which means that the model cannot examine the impact on task allocation between worker groups. The industrial robot already showed that the allocation of tasks among workers shifted, therefore it is relevant to explain how this task allocation changes. Another restriction is that task-replacing technology cannot be included in the analysis, which would imply a substantial limitation for our research. Besides, the focus of our research is broader than only changes and differences in wage distribution. Most of these restrictions can be captured by the Ricardian labour model, which we will therefore use as basis for the analysis. The Ricardian labour model makes a relevant distinction between skills and tasks, and leaves more room to study how different technology developments affect wages and the assignments of skills to tasks. This model and its outcomes will therefore be discussed more extensively in the next chapter. One important aspect to mention already is the role of organizational change. It shapes the demand for skills and also influences the relation between new technologies and distribution of employment.

Chapter 3 – Model of analysis

In the previous chapter we explained that the Ricardian labour model, as developed by Acemoglu and Autor (2011), can be used as a basis for our research. Several relevant aspects for our analysis are included, which makes this Ricardian labour model suitable for this analysis. In order to make this model an even better fit for this research, we will apply the model more specific to our research question by paying more attention to different scenarios concerning the organization of work.

Important aspects in the existing model are that:

- The key equilibrium of the model is the allocation of tasks across skill groups;
- Three skill levels are distinguished: high-, medium- and low-skilled workers;
- The model is task-based, which means that skills are applied to tasks to produce output. This is relevant, because robots can take over tasks of people, not directly skills. This leaves room for occupations to change in the bundle of tasks they comprehend;
- Substitution and complementary properties among skill groups are included.

In this subsection, the relevant parts of the Ricardian labour model as Acemoglu and Autor developed, will be explained. A distinction between skills and tasks is made in this model, because they assume that workers with a certain skill level can perform a variety of tasks and this set of tasks may change when e.g. technology affects the working process. So, tasks are defined as units of labour activity that produce certain output, whereas skills are the capabilities employees have to perform the different tasks. The general idea of the model is to show how workers that are skilled differently can be allocated over the different tasks in the most optimal way. Workers are therefore divided in three groups: high-skilled, medium-skilled and low-skilled. It is assumed that higher-skilled workers are more productive, especially in more difficult tasks. Tasks are ranged in difficulty from [0,1]. Key in the model is that low-skilled workers have a comparative advantage in easier tasks, high-skilled workers in more difficult tasks and medium-skilled worker in medium difficult tasks.

The starting point of the model is a static environment with a unique good Y , a closed economy and no trade in tasks (Acemoglu and Autor, 2011). The production function of each task transfers the four factors of production low, medium and high-skilled workers and capital into the 'output' level of task i , denoted as $y(i)$:

$$y(i) = A_L a_L(i) l(i) + A_M a_M(i) m(i) + A_H a_H(i) h(i) + A_K \alpha_K(i) k(i). \quad (1)$$

A denotes the factor-augmenting technology, which is specific for each task and each skill level. Developments in technology might ease some tasks in the production process, but other tasks will gain less or even nothing from the development. The same holds for the different skill levels of

workers. Technology improvements are assumed to be biased towards one of the three skill levels. In function (1) a shows the skill level related worker productivity for task i and l , m and h show respectively the number of low-, medium- and high-skilled workers allocated to the task. The three different types of workers are perfect substitutes, meaning that for each task only one type of skill level is demanded. The function also implies that low- as well as medium- and high-skilled workers can perform each task, but it is crucial to observe that the comparative advantage of the skill groups across tasks will differ, as shown by the skill level specific productivity (a) and technology (A). Production factor capital is represented by k . At first, capital will be left out of the analysis, but it becomes relevant later when we want to derive from the model what the consequences are when technology or capital replaces workers in performing tasks. Important to note is that capital is not treated in the model as a fourth skill level, as equation (1) might suggest. Capital, or technology, is viewed as complementary or substitutable to tasks of a certain skill level, as further explained in chapter 4. We now first focus on the allocation of skills to tasks, meaning that technology cannot substitute for labour yet in performing tasks.

The Cobb-Douglas production function¹ of the good combines the necessary, various tasks which are represented by the interval $[0,1]$. The output of the final good is:

$$Y = \exp \left[\int_0^1 \ln y(i) di \right]. \quad (2)$$

From this Cobb-Douglas function we can derive that expenditure, defined as production level ($y(i)$) multiplied by the price of services of task i ($p(i)$), is equal across all tasks (for all i). This can be derived by solving the cost minimization problem for the production of the final good. The expenditure of a task should be similar to the value of the final output. Taking into account the choice of the numeraire (so $Y=1$), this can also be written as:

$$p(i)y(i) = Y, \text{ for any } i \in [0,1]. \quad (3)$$

These three equations form the basis of the model of Acemoglu and Autor (2011), and they are necessary later when deriving the final equilibrium condition.

When setting up the framework for the model, a closer look to the characteristics of the three skill groups is required. In the analysis it is assumed that higher-skilled workers are better in performing the more complex tasks. The tasks will be classified in three groups, ranging from $0 < l_L < l_H < 1$. Tasks under threshold l_L will be performed by low-skilled workers and tasks above threshold l_H will be

¹ Equation (2) is a special case of a Cobb-Douglas production function with all exponents a_i being equal to 1. The original function was $Y = y_0^{a_0} \cdot \dots \cdot y_1^{a_1}$, of which the natural logarithm was taken.

performed by high-skilled workers. Tasks in between thresholds I_L and I_H will be performed by medium-skilled workers; examples of such tasks are clerical and administrative support occupations. However, it is assumed that substitution of skills across tasks is possible in this model. This implies that the boundaries of the sets of tasks, I_L and I_H , will respond to technological developments and changes in skill supply. A possible explanation could be that firms then choose a new optimum concerning which tasks will be performed by which skill groups.

This equilibrium is realized under the assumption that workers of the same skill level all receive the same wage, regardless of the different tasks they may perform. The wages for respectively low-, medium- and high-skilled workers are then w_L , w_M and w_H . Within a skill group, the marginal product of all workers must therefore be equal in all tasks:

$$w_L = p(i)A_L a_L(i) \text{ for any } i < I_L, \quad (4)$$

$$w_M = p(i)A_M a_M(i) \text{ for any } i < I_M, \quad (5)$$

$$w_H = p(i)A_H a_H(i) \text{ for any } i < I_H. \quad (6)$$

The implication of these equations is that the productivity difference in different tasks of workers from the same skill level must be offset by the price difference between the tasks. For example, the tasks performed by low-skilled workers differ in intensity and therefore one task can be performed easier than another task. This difference in productivity must be offset by a difference in price $p(i)$, so that the value marginal product and the wage w_L are equal for each low-skilled worker, independent of the task he or she performs. To derive the relative wages of the skill groups, we first need to elaborate on the value of tasks, supply of workers and the allocation of tasks.

To get the relative price of tasks performed by workers of different skill groups, it is necessary to define the value of tasks. The value of a task is determined by the price of services per task and the productivity of that task and is presumed to be equal for all tasks i within the thresholds of the concerning skill group. First, P_L is defined as the value of tasks produced by low-skilled workers and for any $i, i' < I_L$:

$$p(i)a_L(i) = p(i')a_L(i') \equiv P_L. \quad (7)$$

This equation says that the tasks within a skill group satisfy the competitive market assumption. The same reasoning applies for medium- and high-skilled workers. For medium-skilled workers, for any $I_H > i, i' > I_L$:

$$p(i)a_M(i) = p(i')a_M(i') \equiv P_M, \quad (8)$$

and for high-skilled workers, for any $i, i' > I_H$:

$$p(i) a_H(i) = p(i') a_H(i') \equiv P_H. \quad (9)$$

A consequence of this is that in equilibrium also the number of workers allocated to a task is equal for each task. For example, when tasks i and i' are both performed by low-skilled workers the number of workers $l(i)$ must be equal to $l(i')$ for any $i, i' < I_L$. Equation (7) can be extended with the number of workers allocated to the task and becomes:

$$p(i) a_L(i) l(i) = p(i') a_L(i') l(i'). \quad (10)$$

The same logic applies for medium- and high-skilled workers.

Then we introduce the supply of workers into the analysis. We assume for now that the supply of the three types of workers, low (L), medium (M) and high (H), is fixed. This implies that the supply is perfectly inelastic to wages. Later, we will introduce technology in these equations and discuss the corresponding response of supply. In equilibrium, supply is equal to demand plus unemployment. For now we assume unemployment to be zero, so all workers are employed. The condition then holds that the worker supply of a skill group is equally distributed over the tasks of this group, for respectively low-, medium- and high-skilled workers we must have:

$$l(i) = \frac{L}{I_L} \text{ for any } i < I_L, \quad (11)$$

$$m(i) = \frac{M}{I_H - I_L} \text{ for any } I_L < i < I_H, \quad (12)$$

$$h(i) = \frac{H}{1 - I_H} \text{ for any } i > I_H. \quad (13)$$

Now we can combine these equations to compare tasks performed by different skill groups, for example task i performed by a medium-skilled worker and task i' performed by a high-skilled worker ($I_L < i < I_H < i'$). Recall that when including the price of services of a task, the tasks performed by different worker types must be competitive to each other. Therefore the contribution to the output of the final good must be equal for both cases, which can be shown using equation (1) and (3):

$$p(i) A_M a_M(i) m(i) = p(i') A_H a_H(i') h(i') \quad (14)$$

From here the authors work towards the relative price of a task performed by a high-skilled worker compared to a medium-skilled worker. The authors show that from equation (14), we can substitute with equations (8), (9), (12) and (13) and rearrange to obtain this relative price:

$$\frac{P_H}{P_M} = \left(\frac{A_H H}{1 - I_H} \right)^{-1} \left(\frac{A_M M}{I_H - I_L} \right). \quad (15)$$

So, it can be seen that the relative price depends on the supply and factor-augmenting technology of both worker types. A similar comparison and reasoning applies for two tasks performed by medium- and low-skilled workers:

$$\frac{P_M}{P_L} = \left(\frac{A_M M}{I_H - I_L} \right)^{-1} \left(\frac{A_L L}{I_L} \right). \quad (16)$$

The thresholds I_L and I_H are important equilibrium variables in the model. We can derive equations for the tasks at these thresholds when rewriting equations (15) and (16), in which we implement the definitions in (7), (8) and (9). For these threshold tasks, the costs of producing them is equal whether using the upper or the lower skill type worker, which implies that no gain can be made from price differences regardless which worker performs the threshold task. So, for I_H the costs are equal whether the medium- or the high-skilled worker produces it, as shown in the equivalent of equation (15):

$$\frac{A_M a_M (I_H) M}{I_H - I_L} = \frac{A_H a_H (I_H) H}{1 - I_H} \quad (17)$$

Similarly, the equivalent of equation (16) shows that for task I_L there is no cost difference between the low-skilled worker and the medium-skilled worker:

$$\frac{A_L a_L (I_L) L}{I_L} = \frac{A_M a_M (I_L) M}{I_H - I_L} \quad (18)$$

For simplicity, we will not introduce capital yet. Capital only becomes relevant when it replaces tasks earlier performed by workers. Therefore, equations (17) and (18) can be seen as a situation where $k=0$.

The next step in the model is then deriving the relative wages of the different worker types. These relative wages are important, because we want to know what the effects on these wages are when technology is introduced. When the threshold tasks are determined, the wages can easily be derived as they are the values of the marginal products of the skill types. For example, the low-skill wage w_L is equal to the factor-augmenting technology A_L and the value of low-skilled tasks P_L . As noted above, P_L was determined by the worker productivity and the price of a task.

$$w_L = P_L A_L \quad (19)$$

Even more interesting is the wage relative to other skill levels. For example the wage ratio between high- and medium-skilled workers:

$$\frac{w_H}{w_M} = \frac{P_H A_H}{P_M A_M}$$

This wage ratio can be rewritten using equation (15) and (16) in terms of relative supply of labour and the equilibrium variables of task allocation I_L and I_H . For high- and medium-skilled worker wages it is:

$$\frac{w_H}{w_M} = \left(\frac{1-I_H}{I_H-I_L} \right) \left(\frac{H}{M} \right)^{-1} \quad (20)$$

And for medium- relative to low-skilled worker wages:

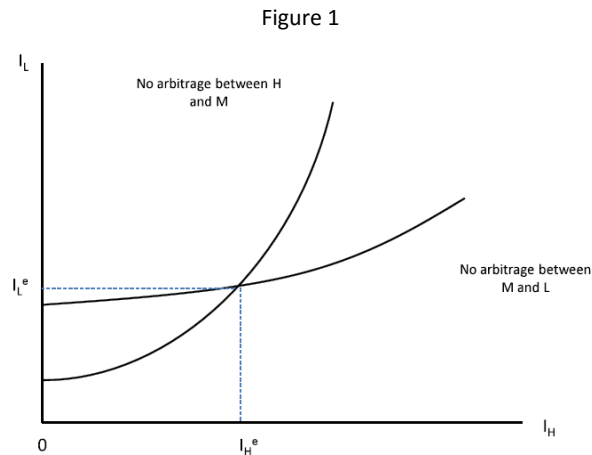
$$\frac{w_M}{w_L} = \left(\frac{I_H-I_L}{I_L} \right) \left(\frac{M}{L} \right)^{-1} \quad (21)$$

In these two equations we can see that the threshold tasks are linked to the relative wages. This means that a change in allocation of tasks always goes together with a change in relative wages, except when wages are rigid.

There is one final condition necessary for the equilibrium, which results from the numeraire ($Y=1$), equation (2) and equation (3). This condition is that the $\exp[\int_0^1 \ln p(i) di] = 1$. In words, this condition is a consequence of choosing the final good as numeraire, which means that its price $p(i)$ is set to 1. This can be rewritten with use of the equations (7), (8) and (9):

$$\int_0^{I_L} (\ln P_L - \ln a_L(i)) di + \int_{I_L}^{I_H} (\ln P_M - \ln a_M(i)) di + \int_{I_H}^1 (\ln P_H - \ln a_H(i)) di = 0 \quad (22)$$

The unique equilibrium of the Ricardian labour model is summarized by equations (15)-(22). Equations (17) and (18) determine the thresholds I_L and I_H and subsequently this can be used to compute the relative wages in equations (20) and (21). The other equations (15), (16), (19) and (22) compute the wage and price levels. In figure 1 the determination of equilibrium threshold levels is illustrated (Acemoglu and Autor, 2011, figure 22).



The figure shows the two partial equilibriums to determine threshold I_H between high- and medium-skilled workers and threshold I_L between medium- and low-skilled workers. At the intersection of

these lines, the threshold conditions as described in equations (17) and (18) are fully satisfied, so the equilibrium threshold tasks are at I_L^e and I_H^e . To use this model to find out what the allocation of tasks to the different worker types is, we need to rewrite equation (17):

$$\frac{1-I_H}{I_H-I_L} \frac{a_M(I_H)}{a_H(I_H)} = \frac{A_H H}{A_M M}. \quad (23)$$

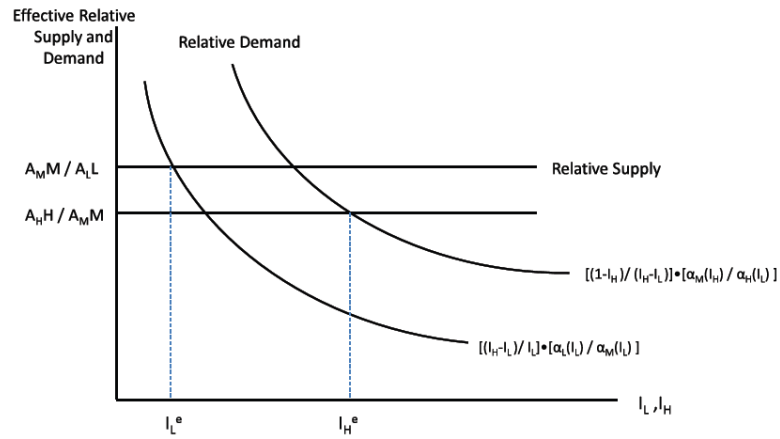
This equation shows the equilibrium between the relative effective demand of high to medium skills (left-hand side) and the effective supply of high relative to medium skills (right-hand side). This equation determines threshold I_H , namely where the two curves cross each other.

Similarly, by rewriting equation (18) this can be done for medium relative to low-skills to determine threshold I_L :

$$\frac{I_H-I_L}{I_L} \frac{a_L(I_H)}{a_M(I_H)} = \frac{A_M M}{A_L L}. \quad (24)$$

In figure 2 the effective supply and demand curves of skills are shown (Acemoglu and Autor, 2011, figure 23). The intersection of the curves shows the equilibrium allocation of skills to tasks, also resulting in the equilibrium threshold tasks I_L^e and I_H^e . Again, the threshold conditions as described in equations (17) and (18) are fully satisfied in this figure.

Figure 2



Once the model is explained, we can use it to derive the consequences of robotization on the labour market in the next chapter.

Chapter 4 – Effect of robotization on the labour market

The Ricardian labour model as discussed above is a suitable basic model that can be applied to our research. In the literature study several factors were distinguished to be relevant, which should therefore be included in the model. In this chapter, we will discuss these aspects and add them to the model, so we can deduce their impact. First, the different consequences for task allocation and wages of the two types of technology² in different sectors will be analysed, namely when it increases productivity and when it replaces workers in performing tasks. This will be done for technology biased toward each of the three worker types. Secondly, we will address different scenarios concerning the organization of work, looking at the rigidity of wages and when the different worker types are not interchangeable in performing tasks of another skill group.

Sectoral differences in impact

The development of technology is not the same for all sectors (eg. Edler and Ribakova, 1994). An important difference that exists between sectors is that in one sector technology is complementary whereas in another sector technology is substitutable. We can apply the model to show the difference in impact these different types of technology may have. When technology is complementary this means that it increases productivity, which can be represented by an increase in A . Technology substituting worker tasks is represented in the model by capital k , which influence was neglected thus far in the model. Additional to these two types of technology, a further distinction can be made. Often technology is biased towards a certain skill level. For example, when complementary technology is biased towards low-skilled tasks, this means that the productivity of the workers performing low-skilled tasks increases. When the technology is substitutable, it substitutes the low-skilled labour. Similarly, technology can be biased towards medium- or high-skilled tasks, for both complementary and substitutable technology.

In the literature a different explanation for sectoral differences was discussed. Engelhardt and Edwards (1992) showed that for example service sectors may lag behind, due to financing and inconveniency reasons. This implies that the size of the effect might differ per sector or industry. However, there is no reason to expect the direction of the effect to be different as only the parameters in equation (1) differ per sector. Therefore we assume that this difference between sectors will have no influence on the qualitative results. The same holds for the difference between a

² Note that when the term technology is used in chapter 4 and 5 this also includes robotization.

³ We saw earlier that I_H increases and I_L decreases, meaning that part of both high- and low-skilled tasks are

labour-intensive industry and a capital-intensive industry. However, the quantitative results will differ as the impact on the labour market is much stronger for the labour-intensive industry by technological improvements. In this section, we will first explore the consequences for technology when it increases productivity and then derive the consequences when technology is task-replacing.

Technological change increasing productivity

Some comparative statics regarding technological change are already obtained from the model by Acemoglu and Autor (2011). As mentioned, in this subsection the technological change that increases productivity is discussed, also called complementary technology as it adds to the work of human workers.

Acemoglu and Autor (2011) show that when the change is biased towards high-skilled tasks and increases productivity, A_H increases in the model and I_L and I_H decrease. Important to note here is that a change in threshold tasks does not take place without a change in wages, so the change in thresholds goes through a change in wages. We will come back to this later in this chapter. The intuitive explanation is as follows: high-skilled workers become more productive due to the technological change, which increases the number of tasks in which they have a competitive advantage. This results in a shift of tasks from medium-skilled to high-skilled workers. As a consequence of the excessive supply of medium workers, also a new equilibrium between medium relative to low skills will be formed. Therefore, both I_H and I_L will be lower. The authors show that taking the logs of equations (17) and (18) yields simpler equations:

$$\ln A_M - \ln A_H + \beta_H(I_H) + \ln M - \ln H - \ln(I_H - I_L) + \ln(1 - I_H) = 0 \quad (25)$$

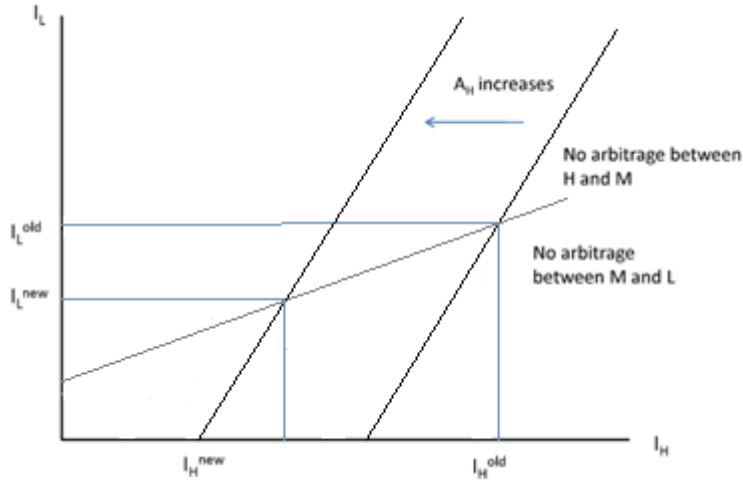
and

$$\ln A_L - \ln A_M + \beta_L(I_L) + \ln L - \ln M + \ln(I_H - I_L) - \ln(I_L) = 0, \quad (26)$$

where $\beta_H(I) \equiv \ln \alpha_M(I) - \ln \alpha_H(I)$ and $\beta_L(I) \equiv \ln \alpha_L(I) - \ln \alpha_M(I)$ are defined.

To illustrate the argument above graphically, equations (25) and (26) are shown in figure 3 on the next page, where equation (25) is the steeper line (adapted from Acemoglu and Autor, 2011, figure 25). An increase in A_H shifts this curve inwards and shows that both I_H and I_L will be lower.

Figure 3



This graphical illustration can also be proven mathematically. Acemoglu and Autor represent the differentiated equation (25) and (26) in a matrix to consider the impact of a technological change. As in figure 3, first an increase in high-skill biased technology A_H is considered:

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1 - I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} d \ln A_H.$$

The determinant Δ of this matrix is calculated by the diagonals of this matrix:

$$\Delta = \left(\beta'_H(I_H) - \frac{1}{1 - I_H} \right) \left(\beta'_L(I_L) - \frac{1}{I_L} \right) + \frac{1}{I_H - I_L} \left(\frac{1}{I_L} + \frac{1}{1 - I_H} - \beta'_L(I_L) - \beta'_H(I_H) \right).$$

Important to note from this determinant is that the value is positive. Then the matrix and its determinant are used to derive the consequences of an increase in A_H on the allocation of tasks:

$$\begin{aligned} \frac{dI_H}{d \ln A_H} &= \frac{\beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L}}{\Delta} < 0 \\ \frac{dI_L}{d \ln A_H} &= -\frac{1}{I_H - I_L} < 0 \\ \frac{d(I_H - I_L)}{d \ln A_H} &= \frac{\beta'_L(I_L) - \frac{1}{I_L}}{\Delta} < 0. \end{aligned}$$

The first two results verify what was seen in figure 3. However, the third result cannot be seen in the graph and is therefore an additional result. This result shows that the set of tasks performed by medium-skilled workers decreases. This was also the case for the lower-skilled workers, whereas the higher-skilled workers now perform a larger set of tasks due to the increased productivity. It implies that the threshold I_H decreases more than threshold I_L .

Acemoglu and Autor only worked this out for the high-skill biased technological change, but our interest is also in technological change biased towards medium- and low-skilled tasks. We will therefore now perform a similar analysis of a sector where the technological change is biased towards low-skilled tasks, represented by an increase in A_L . The same logic is applicable in opposite direction: low-skilled workers become more productive and will perform more tasks for medium-skilled workers, so medium-skilled workers will shift to some tasks of high-skilled workers, in the end resulting in increased thresholds I_L and I_H . Again, the evidence can be provided by a mathematical analysis. An increase in A_L can be represented by the following matrix, again using the derivation of equations (25) and (26):

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1 - I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \end{pmatrix} d \ln A_L.$$

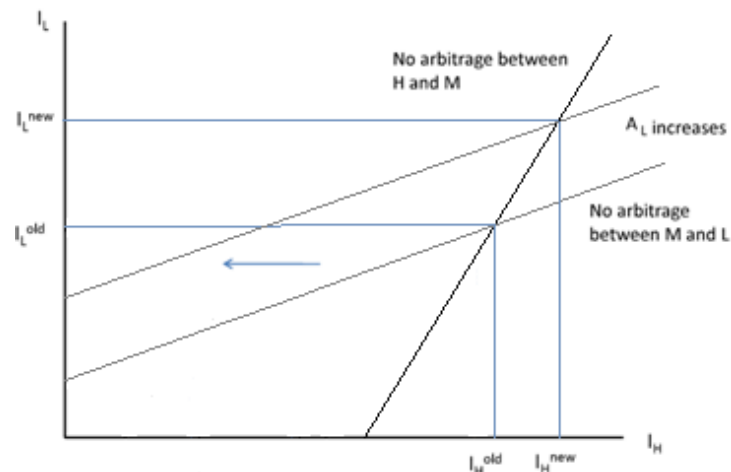
We can use this matrix and its determinant, which is equal to the determinant Δ above, to derive the consequences of the increase in A_L on the allocation of tasks:

$$\begin{aligned} \frac{dI_H}{d \ln A_L} &= \frac{\frac{1}{I_H - I_L}}{\Delta} > 0 \\ \frac{dI_L}{d \ln A_L} &= \frac{-\beta'_H(I_H) + \frac{1}{I_H - I_L} + \frac{1}{1 - I_H}}{\Delta} > 0 \\ \frac{d(I_H - I_L)}{d \ln A_L} &= \frac{\beta'_H(I_H) - \frac{1}{1 - I_H}}{\Delta} < 0. \end{aligned}$$

These results show that both thresholds I_L and I_H increase when low-skill biased technology develops and increases productivity of low-skilled workers. Again, the set of tasks performed by medium-skilled workers becomes smaller. This implies that the threshold I_L increases more than threshold I_H . In figure 4 is shown how this looks graphically.

Figure 4

Source: Authors own elaboration based on Acemoglu and Autor, 2011, figure 25.



In analogy, we can also derive the consequences of an increase of technological change towards medium-skilled tasks, increasing A_M . Medium-skilled workers will get a competitive advantage in tasks earlier performed by both low- and high-skilled workers. Therefore I_L will decrease and I_H will increase. Again, we can confirm this intuitive reasoning with mathematical proof. An increase in A_M can be represented by the following matrix, again using the derivation of equations (25) and (26):

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1 - I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} -1 \\ 1 \end{pmatrix} d \ln A_M.$$

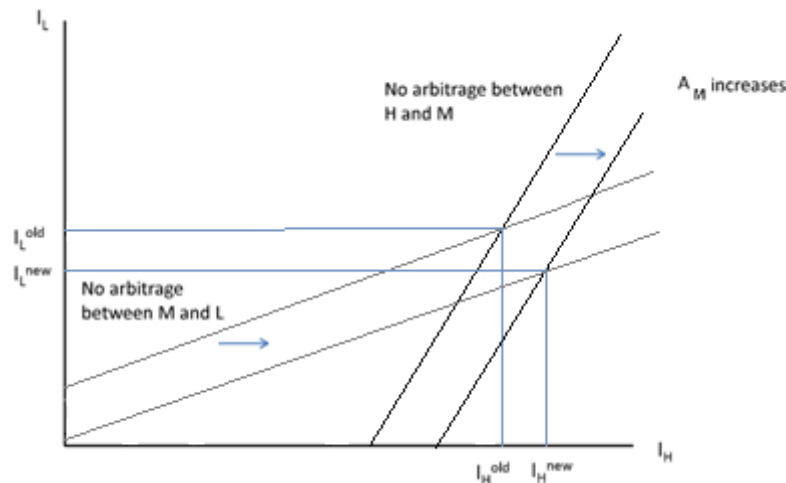
We can use this matrix and determinant Δ to derive the consequences of the increase in A_M on the allocation of tasks:

$$\begin{aligned} \frac{dI_H}{d \ln A_M} &= \frac{-\beta'_L(I_L) + \frac{1}{I_L}}{\Delta} > 0 \\ \frac{dI_L}{d \ln A_M} &= \frac{\beta'_H(I_H) - \frac{1}{1 - I_H}}{\Delta} < 0 \\ \frac{d(I_H - I_L)}{d \ln A_M} &= \frac{-\beta'_L(I_L) - \beta'_H(I_H) + \frac{1}{I_L} + \frac{1}{1 - I_H}}{\Delta} > 0. \end{aligned}$$

The results prove to be as mentioned above. This means that the set of tasks performed by the higher-skilled and the set performed by the lower-skilled are smaller after the technological change. In figure 5 is shown how this looks graphically.

Figure 5

Source: Authors own elaboration based on Acemoglu and Autor, 2011, figure 25.



However, the set of tasks performed by the medium-skilled is larger, as medium-skilled workers are more productive now. Similar reasoning could be used when for example the supply of medium-skilled workers (M) increases. This would also lead to medium-skilled workers taking over tasks from high- and low-skilled workers to reach a new equilibrium (see equations (23) and (24)).

In all three cases of technological change there is substitution of skills across tasks. When looking for example at the industrial robotization in the previous century, which implies that productivity of low-skilled tasks increases, the consequences are that low-skilled workers take over some of the tasks of medium-skilled workers, who in turn take over some of the tasks of high-skilled workers. This means that both medium- and high-skilled worker have a smaller share of tasks to perform, whereas more tasks are allocated towards the low-skilled workers. Important to observe is that all three skill groups experience the consequences, not only the addressed skill group. The consequences might even be worse for the other two groups, as the addressed group is compensated by the larger share of tasks it performs now. So, we can conclude for all three worker types towards which the technology might be biased that the affected group increases its share of tasks, whereas the other two groups get a smaller share of tasks.

In the analysis it was mentioned that the technological developments have corresponding wage implications. These implications are implicit in the changes in task allocation, which were represented by the changing threshold tasks I_H and I_L . This means that the wage changes will not once again have allocation effects. Therefore, as the focus of this research is on the consequences of technology for task allocation and not for the wage implications, we will just recall them from Acemoglu and Autor (2011) as we need them to derive the implications of downward wage rigidity later. They performed comparative statics concerning the consequences of skill biased technology increasing productivity. The relative wage implications of an increase are when A_H increases that $\frac{w_H}{w_M}$ increases, $\frac{w_M}{w_L}$ decreases and $\frac{w_H}{w_L}$ increases. When A_M increases the implications are that $\frac{w_H}{w_M}$ decreases, $\frac{w_M}{w_L}$ increases and $\frac{w_H}{w_L}$ depends on whether the medium-skilled workers take over more high- or more low-skilled tasks³. Lastly, when A_L increases the corresponding wage implications are that $\frac{w_H}{w_M}$ increases, $\frac{w_M}{w_L}$ decreases and $\frac{w_H}{w_L}$ decreases.

³ We saw earlier that I_H increases and I_L decreases, meaning that part of both high- and low-skilled tasks are now performed by medium-skilled workers. When the decrease in share of tasks is equal for both skill groups, the relative wage stays the same.

Technology replacing tasks

Technology can have another consequence than increasing the productivity of the worker.

Technological development, also expressed as increasing capital, can directly displace workers from their tasks as explained before. The analysis for this substitutable technology can have the same outline as in the described model when technology is complementary. What differs is the new presumption that technology will not complement the tasks and increase workers' productivity, but it is a substitute to the workers replacing them in performing (some of) their tasks.

Autor, Levy and Murnane (2003) show that in the current era mainly medium-skilled tasks that are routine or codifiable will be replaced by machines. Acemoglu and Autor (2011) show that in the model this means that $\alpha_k(i)$, as introduced in equation (1), increases for a range of tasks $[l', l'']$ between I_L and I_H , so that they have an economic advantage over medium-skilled workers for these tasks. When machines are performing the tasks in this range now, a new equilibrium will arise with new thresholds \hat{I}_L and \hat{I}_H such that $0 < \hat{I}_L < l' < l'' < \hat{I}_H < 1$. Equations (11)-(13) are used by Acemoglu and Autor (2011) to show the proposition for this new equilibrium: for any $i < \hat{I}_L$, $m(i) = h(i) = 0$ and $l(i) = \frac{L}{I_L}$; for $\hat{I}_L > i > l'$ and $l'' > i > \hat{I}_H$, $l(i) = h(i) = 0$ and $m(i) = \frac{M}{\hat{I}_H - l'' + l' - \hat{I}_L}$; for $l' < i < l''$, $l(i) = m(i) = h(i) = 0$ and for any $i > \hat{I}_H$, $l(i) = m(i) = 0$ and $h(i) = \frac{H}{1 - \hat{I}_H}$. These changing thresholds already show a reallocation of skills to tasks, as medium-skilled workers will start performing some of the low- and high-skilled tasks, thereby increasing supply of these tasks. Note that again the condition is that the total supply of workers is deployed.

We will now show the above mathematically and show the results for the allocation of tasks, before turning to the corresponding wage implications. To derive the results we have to go back to equations (17) and (18).

With respect to equations (17) and (18) we mentioned that $k=0$, as a situation was regarded where capital or technology does not replace tasks of workers. Recalling equations (17) and (18):

$$\frac{A_M a_M (I_H) M}{I_H - I_L} = \frac{A_H a_H (I_H) H}{1 - I_H} \quad (17)$$

$$\frac{A_L a_L (I_L) L}{I_L} = \frac{A_M a_M (I_L) M}{I_H - I_L} \quad (18)$$

Acemoglu and Autor (2011) then introduce capital (k) to derive the consequences when technology does replace tasks. Again, a distinction is made between technology biased towards high-skilled tasks (k_H), medium-skilled tasks (k_M) and low-skilled tasks (k_L).

In equations (17) and (18) the equilibrium was shown for the threshold tasks at which the costs of producing these tasks is equal using the upper or the lower skill type worker. Starting with technology biased towards high-skilled tasks, this means that capital k_H replaces some of the tasks above threshold I_H . This has implications for the costs of producing high-skilled tasks, which is the right-hand side of equation (17). However, we assume worker productivity, technology-augmenting productivity and worker supply to stay at the same level. Only the denominator diminishes as the tasks that are taken over by technology should be subtracted. This denominator becomes $1 - I_H - k_H$. We can use the same logic when introducing task-replacing technology that is biased towards medium-skilled tasks. This means that the denominator on the left-hand side of equation (17) becomes $I_H - I_L - k_M$, which is the same denominator as on the right-hand side of equation (18). When the task-replacing technology is biased towards low-skilled tasks, this implies that the left-hand side denominator of equation (18) become $I_L - k_L$, meaning that technology now performs part of the tasks earlier performed by low-skilled workers.

The next step is to take the logs of the adjusted equations (17) and (18), resulting in equations (25) and (26) but then including task-replacing capital:

$$\ln A_M - \ln A_H + \beta_H(I_H) + \ln M - \ln H - \ln(I_H - I_L - k_M) + \ln(1 - I_H - k_H) = 0 \quad (27)$$

and

$$\ln A_L - \ln A_M + \beta_L(I_L) + \ln L - \ln M + \ln(I_H - I_L - k_M) - \ln(I_L - k_L) = 0. \quad (28)$$

These equations can be used to show the mathematical approach to derive the consequences of task-replacing technology for the allocation of tasks.

This subsection was started with technology replacing medium-skilled tasks. Therefore, first these consequences for the allocation of tasks will be derived as in Acemoglu and Autor (2011). This can be done by taking the total differential of equation (27) and (28), and write it down using matrix notation. Then is evaluated what happens from the initial equilibrium, before the introduction of the task-replacing technology with $k_H, k_M, k_L = 0$. In the new equilibrium holds that $k_M > 0$. We can obtain the comparative statics from these 2 equations, shown in the matrix below:

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1 - I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} -\frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} \end{pmatrix} dk_M.$$

By using matrix algebra, it can be verified that:

$$\frac{dI_H}{dk_M} = \frac{1}{I_H - I_L} \frac{-\beta'_L(I_L) + \frac{1}{I_L}}{\Delta} > 0$$

$$\frac{dI_L}{dk_M} = \frac{1}{I_H - I_L} \frac{-\beta'_H(I_H) - \frac{1}{1-I_H}}{\Delta} < 0$$

$$\frac{dI_H - I_L}{dk_M} = \frac{1}{I_H - I_L} \frac{-\beta'_L(I_L) - \beta'_H(I_H) + \frac{1}{1-I_H} + \frac{1}{I_L}}{\Delta} > 0,$$

where Δ is again the determinant of the above matrix, as shown earlier. This says that as technology replaces tasks of medium-skilled workers, I_H will increase and I_L will decrease and the medium-skilled tasks set is expanded. In normal words, it means that the medium-skilled workers will take over some of the tasks which were earlier performed by the low-skilled and some earlier performed by the high-skilled workers. Note that the research aims at the introduction of tasks, but the qualitative results also hold for the augmenting technology. Above derivation namely shows the change in thresholds relative to the change in capital. This change in capital does not necessarily mean from zero to some positive number, but can also mean a change from current task-replacing capital to new, increased task-replacing capital.

Acemoglu and Autor (2011) only derived the results for task-replacing technology biased towards medium-skill tasks, therefore we will use the same logic for technology replacing low- and high-skilled tasks. Tasks-replacing technology biased towards high-skilled tasks implies that in the new equilibrium $k_H > 0$, whereas k_M and k_L are equal to zero. Filling this into equations (27) and (28), we can obtain the comparative statics and evaluate from the initial equilibrium with $k_H = 0$, shown in the matrix below:

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1-I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} \frac{1}{1-I_H} \\ 0 \end{pmatrix} dk_H.$$

By using matrix algebra, it can be verified that:

$$\frac{dI_H}{dk_H} = \frac{1}{I_H - I_L} \frac{\beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L}}{\Delta} < 0$$

$$\frac{dI_L}{dk_H} = \frac{1}{I_H - I_L} \frac{-\frac{1}{I_H - I_L}}{\Delta} < 0$$

$$\frac{dI_H - I_L}{dk_H} = \frac{1}{I_H - I_L} \frac{\beta'_L(I_L) - \frac{1}{I_L}}{\Delta} < 0,$$

where Δ is again the determinant of the above matrix. So, when technology replaces tasks earlier performed by high-skilled workers, high-skilled workers will take over some of the previous medium-skilled tasks, and subsequently medium-skilled workers will take over some of the previous low-

skilled tasks. The second and third verification show that both medium and low-skilled workers end up with less tasks to perform than before the technology development.

Lastly, we will derive the results for technology replacing low-skilled tasks. This implies that in the new equilibrium $k_L > 0$, whereas k_H and k_M are equal to zero. Filling this into equations (27) and (28), we can obtain the comparative statics and evaluate from the initial equilibrium with $k_L = 0$, shown in the matrix below:

$$\begin{pmatrix} \beta'_H(I_H) - \frac{1}{I_H - I_L} - \frac{1}{1 - I_H} & \frac{1}{I_H - I_L} \\ \frac{1}{I_H - I_L} & \beta'_L(I_L) - \frac{1}{I_H - I_L} - \frac{1}{I_L} \end{pmatrix} \begin{pmatrix} dI_H \\ dI_L \end{pmatrix} = \begin{pmatrix} 0 \\ -\frac{1}{I_L} \end{pmatrix} dk_L.$$

By using matrix algebra, it can be verified that:

$$\begin{aligned} \frac{dI_H}{dk_L} &= \frac{1}{I_L} \frac{1}{\Delta} > 0 \\ \frac{dI_L}{dk_L} &= \frac{1 - \beta'_H(I_H) + \frac{1}{I_H - I_L} + \frac{1}{1 - I_H}}{\Delta} > 0 \\ \frac{d(I_H - I_L)}{dk_L} &= \frac{1}{I_L} \frac{\beta'_H(I_H) - \frac{1}{1 - I_H}}{\Delta} < 0, \end{aligned}$$

where Δ is again the determinant of the above matrix. So, when technology replaces tasks earlier performed by low-skilled workers, these low-skilled workers will take over some of the previous medium-skilled tasks, and subsequently medium-skilled workers will take over some of the previous high-skilled tasks. However, in the end medium-skilled workers have a smaller amount of tasks to perform as shown by the third verification.

When technology replaces tasks there are also corresponding wage implications. The intuitive consequence when technology replaces medium-skilled tasks is that the wages of medium-skilled workers decline in comparison to the wages of high- and low-skilled workers (Acemoglu and Autor, 2011). So, the wage implications are that high relative to medium wages increase and medium relative to low wages decrease. The third implication is somewhat more complex. High relative to low wages can both increase or decrease, depending on whether the displaced medium-skilled workers are better substitutes for high- or for low-skilled workers⁴.

⁴ As before, we saw that I_H increases and I_L decreases, meaning that part of both high- and low-skilled tasks are now performed by medium-skilled workers. When the decrease in share of tasks is equal for both skill groups, the relative wage stays the same.

When technology replaces high-skilled tasks the logic consequence is that the wages of high-skilled workers decline in comparison to the wages of medium- and low-skilled workers. To find out what the implication is for medium relative to low-skill wages we have to see for which group the effect from the technology is stronger. When high-skilled workers take over tasks of medium-skilled workers this is a direct effect, and when medium-skilled workers then take over part of the low-skilled tasks this is an indirect effect. This indirect effect can never be stronger than the direct effect, because even when all displaced high-skilled workers now perform medium-skilled tasks, the number of tasks the medium-skilled workers take over from low-skilled workers can never be higher (Acemoglu and Autor, 2011). This implies here that medium- relative to low-skilled wages decline. The same logic can be applied when technology replaces low-skilled tasks. This implies that the wages of low-skilled workers decline in comparison to the wages of high- and medium-skilled workers. The effect of the technology is larger for the medium-skill group than for the high-skill group, which means that high- relative to medium-skilled wages increase.

Conclusion

To compare the impact of both types of technology on the task allocation, an overview of the consequences is shown in table 1.

Table 1 Consequences of technology

Biased towards:	Productivity increasing	Task-replacing
High-skilled	$I_L \downarrow$ and $I_H \downarrow$	$I_L \downarrow$ and $I_H \downarrow$
Medium-skilled	$I_L \downarrow$ and $I_H \uparrow$	$I_L \downarrow$ and $I_H \uparrow$
Low-skilled	$I_L \uparrow$ and $I_H \uparrow$	$I_L \uparrow$ and $I_H \uparrow$

The general outcome is that when technology was introduced, the share of tasks performed by the concerning skill group increased, whereas the share of the other two groups decreased. Interestingly, the qualitative results are the same per worker skill group. This means that it does matter to which skill group the technology is biased, but the direction of consequences for task allocation is equal for the both technology types. An explanation for this result could be that when productivity increases through technological development, this actually means that part of the tasks are also replaced. However, on basis of this results no firm conclusions can be drawn about the intensity of the consequences. The wage implications namely do differ as expected from the literature. Technology increasing productivity increases the workers competitive advantage and therefore its wage, whereas task-replacing technology decreases the value and corresponding wage of the worker. Therefore, we will continue to make a distinction between the two types of technology when studying the organization of work.

Chapter 5 - Organization of work

From the Ricardian labour model we derive two important factors that concern the organization of work. One factor that is determined by how the working system is organized is the rigidity of wages and the second factor is whether the different worker types are interchangeable in performing tasks. In the application of the model up to here we assumed that the wages are fully flexible and that the different worker types can also perform tasks earlier performed by an adjacent type. This second assumption was represented by flexible threshold tasks I_H and I_L .

Wage rigidity and unemployment

In the model it is assumed that after technological development, a new equilibrium is established where supply and demand of each worker type are in perfect equilibrium. For example, when medium-skilled tasks were replaced by technology, medium-skilled workers would take over low- or high-skilled tasks. This means that according to the model, there will be no redundancy of (certain types of) workers. However, one can question whether the condition that total worker supply is deployed is a realistic thought. In reality, there will be labour market frictions with the consequence that certain worker might become (temporarily) redundant.

Therefore we will translate the earlier wage effects into effects on unemployment. Recall that when wages are perfectly flexible, supply and demand are in equilibrium. Unemployment will arise when H, M or L would have to decrease to restore labour market equilibrium when wages are rigid.

Therefore, we have to recall equation (20) and (21):

$$\frac{w_H}{w_M} = \left(\frac{1-I_H}{I_H-I_L} \right) \left(\frac{H}{M} \right)^{-1} \quad (20)$$

$$\frac{w_M}{w_L} = \left(\frac{I_H-I_L}{I_L} \right) \left(\frac{M}{L} \right)^{-1} \quad (21)$$

Again, we make a distinction between technology increasing worker productivity and technology replacing workers in performing tasks. Note that the results hold both when wages are rigid in absolute terms and when they are rigid in relative terms only.

Technological change increasing productivity

First, the consequences of increased productivity will be discussed one for one. Earlier was shown that an increase in A_H resulted in a decrease in I_H and I_L , as high-skilled workers can perform a greater set of tasks then. This was associated with an increase in w_H and a decrease in w_M . These wage implications partly offset the decrease of I_H , because it improves the competitive position of the high-skilled workers. When we assume that wages are rigid, the allocation of tasks can still change but not via the wage mechanism anymore. This means that increased productivity of high-skilled workers will increase their set of tasks at the cost of medium-skilled workers, so I_H decreases. However, this effect

cannot impact the low-skilled workers and change I_L , because that would only be possible through the wage mechanism. The result is therefore that the set of tasks performed by medium-skilled workers decreases, which means that unemployment u_M among these workers arises. In equations (20) and (21) we can see that when wages are rigid and the threshold tasks change, supply of workers H, M and/or L should adjust, but this is not possible. Because there is less demand for medium-skilled workers, unemployment among them arises.

The same logic can be used to find the employment consequences of an increase in A_M , assuming rigid wages. An increase in A_M was followed by an increase in I_H and a decrease in I_L . This was associated with an increase in w_M and a decrease in w_H . The increase in w_M offsets the decrease in I_L partly, whereas the decrease in w_H partly offsets the increase in I_H . When we assume that wages are rigid, the allocation of tasks still changes, as medium-skilled workers have higher productivity and thus can perform more tasks. However, when wages are rigid they cannot partly undo the effect as the wage mechanism did before. For both low- and high-skilled workers the set of tasks to perform becomes smaller but the wages are not corresponding to this change. Therefore, the result is that unemployment among high-skilled workers u_H and among low-skilled workers u_L arises. Looking at equations (20) and (21) the outcome also is that H and L both have to decrease, which is only possible when unemployment arises among these workers.

An increase in A_L was followed by an increase in I_H and I_L , with corresponding wage implications that w_L increases and w_M decreases. The increase in w_L partly offsets the increase in I_L , and the decrease in w_M partly offsets the increase in I_L and strengthens the increase in I_H . This is due to the improved competitive position of medium-skilled workers. When wages are perfectly rigid, the increase in productivity of low-skilled workers increases the set of tasks they can perform, which means that I_L still increases. However, it cannot impact the high-skilled workers, because the earlier change in I_H was due to wage adjustments. So, the result is that the set of tasks performed by medium-skilled workers decreases, which creates unemployment u_M among these workers.

Technology replacing tasks

Secondly, we will discuss the consequences from task-replacing technology. Recall that technology can replace tasks earlier performed by high-skilled workers, by medium-skilled workers or by low-skilled worker. This technology is respectively named k_H , k_M and k_L . Important here is that demand and supply of labour should be in equilibrium, as in equations (23) and (24). Intuitive logic is that when technology replaces a certain group of workers, the demand for this worker type declines. Under the assumption of sticky wages, this means that not the full worker supply of the particular

type can be deployed and unemployment among the affected skill group arises. So when k_H increases, u_H will arise; when k_M increases, u_M will arise; and when k_L increases, u_L will arise. An overview of the obtained results is given in table 2, to easily compare the consequences between the two types of technologies.

Table 2 Consequences of technology when wages are perfectly rigid

Biased towards:	Productivity increasing	Task-replacing
High-skilled	$I_H \downarrow$; $u_M > 0$	$U_H > 0$
Medium-skilled	$I_L \downarrow$ and $I_H \uparrow$; $u_L > 0$ and $u_H > 0$	$u_M > 0$
Low-skilled	$I_L \uparrow$; $u_M > 0$	$U_L > 0$

It becomes clear that a consequence of wage rigidity is that unemployment arises. When comparing these results to the results in table 1, we can see that the difference between the two technology types becomes more visible in this situation where wage rigidity is considered. The difference between the two types of technology can be explained by the concept of competitive advantage. When technology is substitutable the consequences are entirely attributed to the skill group towards which the technology is biased. When technology is complementary unemployment arises among the adjacent worker groups. The logic behind this is when tasks of a certain skill group are replaced, this implies a competitive disadvantage for the concerning skill group, and unemployment arises. When technology increases productivity of a certain skill group, its competitive advantage improves and the adjacent skill group(s) suffer(s) from unemployment.

Downward nominal wage rigidity

Empirical studies show that often there is only downward nominal wage rigidity (Holden and Wulfsberg, 2008; Lebow, Saks and Wilson, 2003). This means that absolute wages cannot decline, but relative wages can and also an increase of both absolute and relative wages is possible. In this section will be shown what the implications are when technology is introduced in a situation of downward nominal wage rigidity.

Technological change increasing productivity

First the wage implications will be discussed when technology increases worker productivity. When this technology is biased towards high-skilled tasks, the productivity of high-skilled workers rises, which means that they can perform more tasks and threshold task I_H declines. Without wage rigidity, a decrease in w_M would make the medium-skilled worker more competitive, which would lead to an decrease of I_L . However, a downward change in wage is not possible in this scenario, so I_L cannot adjust. Due to the increased productivity of the high-skilled workers, their wage w_H will increase,

which partly offsets the earlier mentioned decline of I_H . The final result is that unemployment among medium-skilled workers arises, because their set of tasks (the range between I_H and I_L) has become smaller. This unemployment u_M is less than with total wage rigidity, because the increase in w_H increased the competitive advantage of medium- over high-skilled workers to a certain extent. In analogy to this, when medium-skilled workers become more productive their set of tasks also expands, increasing I_H and decreasing I_L . These changes are partly offset by the increasing wages of medium-skilled workers, because it reduces their competitive advantage. Without wage rigidity, w_L and w_H would also adjust to come to a new equilibrium, but these downward wage adjustments are not possible here. The result is that still unemployment among low- and high-skilled workers will arise, but less than in a situation of total wage rigidity. The same reasoning holds for technology biased towards low-skilled tasks. The increase in productivity increases threshold task I_L and wage w_L . The wage increases the competitive advantage of the low-skilled workers, which partly offsets the increase in I_L . However, w_M and w_H cannot adjust, which means that I_H does not change and the set of tasks that medium-skilled workers have to perform becomes smaller. The result is that unemployment among medium-skilled workers u_M arise. Again, this unemployment is less than in a situation of total wage rigidity.

Technology replacing tasks

Secondly, we discuss what this means when technology is task-replacing. The consequences are to a large extent similar to the consequences when wages are perfectly rigid. Starting with technology biased towards high-skilled tasks, wage rigidity means that unemployment among high-skilled workers arises. A decrease in high-skilled wages would be necessary to improve the competitive position, but this is not possible. However, whereas the real wage cannot decline, the relative wage can, namely when the medium-skilled wages increase. This will probably not happen at the short term, but at the longer term as all wages adjust to inflation, it is conceivable that medium-skilled wages increase at a higher rate than high-skilled wages. So, unemployment among high-skilled workers still arises, but over time this might decline as relative wages adjust to a new equilibrium. When technology is biased towards medium-skilled workers, the same reasoning holds. We still expect that employment u_M arises, but over time this might decrease when low- and high-skilled wages increase faster over time than medium-skilled wages do. How much time this may take will differ per country and per sector depending on the wage volatility (Hong, Seok and You, 2015). When technology is biased towards low-skilled tasks, unemployment among these workers arises. Again, we expect that this will decrease over time when medium-skilled wages increase relative to low-skilled wages.

Conclusion

An overview of the consequences of technology when wages are downward rigid is shown in table 3.

Table 3 Consequences of technology when wages are imperfectly rigid

Biased towards:	Productivity increasing	Task-replacing
High-skilled	$I_H \downarrow; u_M > 0$	$U_H > 0$ and when $w_M \uparrow, u_H \downarrow$
Medium-skilled	$I_L \downarrow$ and $I_H \uparrow; u_L > 0$ and $u_H > 0$	$u_M > 0$ and when w_L and $w_H \uparrow, u_M \downarrow$
Low-skilled	$I_L \uparrow; u_M > 0$	$U_L > 0$ and when $w_M \uparrow, u_L \downarrow$

The quantitative results do not differ from the results when wages are perfectly rigid. Quantitatively, the consequences will be less strong. Because wages can adjust upwards, the relative wages can also change, which reduces the level of unemployment that arises.

Interchangeability of workers

The final theme we want to give attention is what the consequences of increasing technology would be when workers are not interchangeable in performing tasks. At first, we assumed that workers of low and medium skill, and medium and high skill could also perform the tasks of one another. This was shown above by the flexible threshold tasks I_H and I_L . However, it is not unthinkable that there are tasks that only a specific workers type can complete. High-skilled tasks require a certain intellectual ability or analytical thinking that low- or medium-skilled workers may not possess and therefore also cannot be acquired by training. Examples of such jobs are the job of a scientific researcher or a job in a higher management position in which one needs to assess complex situations and take responsible, strategic decisions. On the other hand, low-skill jobs require certain practical skills and dexterity that higher-skilled workers may not have. Examples are the jobs of a carpenter and a nurse.

This implies that there will be no substitution of skills across tasks. To find out what happens when this is the case, we assume rigid threshold tasks I_H and I_L . Originally I_H and I_L are the equilibrium threshold tasks that divide the workers into three skill groups, but now there is no change in allocation of tasks over the three groups. This implies that an increase in technology biased towards a certain skill level cannot influence the demand and with that the wages of the other two skill levels. It is counterintuitive to set the equilibrium variables fixed, but it would not make sense to adjust the model. This is because there is no way that the impact for the affected skill group is partly passed on to the other two skill groups. When for example the model was changed in such a way that wages were the new equilibrium variables, interaction between the different skill groups is still not possible.

As before, a distinction is made between the productivity increasing technology and the task-replacing technology.

Technological change increasing productivity

When technology is biased towards high-skilled tasks and productivity A_H increases, the wages of these high-skilled workers also increase. However, the share of tasks these workers have to perform cannot change due to the fixed thresholds when workers are not interchangeable. The result is that less workers are needed to perform these tasks above I_H , so unemployment u_H arises. This can be verified by looking at equation (23):

$$\frac{1-I_H}{I_H-I_L} \frac{a_M(I_H)}{a_H(I_H)} = \frac{A_H H}{A_M M} \quad (23)$$

Holding I_H and I_L constant when A_H increases, this implies that H must decrease. A decrease in H actually means that demand is lower than supply, which implies that unemployment among high-skilled workers arises.

The same reasoning can be used when A_M increases. The increased productivity makes some of the medium-skilled workers redundant, so unemployment u_M arises. Using equation (24) we can also see that, when the threshold tasks cannot change, an increase in A_M has to go along with a decrease in M :

$$\frac{I_H-I_L}{I_L} \frac{a_L(I_H)}{a_M(I_H)} = \frac{A_M M}{A_L L} \quad (24)$$

Using equation (24) the consequences can also be derived for an increase in A_L . An increase in A_L has to go along with an decrease in L , when I_H and I_L remain constant. This is logical because the increased productivity of low-skilled workers implies that less workers are necessary to perform the tasks, meaning that unemployment among low-skilled workers u_L arises.

Technology replacing tasks

To derive the consequences for task-replacing technology, k_H , k_M and k_L can be introduced in equations (23) and (24). When task-replacing technology is biased toward high-skilled tasks, equation (23) becomes $\frac{1-I_H-k_H}{I_H-I_L} \frac{a_M(I_H)}{a_H(I_H)} = \frac{A_H H}{A_M M}$. The initial results will be the same as when technology increases productivity, as less high-skilled workers are necessary to perform the set of tasks. This means that the decrease in demand which causes unemployment is equal for both types of technology. However, task-replacing technology also leads to a decrease in high-skilled wages and from classic economic theory we know that this will negatively influence the supply of high-skilled labour H . As we defined unemployment as supply minus demand, a decrease in supply when demand stays at the same level, then implies a decrease in unemployment.

When task-replacing technology is biased towards medium-skilled tasks, equation (24) becomes

$\frac{I_H - I_L - k_M}{I_L} \frac{a_L(I_H)}{a_M(I_H)} = \frac{A_M M}{A_L L}$. The same argumentation as before applies. Less medium-skilled workers are necessary to perform the set of tasks between I_L and I_H and they cannot take over tasks of low- and/or high-skilled workers. Therefore, unemployment among medium-skilled workers u_M arises. However, the decrease in w_M that also follows on the introduction of k_M may reduce supply M , so that unemployment also reduces.

When technology replaces low-skilled tasks, equation (24) becomes $\frac{I_H - I_L}{I_L - k_L} \frac{a_L(I_H)}{a_M(I_H)} = \frac{A_M M}{A_L L}$. Less low-skilled workers are needed to perform the set of tasks under I_L and they cannot take over tasks of low- and/or high-skilled workers. Unemployment among low-skilled workers u_L will therefore arise. However, this unemployment will reduce somewhat, because the decrease in w_L that also follows on the introduction of k_L may reduce supply L , and therefore also u_L .

Conclusion

An overview of the consequences of technology when workers are not interchangeable is shown in table 4.

Table 4 Consequences of technology when workers are not interchangeable

Biased towards:	Productivity increasing	Task-replacing ⁵
High-skilled	$U_H > 0$	$U_H > 0$
Medium-skilled	$u_M > 0$	$u_M > 0$
Low-skilled	$U_L > 0$	$U_L > 0$

When the allocation of tasks cannot change the consequences of robotization are only for the affected skill group, resulting in unemployment for this group. When the robots are replacing workers, this can also be compensated by a decline in wages of this skill group.

⁵ The unemployment that arises here is lower than the unemployment that would arise as a consequences of productivity increasing technology, due to the declining wages.

Chapter 6 – Conclusion, policy recommendations and discussion

In this chapter we will conclude from the literature study and the theoretical analysis what the consequences of robotization are for the labour market. Then we will give policy recommendations for both firms and governments on basis of these results. Finally, the discussion of the results and the research as a whole is also part of this chapter, including its limitations and some suggestions for further research.

Concluding remarks

One of the most obvious findings about technological developments in the past was that it mostly affected the industrial sector. This implies that especially the tasks performed by low-skilled workers were (partly) replaced by machines and robots. These industrial robots therefore significantly influenced the occupational structure of the economy. In other words, robotization has consequences for the allocation of tasks across skills. In the literature it is shown how this technology biased towards low-skilled tasks can lead to unemployment when low-skilled workers are displaced by technology (Edler and Ribakova, 1994; Ebel, 1987). Further, it became clear that the impact of robotization will differ per sector. In the analysis this was pointed out by distinguishing in what different ways technology might have impact. For some sectors technology might be complementary to workers whereas for other sectors it substitutes them in performing tasks. Additionally, sectoral differences may depend upon the skill group towards which the technology is biased. Another development, which is more in its infancy, will be that also in sectors where human workers had a comparative advantage over robots, e.g. in the service and health care sector, the role of robots will become more prevalent. A quantitative indication was also given in the literature, that technological developments will continue at a higher rate than in the past. The consequences will therefore be larger, although on basis of this analysis we cannot say whether this increase is at an increasing or a decreasing rate. So, the consequences will be more severe and more spread over all skill groups. The overall role of robotization will become larger which may lead to a surplus of workers in the longer term.

Whereas technology first mainly affected low-skilled workers in industrial sector, nowadays and in the future technology and robotization is expected to affect all three skill levels in a wide range of sectors. Robots will become more ingenious and sophisticated, so that they can also perform the more difficult tasks. From the literature we conclude that the era of low-skill biased technological development is already over to a large extent. So, for the future especially the consequences for medium- and high-skill biased technology are relevant.

In the microeconomic analysis we saw that introducing or increasing robotization greatly influences task allocation, wages and unemployment. Some general conclusions can be drawn, comparing the consequences that resulted from the different scenarios. The first and most important conclusion is the difference in consequences between the two types of technology. When workers are interchangeable and wages are perfectly flexible this becomes visible in the contrast in wage implications. Task-replacing technology reduces the wages of the affected skill group, whereas productivity increasing technology increases them. Related to this difference in wage implications is the difference in consequences when there is wage rigidity. When technology is task-replacing, the negative consequences of unemployment are for the affected skill groups, whereas with productivity increasing technology the adjacent skill group(s) suffer(s). The second conclusion from this research is that both when (imperfect) wage rigidity exists and when workers are not interchangeable, unemployment arises. The level of unemployment and which skill group it concerns differs over the different scenarios, but it arises in all cases which is of importance for government policy. The third conclusion concerns the difference between downward wage rigidity and perfect wage rigidity. Although the consequences differ in intensity, in essence the consequences are the same in both cases. This means the consequences of downward wage rigidity are qualitatively similar, but quantitatively they are less strong than with perfect wage rigidity.

Policy recommendations: improving the labour market

In this subsection we will provide policy recommendations for both firms and the government to improve the adaption of the labour market to technological developments. First will be defined which of the consequences of increasing technology are not desirable and deserve further thought and intervention. On basis of these outcomes some more specific literature-based recommendations will be given for firm and government policy to improve the connection between the development of robotics and the labour market.

Government

The government can play an important role in encouraging firms and organizations to invest in capital. They also have an incentive and interest to stimulate technology development and innovation, as it is beneficial for the economic climate and for the international competitive position (Porter, 1990). Porter also emphasizes that, when a country suffers from local disadvantages, innovating within the country itself is better than outsourcing, because it makes the country more independent from the foreign.

However, the results showed that technology also has consequences that are not desirable for the government. When workers are interchangeable and wage perfectly flexible, no real government intervention is needed. Dependent on the preference of the government, in a case of technology replacing tasks, she may choose to protect the affected skill group from a fall in wages that is too big according to them. When intervening in such a perfectly competitive market, the government should be aware of the consequences. For example, when the government wants to protect a skill group from falling wages, a situation with downward wage rigidity will arise with its corresponding consequences.

In most countries the government does intervene via legislation or trade unions claim wage protection, which might lead to wage rigidity. The main consequence of wage rigidity is that unemployment arises. The government should consider this consequence when making laws to protect workers from declining wages. Moreover, the government should be aware that not always the worker group that is affected by the technological development suffers. We saw that when technology increases productivity it are the adjacent skill groups that have to deal with unemployment. Distinguishing between the two technology types and looking towards which skill group(s) the technology is biased is therefore essential for the government to take into account. In reality, wage rigidity will not always be perfect as in the analysis. However, we saw that the results from imperfect, downward wage rigidity were qualitatively similar. Therefore, we expect that these results are also applicable to countries and regions where partial wage rigidity exists.

The last part of the analysis showed that when workers are not interchangeable the total effects of technology are borne by the affected skill groups. When interchangeability of workers is stimulated, these effects can be distributed over all worker groups, which makes them less intense. The government can play an active role in stimulating this interchangeability, together with firms. When technology is introduced there is a transition period of adjustment to the new technology. In this transition period there are several difficulties that need to be overcome. One of these difficulties is that employees need to learn how robots should be used, and how they can be integrated in the working process in an efficient and effective way. Edler and Ribakova (1994) show that to smoothen this transition within firms training is helpful and they recommend that the government should pay for this training. However, respondents in the study of Hollon and Rogol (1985) assign also responsibility to firms for this retraining, otherwise this would advantage the firms that use robots too much over the other firms. Based on this we recommend that government subsidise retraining to introduce robots in the firm. Note that this recommendation only applies for introduction of robots.

When firms are already working with robots they will more easily choose to invest in more robotization and also more easily adjust to this.

A concluding remark concerning the government is that it is important to balance between stimulation technology and innovation, but not doing this too fast. Firms should have some time to adjust to these new developments and come along with it.

Firms

How robotization is beneficial for firms is quite intuitive, as it increases efficiency and has cost benefits. As mentioned in the introduction, robots are much less demanding than employees concerning among others wages and the working environment. Policymakers in firms should occupy themselves how firm policy can facilitate the implementation of robotic technology in the best way (Hollon and Rogol, 1985). They should be aware that there might arise unexpected problems and situations in the organization.

Most of the consequences of technology are not problematic for firms. In the competitive market and under wage rigidity, the main consequence is a different allocation of tasks. When the transition to a new task allocation goes fluently as assumed in the model, this is not a problem for firms. However, workers need to be retrained and prepared for their new task. We already addressed the responsibility of the government in this, but the firm has the specific information and knowledge to realize this retraining of employees. This retraining should concern the firm as a whole. In the analysis was seen that robotization often is biased towards certain tasks, but when implementing it not only the directly affected employees should be retrained. Robotization should be integrated in the whole working process (Knod et al., 1984). The analysis showed that the effects work through and also affect other skill groups in changes in wage and tasks allocation.

Related to this is that the firm should be aware that it highly depends on the loyalty of its employees. For example, retraining of employees might partly be done by employees that performed a certain task before. Also, the employees that have to switch tasks should be willing to perform this new task and follow the retraining. The cooperation of employees is therefore vital to successful implementation of robotization (Knod et al, 1984). To improve their goodwill it is important to create a positive working environment. In this context Benders (1995) stresses that managers should be aware that robots not always improve the working conditions for human workers. Firm managers can show in their policy that they are aware of this.

A second consequence of technology is the change in wages. When wages decline this is only beneficial for firms, but an increase in wages can be problematic for firms. The firms should be aware that when technology increases wages this also increases the firm costs and can reduce profits. So, not only the costs of introduced capital, but also the costs of possibly increasing wages should be taken into account by firms.

Thirdly, we want to mention what it means for firms when workers are not interchangeable. Because the thresholds cannot adjust in that situation, the price the firms pay for the services of a task is not perfectly competitive. This means that the firms have an additional reason to help improving the interchangeability of workers, namely the wages will then become more competitive, which is beneficial for firms.

It might not always be possible to retrain workers, and also under wage rigidity the arise of unemployment is unavoidable sometimes. Therefore, a final recommendation is about dealing with workers that are displaced. Firm managers should handle this with care as job security is important for the wellbeing of workers. One way to successfully handle a reduction in workers is natural attrition (Argote and Goodman, 1985). If natural attrition costs too much time, it is better to be open with the employees and be clear about what the consequences are. That might still be painful but at least it removes the uncertainty. Preferably, the firm should facilitate the workers in finding a new job, eg. through writing good references (Argote and Goodman, 1985).

Discussion

In this research the model of Acemoglu and Autor (2011) is discussed and applied to the introduction of two types of technology. As far as we know, such an analysis was not performed before. It is relevant to know what the consequences of robotization are, as this development is going further at an increasing rate. Both firms and governments should therefore be aware of the impact robotization has on the labour market and society as a whole. We have begun to explore also what the consequences are in different scenarios concerning the organization of work. In many countries, wage rigidity will exist to a certain extent. Furthermore, there will be many tasks in society that other skill groups are not able to perform with the same value as the original skill group workers can.

However, there are also limitations to this research. One important issue to realize is that a model is always an abstraction of reality, which means that many assumptions had to be made. The consequences of this is that results are not one to one applicable to all situations, but per situation the consequences should be derived. Mainly the extreme scenarios are covered. To address this limitation the research should be complemented with an empirical study. Another limitation is that

only qualitative results are obtained, and not quantitative. A relevant suggestion for further research is to analyse what difference in impact is between a capital-intensive sector and a labour-intensive sector. The only sectoral difference covered in this research was the difference between complementary and substitutable technology, but there might be many more ways in which a sector differs. For example, it would be useful how exactly robotization and its impact differs between the service sector and the industrial sector. Further, in the model is not accounted for the short term benefits of the production of robots and their implementation in the working process, creating new tasks in the short term. The model is based on quick adjustments to the introduced technology and therefore the results are more long term. A suggestion for further research would therefore also be to study in more detail what problems will arise in the transition period.

In this research we explored the consequences of robotics for the labour market. We saw that the consequences of technology will become visible in changes in wage, allocation of tasks and unemployment. The adjustments in the real world may not always go as fluent as it is assumed in the model, but appropriate government and firm policy can help to smoothen this process and lower the undesirable consequences.

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