Employing disabled workers in production: simulating the impact on performance and service level

Paweł Litwin[a]*, Dario Antonelli[b] and Dorota Stadnicka[a]

[a]*Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Rzeszow, Poland;* [b]*Department of Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy*

*corresponding author: Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Al. Powstańców Warszawy 12 35-959 Rzeszów, Poland
e-mail: plitwin@prz.edu.pl

Employing disabled workers in production: simulating the impact on performance and service level

Abstract: Disabled people can be successfully employed in most production processes, provided that one knows how to exploit their abilities and take into account their limitations in order to give them an appropriate job. However, because the level and type of production must be constantly adapted to the needs of the market, the involvement of disabled people in the production process may also change. Additionally, people with disabilities have limitations as well as additional rights that must be considered. As a result, the organization and planning of their work, side by side with other employees, becomes more complex. Computer simulations can be a support for organizing and planning the involvement of employees with disabilities in production processes. The aim of the article is to show how simulations can facilitate the organization of work of employees with disabilities, with the changing demand for manufactured products. The paper identifies the factors that should be considered, and then presents how the employment of disabled people can affect the operation of the production line and the commercial image of the company. The study uses a combination of System Dynamics and Discrete Event Simulations. The relevant data for the simulation were derived from a real production company.

Keywords: manufacturing systems, modelling, system dynamics, discrete event simulation, disabled employees.

1. Introduction

People with disabilities often face significant barriers to accessing employment and are therefore at greater risk of poverty or social exclusion. In 2010, the European Commission adopted the United Nations Convention on the Rights of Persons with Disabilities and established the European disability strategy for 2010-2020 (A/RES/61/106). One of the goals of the strategy was to enable more people with disabilities to enter the labour market through, among others: analysing the level of employment of people with disabilities, assisting their integration in the labour market with the use of the European Social Fund and increasing the availability of jobs.

In September 2015, the General Assembly adopted the 2030 Agenda for Sustainable Development and 17 Sustainable Development Goals (SDGs) (The 2030 Agenda). The world in 2030 should be fully inclusive for people with disabilities. Goal 8 states: 'Decent work and growth' is about promoting sustainable, inclusive and sustainable economic growth, full and productive employment, and decent work for all.

In March 2021, the European Commission published the European Union Strategy for Equality of the Rights of Persons with Disabilities for 2021-2030. The strategy aims to address the challenges faced by people with disabilities. It aims to ensure progress in the rights of people with disabilities. It includes a number of initiatives to support the integration of people with disabilities into the labor market, including financial support for employers. Typically, financial assistance for employers is allocated to creating new jobs for employees with disabilities, adaptation of the position and workplace along with the purchase of specialized equipment, partial coverage of the employee's remuneration costs due to reduced work efficiency. Financial support may not be sufficient to motivate employers to hire people with disabilities. From the employer's point of view, employing a disabled employee is associated with the need to prepare special equipment, more complex organization of work, reduced work efficiency, and additional bureaucracy and inconvenience.

Employing disabled workers on the manufacturing line (ML) requires special attention in the planning and organization of their work, because their efficiency and work performance differ from workers without disabilities. In many countries, there is the requirement to employ a percentage of disabled employees. There are no specific constraints regarding the type of work. Therefore, the custom is to assign them low-skilled jobs away from the production line (Mark, 2019). To facilitate the participation of workers with disabilities in production operations, a tool and a method of analysis that allows to simulate the impact of their insertion on production variables can be useful. This is exactly the proposal of this paper.

Commercial tools such as Tecnomatix Plant Simulation Software (Kłos and Trebuna, 2015), FlexSim (Antonelli and Stadnicka, 2018), Vensim (Stadnicka and Litwin, 2019), Enterprise Dynamics (Gola, 2019) have been used to conduct simulated experiments of various production scenarios. Simulations make it possible to assess the effects of a specific work organization and the involvement of disabled employees along various stages of production before assigning them to a specific task.

To the authors' best knowledge, the impact of the number of disabled employees on production factors, and in particular on the service level (SL), has not been analyzed in literature so far, because of apparent difficulties to collect sensitive data. At least in the form of a simulation, the gap has been filled in this paper.

Since the problems concern industrial planning at both strategic and operational levels, the article applies two different simulation methods to deal with such different levels of abstraction: SD (System Dynamics) and DES (Discrete Event Simulation). The researched effects of employment of disabled employees include employee productivity, work subsidies for disabled employees, SL, changes in product costs and demand. The authors present the procedure for creating a simulation model and conducting simulations in such a way as to enable its replication in other cases as well as the application of different national regulations.

In the next chapter, the influence of disabled workers employment on Sustainable Development Goals achievement is discussed. Section 3 analyses the inclusion of disabled workers in manufacturing processes and their performance. The main goal of the section 2 and section 3 is not only to justify the work undertaken, but also to show a broader context, in particular referring to specific sustainable development goals. Section 4 describes the research procedure and methods. Section 5 identifies the problem and presents research questions. Section 6 shows the results of the DES simulations and section 7 shows the results of the SD simulations. Finally, section 8 presents the discussion and conclusions.

2. Influence of disabled workers employment on Sustainable Development Goals achievement

A disabled person is a person who has a physical or mental impairment that significantly affects his or her ability to perform normal daily activities (Disabled World, 2009). There are estimated 87 million people with disabilities in the EU (European Parliament, 2021). Ensuring employment for people with disabilities is a great challenge for today's society. In this section, we discuss how the employment of workers with disabilities can contribute to the Sustainable Development Goals.

Sustainable Development Goals related to people with disabilities and their employment are identified in Figure 1. It is worth emphasizing that also the strategy on the rights of persons with disabilities (2021-2030) is related to the SDGs, therefore the discussion will be conducted in the context of EU Disability Strategy for 2021-2030.

Figure 1. Sustainable Development Goals and Strategy on the Rights of Persons with

Disabilities (2021-2030). Based on (https://sdgs.un.org/goals)

28.4% of people with disabilities in the EU are at risk of poverty or social exclusion, compared to 17.8% of the general population (European Parliament, 2021). Employing people with disabilities can improve their economic conditions, so it supports *SDG1 – No poverty*, *SDG2 – Zero hunger* and *SDG3 – Good health and well-being*. Providing inclusive education is crucial to helping children, including children with disabilities, cope with current and future crises (*SDG4 – Quality education*). The European Accessibility Act (2019) gives people with disabilities access to more products and services, such as tablets and e-books, which can facilitate the education process. The support of the education process of disabled people can in turn facilitate their inclusion into the labour market. The employment rate for people with disabilities (aged 20-64) is 50.8%, compared to 75% for people without disabilities (European Parliament, 2021). Lack of work affects people with disabilities more than other categories. Employing people with disabilities can support *SDG8 – Decent work and economic growth*. Innovative solutions can facilitate the inclusion of workers with disabilities in industry (*SDG9 – Industry, innovation and infrastructure*).

Since the publication of 2030 Agenda, there have been significant progresses, showing a better inclusion of people with disabilities in social and professional life (A More Accessible and Sustainable World, 2020). There are new opportunities, but also new obligations for employers have been introduced. This work can further support the inclusion of people with disabilities in production processes by facilitating the planning of work with the participation of people with disabilities.

Commentato [PL1]: Citation needed.

Commentato [DS2R1]: Done.

Figure 2 presents 20 principles of the European Pillar of Social Rights (The 20 principles of the European Pillar of Social Rights, May 05, 2021).

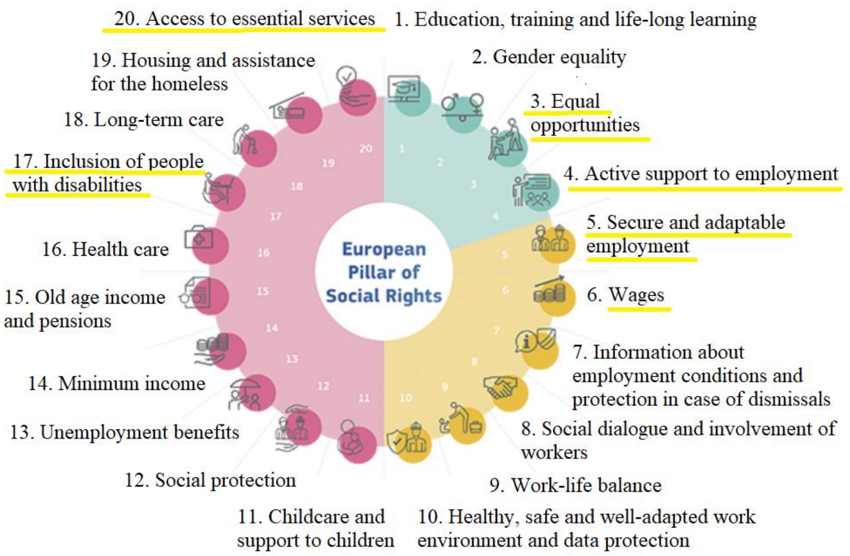

Figure 2. 20 principles of the European Pillar of Social Rights with highlighted the ones concerning inclusion. Based on (The 20 principles of the European Pillar of Social Rights, May 05, 2021).

Six principles are closely related to employment of people with disabilities, namely:

- Principle 3. Equal opportunities – regardless of disability, everyone has the right to equal treatment and equal employment opportunities.
- Principle 4. Active support to employment – everyone has the right to tailor-made assistance to improve employment prospects. Disabled people in particular need help finding a job or training.
- Principle 5. Secure and adaptable employment – employees have the right to equal treatment in terms of working conditions. Innovative forms of work that provide appropriate working conditions for people with disabilities should be

Commentato [PL3]: Can we delete picture 2 andonly comment principles related to PWDS?

Commentato [DS4R3]: Please, do not do it.

supported.

- Principle 6. Wages – wages of employees with disabilities should be non-discriminatory even if their efficiency can be lower. The wages should be set transparently according to national rules. The additional incentives that employers of PWDS receive may compensate them to some extent the reduced efficiency of workers with disabilities.
- Principle 17. Inclusion of people with disabilities – people with disabilities have the right to income support to enable them to participate in the labour market and to a working environment adapted to their needs. Additional incentives that employers receive may contribute to covering the costs of appropriate preparation of the workplace of a disabled person.
- Principle 20. Access to essential services – Everyone has the right to access good quality basic services, including transport and digital connectivity, which can make it easier for people with disabilities to commute to work or to work remotely.

Commentato [DA5]: I don't know the answer to R28

Commentato [DS6R5]: Is there a way to tie these Social Rights back to incentivization or other tax benefits for employing PWDS? This would help build out justification for your simulations in a more financial sense.

Commentato [PL7R5]: I think that principles 6 and 17 show a need to financial incentives

Commentato [DS8R5]: I have added info.

3. Disabled workers in manufacturing processes and their performance analysis

Employment leads to social inclusion and provides the financial means to ensure a dignified life (Lecerf, 2020). Therefore, all forms of support for enterprises, both financial and non-financial, should be engaged in order to increase the level of employment of people with disabilities. Financial forms include, among others, government subsidies for creating and maintaining jobs for people with disabilities. In this work, the impact of financial support for companies employing disabled workers is examined. Despite its various forms, this support can be expressed through the level of subsidy to remuneration (IL - incentive level). Nonfinancial forms may include, for example, tools such as simulations described in this work, which show how to engage employees with disabilities to work on a specific production line, with specific assumptions and constraints. One of the fears of enterprises is the concern that the work of a disabled person will have a negative impact on service level (SL). However, there are many factors that may influence the decision to employ a disabled person and may influence and support such a decision.

EU countries support the employment of people with disabilities in different ways (Rabiega, 2014) (Wagner et al., 2001). For example, in Germany, France, and Italy, companies face penalties if, for every 15 or 20 (France) workers, the company does not employ a disabled person. In Poland, however, a company that employs a disabled person receives financial support. At the same time, there is a shortage of labour on the market, especially for low-wage jobs (Deloitte Insights, 2021). But income is just one of the drivers for being employed. According to (Heron, 2003) also the gratification coming from social contacts and the increased self-esteem are important motivations for workers with disability. It is worth highlighting that people with disabilities account for one sixth of the entire EU working-age population (Lecerf, 2020). Moreover, according to (Stefanos, 2013) in the EU, only 34% of people with disabilities work full-time. In addition, the level of part-time employment of people with greater disabilities is higher. It should be noted that the unemployment rate among people without disabilities is 10%, while among people with moderate disabilities it is already 15%, and among people with severe disabilities it is 28%. The percentage of people with severe disability is the highest probably because such employees requires, compared to other disability levels, supervision or support in social situations. Since improving the quality of life is one of the goals of the European Union, it is extremely important to take initiatives to improve the quality of life of people with disabilities,

Commentato [DA9]: Dorota, please answer R211

Commentato [DS10R9]: Done.

who constitute such a large percentage of our society. This also applies to the inclusion of disabled employees in manufacturing processes (Stefanos, 2013).

The problems of effective involvement of disabled employees in production processes have already been discussed in previous publications. Disability can have a significant impact on the productivity of work, both for the individual and the organization. Some of the possible effects are:

- Reduced output: Disability may limit the amount or quality of work that a person can produce in a given time frame (Narayanan, 2020).
- Increased absenteeism: Disability may increase the frequency or duration of absences from work due to health issues, medical appointments, or personal reasons. In addition, in some cases, employees with disabilities cannot commit to full-time employment.
- Decreased engagement: Disability may affect the level of motivation, satisfaction, or commitment that a person has towards their work or their employer (Malo, 2012).

Research paper (Miralles et al., 2007) discusses the issue of engaging workers with disabilities to work on the assembly line and focusses on the organization of work, while the article (Araújo et al., 2012) discusses the problem of assigning work to heterogeneous workers (employees with disabilities can be among them) and balancing their workload. In the paper (Ritt et al. 2016) a proposal is presented to solve the Assembly Line Worker Assignment and Balancing Problem (ALWABP). Assembly lines can be used successfully in sheltered workshops to better integrate people with disabilities into the labour market. Computational experiments (Ritt et al. 2016) shown that stochastic modelling can help improve line performance, and the proposed

Commentato [DA11]: Really don't know how to cope with R212

Commentato [DS12R11]: Done.

heuristics yield good results for practical use. The article (Ming et al. 2022) continued ALWABP studies with uncertain availability of workers with disabilities, limited number of temporary workers, and displacement of workers to minimize the risk of cycle time and number of temporary workers employed. The work (Litwin et al., 2022) analyses how the employment of disabled people can influence the operation of a manufacturing line and how engaging persons with disabilities (PWDS) can shape customer demand. The assignment of tasks can be can be formulated as a mathematical program and supported by using genetic algorithms as described in the article (Liu et al., 2021). These issues are important because employees with disabilities may have variable availability, may have breaks at different times than other employees, or may have unscheduled breaks. Therefore, the aim of the analyses and simulations carried out is to minimize the cycle time under the conditions of variable availability of disabled employees with limited availability of temporary employees.

Table 1 summarizes works that discuss issues related to the inclusion of people with disabilities in work on the production line.

Commentato [DA13]: This is a serious problem. One reviewer asked for this table, another says that it is thrown in. What to do?

Commentato [DS14R13]: This table seems like a bit of a thrown in aspect. If it relates to what you are doing, shouldn't there be a small paragraph to cover the points your study either builds on or changes? Then in your discussion, could relate back to where you have taken the science that these didn't

Commentato [DS15R13]: I have added a sentence to answer R215.

Table 1. Summary of problems discussed in relation to inclusion of people with disabilities in work on the production line

Paper	**Problem discussed**
Miralles et al., 2007	Organization of work of employees with disabilities in assembly line.
Araújo et al., 2012	Assigning work to heterogeneous workers and balancing their workload.
Ritt et al. 2016	Application of the stochastic modelling to improve line performance.

Ming et al. 2022	Assembly line worker assignment and balancing problem taking into account uncertain availability of workers with disabilities, limited number of temporary workers, etc.
Litwin et al., 2022	Influence of disable people engagement on the operation of a manufacturing line and customer demand.
Liu et al., 2021	Application of the genetic algorithms in tasks assigning.

The topics discussed in the literature mainly concern the organization of work of disabled employees, task allocation, workload balancing, efficiency improvement, uncertain availability of employees and the impact on timely deliveries. From the performed literature review and according to the best knowledge of the authors there are no works discussing variable assignment of disabled employees to work on an assembly line, taking into account the changing demand, in order to minimize labour costs and the presence of incentives related to employing of people with disabilities.

Employees may have different degrees of disability (slight, moderate, or severe), they can also have different types of disability, namely physical, intellectual, and mental disabilities. The different kind and level of disability should be considered case by case. For the sake of discussion, the authors include in the present study only two types of disability, namely moderate physical disability (MPD) and moderate mental disability (MMD). According to WHO MMD is characterized by significant disturbance in an individual's cognition, emotional regulation, or behaviour, while MPD is related to a limitation on a person's physical functioning (WHO, 2021). However, an employee is still able to perform the work.

Commentato [DA16]: Commented [R214]: How are these defined in this case? what are the limitations associated with these? Given that you are making the case to employ these persons, it is important to at least briefly outline what the definition is for this case study. It adds to the applicability of what you are doing for others, even though you later state that case by case trials would be required. Can some high level lessons be taken away from this work?

Commentato [DS17R16]: The explanation was added.

Computer simulations may be a good way to assess the effects of including disabled workers in the production system. Simulations have been used many times in various works to assess the effects of changes introduced on production lines and are becoming increasingly popular in digital factories (Mourtzis, 2020). Simulation of the operation of production systems is a valuable tool for the design and evaluation of a production system, mainly due to the low cost, but also the short time needed to perform the analysis. Additionally, the risks associated with experimenting on the actual production line are eliminated. In addition, many experiments can be carried out in a short time and a lot of data will be obtained, which can then be the basis for making decisions. Simulations allow for a detailed analysis of the impact of each component of the production line (machine, employee) on its functioning and achieved results. In the work (Bratcu & Dolgui, 2009) simulations are applied to self-balancing production lines where a human operator can move from one station to the next to continue working on the product.

To analyse the behaviour of the system in the situation of including disabled employees on the production line, SD and DES simulations were used at work. Both of these methods are widely used in the analysis of production systems. SD allows to model the structure and dynamics of complex systems. It allows you to build continuous simulation models. Edghill and Towill (1989) applied SD simulations to model orders, materials, and information flows in manufacturing systems. Stadnicka and Litwin (2017; 2019) used SD to enrich the method with value stream mapping for manufacturing system modelling.

The basis of DES is the numerical solution of the problems of queuing network theory. In the work (Kellner et al., 1999), various scenarios were analysed using simulations, allowing unexpected discrepancies to be detected. Of course, built models do not fully reflect reality due to the need to introduce simplifications in the modelling process, but they are sufficient to simulate the operation of the production line.

The SD and DES models reflect the behaviour of the system in various circumstances at a sufficient level to make appropriate decisions based on the simulation results (Sweetser, 1999). In addition, thanks to the integration of both systems, the strengths of each of them can be used. The work (Helal, 2007) presents a methodology of modelling and simulation of an integrated manufacturing enterprise using both methods, SD and DES. The paper (Venkateswaran and Son, 2005) shows how SD can be used for long-term production planning and DES for short-term production planning. In turn, in the work (Rabelo et al., 2005) SD is applied to analyse the financial activities in a manufacturing company, while DES is used to model a manufacturing line. Table 2 summarises application of simulations in different context.

Table 2. Application of simulations

Work	**Problem discussed**
Mourtzis, 2020	Assessment of the effects of changes introduced on production lines.
Bratcu & Dolgui, 2009	Self-balancing of the production lines.
Edghill and Towill, 1989	Modelling orders, materials, and information flows in manufacturing systems.
Stadnicka and Litwin, 2017; 2019	Application of the simulations to enrich value stream mapping for manufacturing system modelling.
Kellner et al., 1999	Application of the simulations to detect unexpected discrepancies.
Sweetser, 1999	The use of SD and DES models to reflect the behaviour of the system in various circumstances for the purpose of the decision-making process.

Helal, 2007	Modelling and simulation of an integrated manufacturing enterprise with the use of DES and SD.
Venkateswaran and Son, 2005	Application of SD in long-term production planning and DES in short-term production planning.
Rabelo et al., 2005	Application of SD analyse the financial activities in a manufacturing company.

This article attempts to integrate DES and SD in order to assess the throughput of the production line (DES) and to adjust the number of disabled employees to market conditions (SD).

4. Research procedure and methods

4.1. General Overview of the research methodology

The first action taken in this research was to identify the research problem. For this purpose, the functioning of a production line operating in a company employing disabled workers was analysed. Data related to time needed to perform manufacturing operations by employees was collected with the use of time study and analysed. Mean, minimum and maximum values were determined. Based on the results of the analysis, research questions were identified and further steps were decided. The entire research procedure is shown in Figure 3.

The second stage of the research was to develop a model of the production line and perform DES simulations. The simulations were performed at the operational level. In the next step, SD simulations were performed on a strategic and tactical level. The simulation results were then discussed in the context of the research questions.

Commentato [DA18]: Commented [R217]: What data was collected,
how was it collected, how was it analyzed?

Commentato [DS19R18]: Answered.

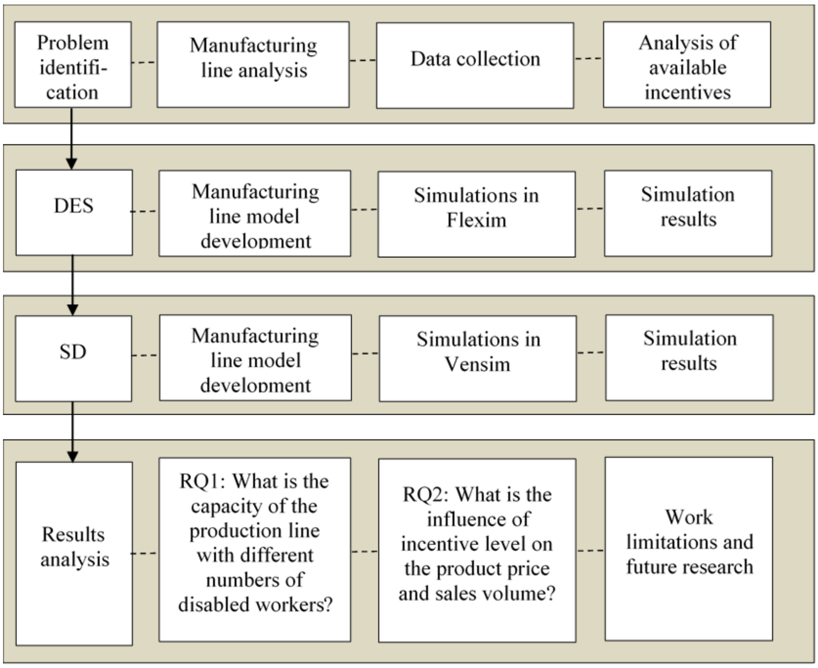

Figure 3. The research procedure

4.2. Data collection

In order to carry out the analyses, this paper presents a case study based on data collected from a real-world production line. The data was collected within one month. Four disabled workers as well as workers without disabilities can work on this production line. The workflow on the manufacturing line was identified and then analysed and the production operations were measured.

Commentato [DA20]: Commented [R218]: Numbers of each? How many PWDS were used in simulation?

Commentato [DS21R20]: Answered.

4.3. DES simulations

At operational level, the inclusion of a worker with disability in a workstation along the production line affects the mean process time and the standard deviation. Furthermore, it changes the number and the frequency of outages on the workstation. It is possible to predict with reasonable accuracy the global impact on the production throughput by a numerical simulation (DES) of the production line represented as a queueing network. The main justification of DES in present application is the possibility of taking into account the consistent increment of variability in process time experienced with the employment of disabled workers. The drawbacks, apart from the difficulty to match with a real system not completely known, are related to common assumptions of queueing network theory: pre-emption, and memoryless queueing. It is the same as to say that DES does not take into account feedback effects, as opposed to SD. The statement can be rephrased as follows: DES does not consider that other workers can modify their way of working to meet additional requirements introduced by disability. Bearing in mind these limitations with DES it is possible to determine the impact of the introduction of every additional disabled worker on the production rate depending on the workstation where the worker is employed. The simulation requires a thorough knowledge of the production line and of the scheduling policy adopted in the factory.

DES answers RQ1: What is the capacity of the production line as a function of the number of disabled workers employed?

While the SD simulation model of the system at an abstraction level that includes the market reaction to the company producing and selling strategy can be easily generalized such to be applied to whichever manufacturing company, the implementation of DES at operational level must be tailored to the specific production line. Therefore, in order to apply the proposed methodology to another company, the simulation of the process must be repeated with new data.

4.4. SD simulations

The main challenge for SD simulation is to develop a model of the manufacturing process that meets market demand. The model must take into account the variability of productivity and production costs, more or less related to the retail price as a function of the involvement persons with disabilities (PWDS). At the same time, the model must map the effect of product price and service level on consumer demand. The research will determine the number of PWDS and IL to ensure the highest number of products delivered to the market.

5. Problem identification and research questions

The methodology presented in this paper has been verified in a case study on a production line in a company that manufactures kindling and employs some people with disabilities. For sake of brevity, the results are presented only for the work stations where people with disabilities work. Only data on selected types and levels of disability were taken into the analysis to simplify the model and focus more on the proposed analysis approaches than on the complexity of the production system.

The model consists of four assembly stations that work in parallel, and a cutting process workstation, where the next operation is carried out after the assembly operation (Figure 4). Finally, quality control is carried out. The assembly stations are organized in such a way that the assembly process can be carried out by employees with either physical or intellectual disability. One worker works at one assembly station and it can be an employee without a disability or an employee with a disability. So a total of 4 employees are needed to work on the assembly stations.

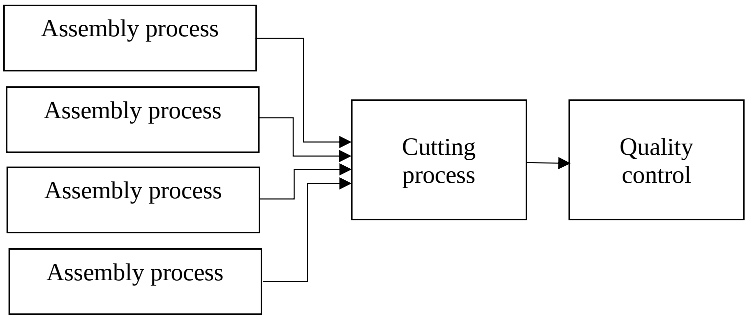

Figure 4. Schematic representation of manufacturing process flow

The problems that were identified during the analysis of work on the ML are as follows:

- Different capacity for disabled and non-disabled employees,
- Different capacity among disabled employees,
- Difficulties in planning process to ensure the expected service level (SL).

Commentato [DA22]: Commented [R220]: Were differences between the PWDS observed?

Commentato [DS23R22]: Yes.

Disabled workers perform production tasks with a slower pace. The time needed to perform tasks depends on the type and level of disability, and additionally varies significantly over time, even for the same employee. In addition, employees with disabilities may take unscheduled breaks. This causes additional difficulties in the process of planning and assigning work to employees. In a nutshell the process time of stations employing PWDS displays a steep increase in variability.

This can also affect the level of customer service. It can be seen that the level of customer service depends not only on employee capacity but also on demand, while demand depends on price. Manufacturing costs will affect the price that can be offered to customers. With lower costs, company can lower price to increase demand. Labour costs will be lower when employing workers with disabilities, as the government provides financial support to companies employing PWDS. However, with an increase in the number of disabled workers, the capacity of the workforce will decrease. Therefore, a balance must be found. Thus, the main goal of this work is to propose an analysis methodology that will allow the company to find such a balance using simulation methods. For that reason, the following research questions were posed:

- RQ1: What is the capacity of the production line as a function of the number of disabled workers employed?
- RQ2: What is the influence of incentive level on the product price and sales volume?

Furthermore, because the employment of people with disabilities is one of the important tasks to achieve the goals of sustainable development, the specific connection of this task with specific goals of sustainable development was analysed.

Data was collected from the operation of an existing manufacturing line that employ workers with various types and degrees of disability worked at the assembly stations. Table 3 shows the sheet prepared for data collection and statistical analysis. In the case study the following employees were engaged in the manufacturing process on the analysed production line: employees with moderate mental disability (MMD), employees with severe mental disability (SMD), employees with moderate intellectual disability (MID), employees with severe intellectual disability (SID), employees with moderate physical disability (MPD), employees with severe physical disability (SPD), and employees without disabilities (WTD).

The simulation uses the data of Table 3 which integrates the data collected during the ordinary working in the same factory where the process times on every workstation were measured. General limitations related to the collection of data from the work of people with disabilities may be associated with difficulties in planning the experiment and therefore data must be collected during the ordinary working.

Table 3. Sheet for data collection and analysis

Process time [s]	Type and level of disability						Without disabilities (WTD)
	Moderate mental disability (MMD)	Severe mental disability (SMD)	Moderate intellectual disability (MID)	Severe intellectual disability (SID)	Moderate physical disability (MPD)	Severe physical disability (SPD)	
min	250.28	546.82	351.24	497.13	432.58	N/A	129.34
mean	406.82	609.67	370.61	538.96	471.74	N/A	139.63
max	544.27	725.25	383.92	593.04	499.65	N/A	158.02
st. dev.	107.17	63.49	11.90	34.64	24.84	N/A	10.62
mean %	291.35	436.63	265.42	385.99	337.85	N/A	100.00

The data in the table 3 shows how large a discrepancy there is in the execution times of production operations between workers without disabilities and workers with disabilities, as shown by mean % values. For example, the mean time of performing an operation by an MMD employee is over 291% of the time of performing work by an employee without a disability. The data from the table were only partially used in the studies discussed in this paper. As the data were collected based on the current work plan, no figures were obtained for SPD who were absent during the analysed period.

6. DES implementation

The experiment consists in simulating the daily throughput at varying number of disabled workers. The experiment was repeated with different types of disability. In Figure 5 results are reported for moderate mental disability. In Figure 6 results are reported for moderate physical disability.

Commentato [PL24]: It was stated earlier: "For the sake of discussion, the authors include in the present study only two types of disability, namely moderate physical disability (MPD) and moderate mental disability (MMD" Maybe we should leave only MMD and MPD results in the table 3?

Commentato [DS25R24]: Even, if we use the data just partially, they show very well what is the problem, and I do not see any reviewer comment asking to change something n the table.

Commentato [DA26]: **Commented [R221]:** The number of persons
within each class can impact the SDs greatly, IE 2 different worker in the MMD with large differences in individual production times

Commentato [DS27R26]: We can only agree with the reviewer and do nothing in the paper, in my opinion.

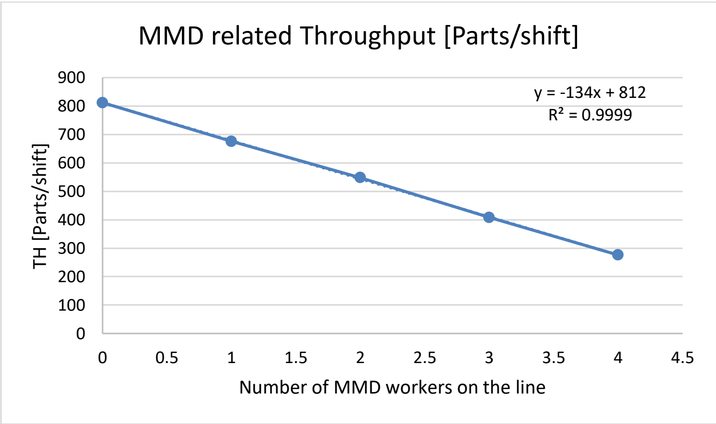

Figure 5. Production per day as a function of the number of MMD workers employed

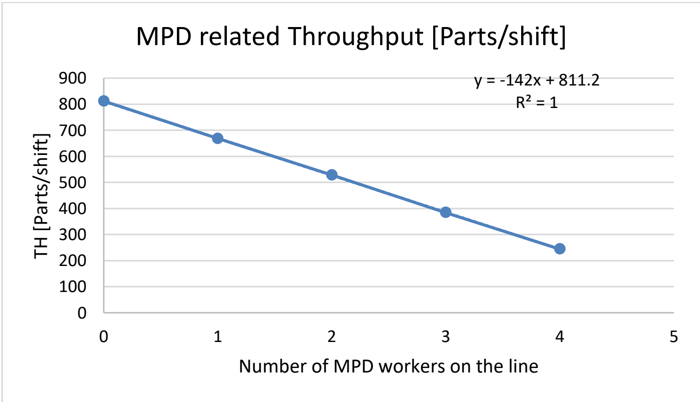

Figure 6. Production per day as a function of the number of MPD workers employed

The results have been interpolated to build the equation of the regression line. While it is meaningless to consider a fractional number of disabled workers in a shift, on a longer time period, it represents the effect of employing a disabled worker for a limited part of the year. Figures 5 and 6 show similar results, despite the fact that physically disabled workers require longer process times. The reason is that MMD workers in the analysed production suffer periodic breakdowns with a measured Mean Time To Break (MTTB) of 3.25h and a Mean Time Of Break of 0.23h. As a result, the mean throughput of both types of disabled are similar during one shift and completely overlapping on the long term. The coefficient of determination of 1 is suspicious in an actual production workplace. Here is justified because of the extreme simplicity of the production line with the assembly stations in parallel. Since the data were taken from this plant, fidelity to the real situation was maintained. On the other hand, a more complex production line would have had no effect on SD analysis, which still refers to linear models.

Another significant result of the simulation was the utilization of the downstream workstation: cutting workstation. Figure 7 shows that the utilization is less than 1 also working with non-disabled workers (WTD). The reason is that production control adopts a pull strategy without buffers along the line.

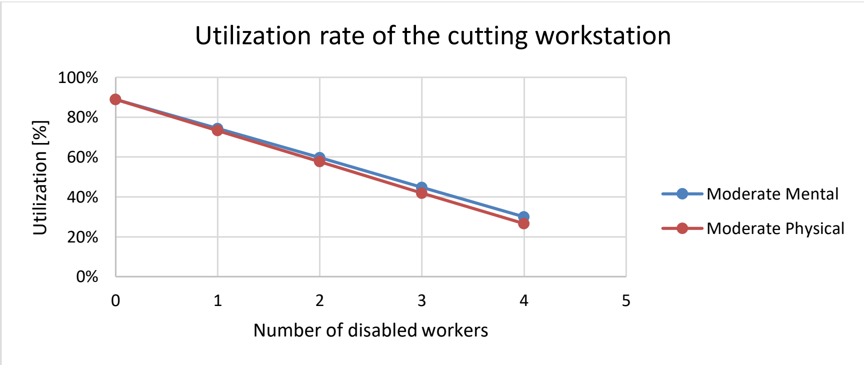

Figure 7. Utilization rate of cutting workstation per number of disabled workers employed

While this figure is not used by SD, one can observe that such a low utilization introduces serious imbalances in line management. In the real process this effect could be source of additional problems difficult to predict by simulation.

7. SD implementation

7.1 SD model development

The SD model developed for assessing the impact of PWDS engagement on the manufacturing performance is presented on Figure 8. The assumptions made in the modelling process are discussed below.

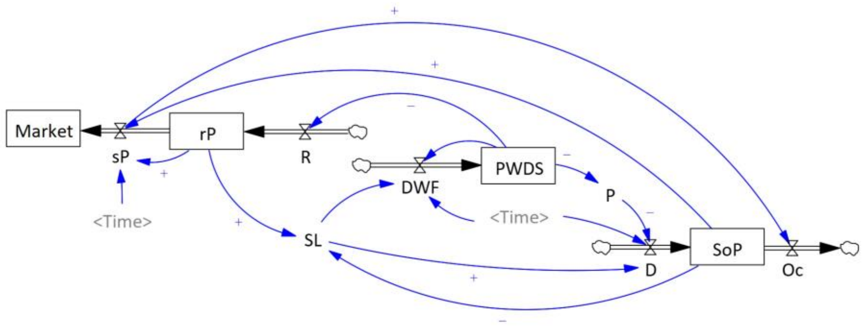

Figure 8. SD model with disabled employees (PWDS) engaged

The elements of SD model are defined as follows:

(1) *R* – production rate

The production rate (*R*) models the ML throughput and can be calculated as (1):

$$R = \sum_{i=1}^{k} \frac{n_i}{OT_i} \qquad (1),$$

where:

n_i – the number of workers of specified type (PWDS, WTD),

OT_i – the processing time of the worker of specified type.

Calculations become more complex in the case of disabled employees. In this case, the additional breaks available to employees and the large spread in the processing time of the employees must be taken into account. In the research, the *R* value is obtained from

DES experiment, which takes into account the factors mentioned above.

(2) *sP* – shipped products

The shipping process is responsible for sending products to the market after each shift. The number of products shipped (*sP*) sent to market is equal to the number of products ordered (*oP*) if the number of ready products (*rP*) is greater than or equal to *oP*. Otherwise, *sP* is equal to the number of *rP* (2).

$$(rP \geq oP \rightarrow sP = oP) \vee (rP < oP \rightarrow sP = rP) \quad (2),$$

where:

oP – the number of ordered products,

rP – the number of ready products.

(3) *SL* – service level

The variable represents the calculated value of the service level (*SL*) (3).

$$\left(\left(\frac{rP}{oP} \geq 1\right) \rightarrow SL = 1\right) \vee \left(\left(\frac{rP}{oP} < 1\right) \rightarrow SL = \frac{rP}{oP}\right) \quad (3),$$

If *rP* is lower than *oP*, the service level decreases below 1, leading to customer dissatisfaction. Furthermore, it means that with actual employee assignment, the company is not able to manufacture the expected number of products, and possibly changes in employees assignment in the ML should be considered. *SL* is always considered to be lower than or equal to 1.

(4) *DWF* – disabled workers flow

DWF presents the rules for the assignment of persons with disabilities (PWDS) to the manufacturing process. In the simulation model, the assignment of PWDS can change after each shift based on the ratio of the number of products that can be produced with the capacity of a production team (ML_C) and the number of products ordered by the customer (*oP*). This feature of the model will be used in the initial phase of ML analysis to estimate the number of PWDS employees needed to meet customer demand. We assume that a number of PWDS workers equal *AC* (assignment change), can be added or subtracted after each shift to the analysed manufacturing line, $AC \in (0,1>$. It is also assumed that there is a fixed number of employees (*m*) working on ML (*WTD* + *PWDS* = *m*), only a share of each type of employee can be changed.

Generally, it is assumed that if ML_C is greater than *oP*, the share of disabled workers increases. If $\frac{ML_C}{oP} \in < 0.95, 1 >$, the share of disabled workers doesn't change, and if $\frac{ML_C}{oP} < 0.95$ the share of disabled workers is reduced.

Formula (4) shows how the DWF changes depending on the current situation. We assume that a number of *PWDS* equal to *AC* (assignment change), can be added or subtracted from the ML, $AC \in (0,1 >$.

$$\left(\left(\frac{ML_C}{oP} > 1\right) \rightarrow DWF = AC\right) \vee \left(\left(\frac{ML_C}{oP} < 0.95\right) \rightarrow DWF = -AC\right) \vee \left(\left(\frac{ML_C}{oP} \leq 1 \wedge \frac{ML_C}{oP} \geq 0.95\right) \rightarrow DWF = 0\right) \quad (4),$$

where:

ML_C – the number of products that can be produced with the current capacity of a production team (*PWDS* + *WTD*),

m – total number of workers in an assembly process,

AC – number of *PWDS* workers added or subtracted from ML.

(5) *D* – customer demand.

Demand is widely known as a function of product attributes (Federgruen A., Heching A., 1999) such as price – P, service level – SL, quality – q, delivery time – t, (5):

$$D = F(P, SL, q, t) \quad (5).$$

For sake of simplicity demand here can be modelled as a linear function (Qian2014) expressed as (6):

$$D = a - \beta_p * P + \beta_{SL} * SL + \beta_q * q - \beta_t * t \quad (6),$$

where:

a – market size,

P – product price

β_p – price sensitivity coefficient,

SL – service level

β_{SL} – service level sensitivity coefficient,

q – product quality,

β_q – product quality sensitivity coefficient,

t – delivery time

β_t – delivery time sensitivity coefficient.

Demand increases when: the selling price decreases, the quality of the product increases, the service level increases, and the delivery time decreases. In the investigation we assume that the change in the number of workers (PWDS, WTD) does not affect the quality and delivery time, so $\beta_q, \beta_t = 0$, and the demand depends only on P and SL. Obviously, this is a simplified model of the complex dependence between demand and production factors, which does not take into account the influence of competitors. As described in detail in (Ray, 2005) and in (Qian, 2014) demand is also a function of the actors taken into consideration: the manufacturer – final customer or the manufacturer – retailer. It also depends on the type of industry and product, as well as on the production type. The approach used here assumes that demand increases with a decrease in the price and decreases with a decrease in the service level. In order to show the impact of other above mentioned factors affecting demand the random component is included to the demand equation (7):

$$D = \left(a - \beta_p * P + \beta_{SL} * SL\right) * N(\mu, \sigma^2) \quad (7),$$

where:

$N(\mu, \sigma^2)$ – random normal value with mean μ and variance σ^2.

(6) P – product price

Product price (P) is important factor influencing purchasing decisions and thus affecting demand. In simplified terms price can be expressed as (8):

$$P = c_l + c_o + I_u \quad (8),$$

where:

c_l – unit labour cost,

c_o – other cost per unit (raw material, energy, production capacity cost, etc.),

I_u – unit profit.

All costs listed are important components of the product price, but from the point of view of this research, unit labour cost (c_l) is the most significant factor affecting the price change. This is because the research question deals with the participation of employees with different employment costs (employment of disabled people is subsidised by the government) and different processing times, affecting the unit labor cost.

The unit labour cost is calculated based on the total number of workers *(m)*, number of disabled workers (*PWDS)*, number of *WTD (WTD = m – PWDS)*, and worker's specific unit labor costs C_{WTD}, and C_{PWDS} (9).

$$c_l = \frac{PWDS * C_{PWDS} + (m - PWDS) * C_{WTD}}{m} \qquad (9),$$

where:

C_{WTD} – WTD worker unit labour cost,

C_{PWDS} – PWDS worker unit labour cost,

PWDS – number of disabled workers.

Taking into account that disabled workers salary is partially covered by government, C_{PWDS} is usually lower than C_{WTD}, thus assigning PWDS can result in price decrease.

(7) *SoP* – stack of orders

The stack of orders (S*oP*) represents the number of ordered products (*oP*) reduced by shipped products (*sP*) (which refers to completed orders – Oc) (10).

$$SoP = oP - sP \qquad (10).$$

(8) Market – represents the aggregate number of products shipped to market.

In the SD model (Figure 8) causal relations with polarity signs between main factors are shown. Increasing the number of PWDS involved in the ML can decrease the price because the government subsidises the employment of people with disabilities. Decreasing the price increases demand. At the same time, increasing the number of PWDS involved in ML decreases the number of manufactured products, because the efficiency of workers with disabilities is lower than the efficiency of workers without disabilities.

Decreasing the number of manufactured products decreases *SL*, and lower *SL* decreases demand. If the demand decreases, the number of workers with disabilities involved in the ML can increase. Conversely, increasing the number of manufactured products increases *SL* and the demand. With increasing demand, more WTD workers should be assigned, which increases price. An increase in price will decrease demand.

7.2. Results of the SD simulations

PWDS workers concerned in SD simulation are MMD (moderate mental disability) type only. In the DES simulation, the throughput was determined for the assembly process with the specified numbers of PWDS and WTD workers assigned (Figure 5). The results of the DES experiment are crucial for the next stage of research conducted on the SD model. On the basis of DES simulations worker's specific unit labour costs were calculated. The WTD worker unit labour cost C_{WTD} is calculated from Formula (11).

$$C_{WTD} = \frac{HS_{WTD}}{TH_{WTD}} \quad (11),$$

where:

HS_{WTD} is hourly salary of WTD worker,

TH_{WTD} is hourly throughput of WTD worker.

Similarly disabled worker unit labour cost (C_{PWDS}) can be calculated (see equation 12). To be precise, the part of the cost that is paid directly by the company (taking into account the government *IL)* is calculated (12).

$$C_{PWDS} = \frac{HS_{PWDS}}{TH_{PWDS}} = \frac{HS_{WTD}*(1-IL)}{TH_{PWDS}} \quad (12),$$

where:

HS_{PWDS} – hourly salary,

IL – incentive level,

TH_{PWDS} – hourly throughput of PWDS worker.

The *IL* value can vary depending on national law regulations. The results of C_{PWDS} calculations for different *IL* values and for the average wage adopted in the enterprise of the case study are given in the Table 4.

Table 4. C_{PWDS} values for specified *IL* and average wage in the enterprise

IL	0.9	0.85	0.8	0.75	0.7	0.66
C_{PWDS}	0.267	0.4	0.53	0.67	0.8	0.904

From the results shown in Table 2, it can be seen that C_{PWDS} values rise with decreasing *IL*. When $IL < 0.66$ then $C_{PWDS} > C_{WTD}$, so it is not economically justified to assign disabled workers to manufacturing. Finally, the research plan includes simulation experiments with the *IL* values: 0.9, 0.85, 0.8, 0.75 and 0.7. The number of PWDS assigned to the manufacturing line influences labour cost (which affects the price) and throughput, which affects the *SL* given by formula (3). For the purpose of this paper, we assume that price components (for instance, unit profit) other than labour costs are constant. Assuming that price minus labour costs equals 2 $(P – c_l = 2)$ and that total number of workers $m = 4$, the price formula used in simulations for variable *PWDS* and *IL* calculated from (8) and (9) is as presented in formula (13):

$$P = 2{,}904 + PWDS * (0.44 - 0.67 * IL) \quad (13)$$

As a result of the different number of PWDS assigned on the manufacturing line and different values of *IL*, the company can offer a product price in the range of 2.267 to 2.904.

In the case of the product under study on the basis of data acquired from the company, the demand (Formula 7) is determined by equation (14):

$$D = (800 - 160 * P + 130 * SL) * N(\mu, \sigma^2) \quad (14),$$

with the following values of the parameters of the random distribution $N(\mu,\sigma^2)$:

min = 0.995, max = 1.005, mean = 1, σ = 0.0017.

In sections 7.2.1 and 7.2.2 we try to answer RQ2: What is the influence of incentive level on the product price and sales volume?

7.2.1 SD-1: Finding price – SL – demand equilibrium.

In the first simulation experiment (SD-1), the model is used to determine the number of PWDS assigned to the manufacturing line. The PWDS number can be changed after every working shift by *AC = 0.02*. The change of PWDS assignment is governed by formula (4). The goal of the simulation is to determine the number of PWDS assigned to the manufacturing line to provide certain *SL* values, under dynamic market conditions. In the SD-1 experiment we assume that when $SL \leq 0.95$ the system should rise productivity by decreasing the number of PWDS, and when $SL = 1$ the system can lower productivity by increasing the number of PWDS. The results of the SD-1 experiment for different *SL* values are shown in Table 5.

Table 5. Results of SD-1 experiment

IL	**PWDS**	**D**	**SL**	**Market**	**P**
0.90	**2.18**	**519.88**	**0.991**	**129970**	**2.55**
0.85	2.26	509.16	0.986	127301	2.62
0.80	2.34	498.44	0.985	124632	2.68
0.75	2.44	485.04	0.976	121295	2.76
0.70	2.54	471.64	0.967	117958	2.84

The results of the SD-1 experiment given in Table 3 show the ML parameters for different levels of government support (*IL*). In each case analysed, the *SL* is within the range of acceptable values (0.95, 1). The results clearly show that as *IL* decreases, the price of the product (*P*) increases and *SL* decreases. The results also show that as the *IL* decreases, the equilibrium point of the market shifts toward less demand, and thus fewer products are supplied to the market. At the same time, there is a slight increase in the expectation for *PWDS* involvement, which in the analysed range of *IL* varies from 2.18 to 2.54. It is worth noting, however, that despite the simulation environment in the real-world conditions the company has the ability to hire employees at a rate of not less than *0.5 FTE* (full time equivalent), so in the second stage of the study the system's performance with 2 or 2.5 PWDS assigned on the manufacturing line will be analysed.

Another important result of the experiment is the dynamics of the system under consideration. The values shown in Table 3 represent the equilibrium point reached by the system after starting from a fixed initial value of *PWDS*. Regardless of the starting conditions, the system reached equilibrium for the *PWDS* value given in Table 3, only the 'stabilisation' time of the system differed. Figure 9 shows the graphs of *PWDS*, *D*, and *SL* in the SD-1 experiment for *IL* = 0.7 with the random factor in the demand equation.

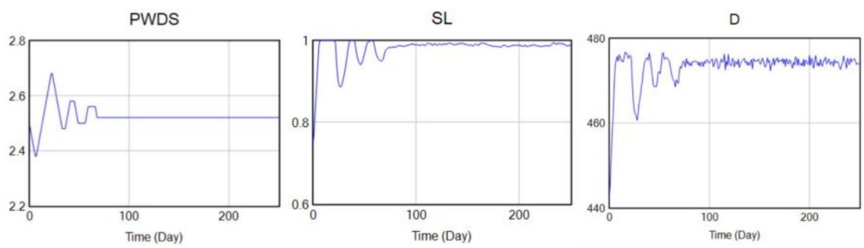

Figure 9. *PWDS*, *D* and *SL* dynamics in SD-1 experiment with random demand factor

In Figure 9, slight fluctuations in *SL* and *D* can be observed after the *PWDS* has reached a stable value due to the inclusion of a random component in the demand equation. Figure 10 shows the behaviour of the system without considering the random component of demand.

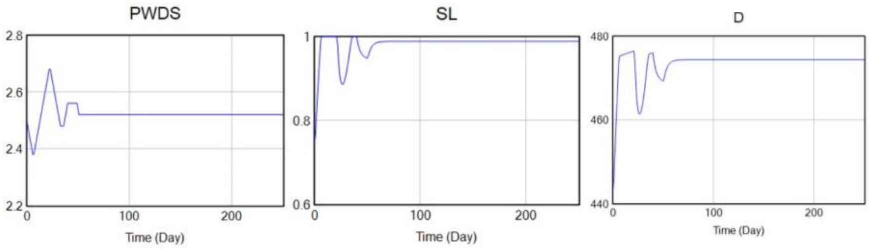

Figure 10. *PWDS*, *D* and *SL* dynamics in SD-1 experiment without random demand factor

If the random factor is omitted, the system under consideration reached its equilibrium point at approximately the same time, and since then the values of *PWDS*, *SL* and *D* have remained stable. As mentioned above, the next part of the study will evaluate feasible real-world assignments of workers to the production line.

7.2.2 SD-2: Finding PWDS – IL combination for production maximization

A previous experiment showed that for *IL* in the range of 0.7-0.9, the system maintained equilibrium when 2.18 to 2.54 PWDS were assigned to the assembly process. In a subsequent experiment, 10 simulations were performed. In each simulation run, the number of employees with disabilities engaged in the MP and *IL* is fixed, which means that it does not change during the simulation time. The *PWDS* was 2 or 2.5 and *IL* values were 0.9, 0.85, 0.8, 0.75 and 0.7. The results shown in Table 4 confirm that highest sales volume and lower price levels are observed with the highest *IL*. The company, depending on the *IL* which it receives, should assign workers to the production line in a way that ensures high *SL* and demand, resulting in a highest number of products sold. This, assuming a constant unit profit (see section 6.2), will contribute to global profit maximization. For most *IL* values, it will be more favourable to assign 2 PWDS to the ML. Only in the case where *IL* = 0.7 the enterprise should assign 2.5 PWDS to the ML.

Table 6. Results of SD-2 simulations

IL	*PWDS*	*D*	*SL*	Market	P
0.9	**2**	**516.56**	**1**	**129 246**	**2.58**
	2.5	477	0.597	119 293	2.50
0.85	2	505.68	1	126 549	2.65
	2.5	477	0.702	119 293	2.59
0.8	2	495.28	1	123 965	2.72
	2.5	477	0.801	119 293	2.67
0.75	2	484.08	1	121 183	2.79
	2.5	477	0.909	119 293	2.76
0.7	2	473.68	1	118 597	2.85
	2.5	475.76	1	119 000	2.84

The results presented in Table 4 show that for *IL* = 0.9 and *PWDS* = 2 the largest number of products (129 264) is delivered to the market. At the same time, high *SL* is maintained (*SL* = 1). From results presented in table 6 we can also see that *IL* can strongly affect the number of products shipped to market. When *IL* = 0.7 and *PWDS* = 2 only 118 597 products are sent to market, which is 91.7% of the best result. The reason of lowering the amount of products sold is the high price affecting demand.

8. Discussion and conclusions

Engagement of workers with disabilities requires an appropriate approach, as our research, as well as other studies presented in the literature, show that differences in performance between workers with disabilities can be significant, even if they are in the same disability group. For example, the authors of the work (Peltokorpi et al., 2023) examined the impact of the form of instruction (paper, animation, projection, adaptive projection) as well as the type of disability of the worker to manage assembly tasks. Based on the research results, the authors found that the differences between operators as well as their adaptation to cognitive assistance systems vary a lot, even within the same group of disability. Therefore, the forms of instructions should be individually selected.

It should be noted that the results obtained are associated with the adopted co-financing, the employment of PWDS, and the assumed example relationship between demand, price, and SL. Previous works (Miralles et al., 2007) (Araújo et al., 2012) did not take into consideration SL– price – demand relations. Our previous article (Litwin et al., 2022) considers the demand formula, but does not take into account the IL, which may vary in different countries. This paper considers several levels of subsidies, and the results show the relation between *IL, the* number of PWDS engaged and the overall system performance.

The results of the study confirm the business rationale for employing PWDS when employment is co-financed by government. The study showed that as the value of *IL* increases, the demand for the manufactured product increases due to the ability to reduce the price. The case study also showed the existence of a cut-off value of *IL*, below which engaging in PWDS is not economically justified. The presentation of evidence (both social and economic) on the rightfulness of employing PWDS workers and the methodology of the analysis are the main contributions of this work to science. This study has shown that employing PWDS in a regulated labour market can, within certain limits, benefit companies.

The inclusion of workers with disabilities in production processes is important for a number of reasons, which are detailed in Section 2. However, from the point of view of running a business, the economic aspects are the most important. The involvement of employees with disabilities should not disrupt the company's financial liquidity. Therefore, it is important to analyse the possibilities of including disabled employees in the production line and make economically justified decisions. Therefore, our model covers mainly economic aspects, although in the future it may be considered to include other aspects, such as emploees' job satisfaction level.

The methodology presented in this paper can be applied under different circumstances to determine the best option to involve people with disabilities in production lines work to achieve the expected service level. However, it should be emphasized that this study has some limitations. The first concerns the available working time, which was adopted only for work on the first shift. With certain levels and types of disabilities, employees cannot, for example, work the third shift. In future studies, the simulation models will take it into account.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Availability of data

The authors confirm that the data supporting the findings are available in the article.

REFERENCES

Antonelli, D., Stadnicka, D. (2018). Combining factory simulation with value stream mapping: A critical discussion, in: Procedia CIRP. Elsevier B.V., pp. 30–35.

Araújo, F.F.B., Costa, A.M., Miralles, C. (2012). Two extensions for the ALWABP: Parallel stations and collaborative approach. Int. J. Prod. Econ. 140, 483–495.

Bratcu, I. & Dolgui, A. (2009). Some new results on the analysis and simulation of bucket brigades (self-balancing production lines), International Journal of Production Research, 47:2, 369-387, DOI: 10.1080/00207540802426128

Convention on the Rights of Persons with Disabilities [A/RES/61/106], https://www.un.org/development/desa/disabilities/resources/general-assembly/convention-on-the-rights-of-persons-with-disabilities-ares61106.html

Disabled World. (2009). Definitions of Disability : https://www.disabled-world.com/definitions/ disability-definitions.php (accessed 4.12.21).

Edghill, J.S., Towill, D.R., Husband, T. (1989). Dynamic Behaviour of Fundamental Manufacturing System Design Strategies. CIRP Ann. - Manuf. Technol. 38, 465–468.

European Disability Strategy 2010-2020, https://www.alzheimer-europe.org/policy/eu-action/european-disability-strategy-2010-2020#:~:text=The%20European%20Commission%27s%20European%20Disability%20Strategy%202010-2020%2C%20builds,disabilities%20and%20promote%20the%20market%20of%20assistive%20devices

European Parliament (2021). A new ambitious EU Disability Strategy for 2021-2030. https://www.europarl.europa.eu/news/en/headlines/society/20200604STO80506/a-new-ambitious-eu-disability-strategy-for-2021-2030 Updated: 12-05-2021

Federgruen A., Heching A., (1999). Combined Pricing and Inventory Control Under Uncertainty. Operations Research 47(3):454-475

Grammenos S., (2013). European comparative data on Europe 2020 & People with disabilities Final report prepared by Stefanos Grammenos from Centre for European Social and Economic Policy (CESEP ASBL) on behalf of the Academic Network of European Disability Experts.

Gola, A. (2019). Reliability analysis of reconfigurable manufacturing system structures using computer simulation methods. Eksploat. i Niezawodn. 21, 90–102.

Helal, M. (2007). A methodology for integrating and synchronizing the system dynamics and discrete event simulation paradigms. 25 Int. Conf. Syst. Dyn. Soc. 3, 1–24.

Heron, R.; Murray, B., (2003). Assisting Disabled Persons in Finding Employment: A Practical Guide, 2nd ed.; International Labor Office: Geneva, Switzerland, p. 5.

Kellner, M.I., Madachy, R.J., Raffo, D.M. (1999). Software process simulation modeling: Why? What? How? J. Syst. Softw. 46, 91–105.

Kłos, S., Trebuna, P. (2015). Using computer simulation method to improve throughput of production systems by buffers and workers allocation. Manag. Prod. Eng. Rev. 6, 60–69.

Lecerf M. (2020). Employment and disability in the European Union. European Parl. Research Service. PE 651.932.

Liu M., Liu Z., Chu F., Liu R., Zheng F., Chu C. (2021). Risk-averse assembly line worker assignment and balancing problem with limited temporary workers and moving workers. Int. J. Prod. Res.

Litwin, P., Antonelli, D., & Stadnicka, D. (2022). Disabled employees on the manufacturing line: Simulations of impact on performance and benefits for companies. IFAC-PapersOnLine, 55(10), 848-853.

Malo, Miguel Á., and Ricardo Pagán. "Wage differentials and disability across Europe: Discrimination and/or lower productivity?." International Labour Review 151.1-2 (2012): 43-60.

Mark, B. G., Hofmayer, S., Rauch, E., & Matt, D. T. (2019). Inclusion of workers with disabilities in production 4.0: Legal foundations in Europe and potentials through worker assistance systems. Sustainability, *11*(21), 5978.

Ming Liu, Zhongzheng Liu, Feng Chu, Rongfan Liu, Feifeng Zheng & Chengbin Chu (2022) Risk-averse assembly line worker assignment and balancing problem with limited temporary workers and moving workers, International Journal of Production Research, 60:23, 7074-7092, DOI: 10.1080/00207543.2021.2002960

Miralles, C., García-Sabater, J.P., Andrés, C., Cardos, M. (2007). Advantages of assembly lines in Sheltered Work Centres for Disabled. A case study. Int. J. Prod. Econ. 110, 187–197.

Mourtzis, Dimitris (2020) Simulation in the design and operation of manufacturing systems: state of the art and new trends, International Journal of Production Research, 58:7, 1927-1949, DOI: 10.1080/00207543.2019.1636321

Narayanan, Sriram, and Ed Terris. "Inclusive manufacturing: The impact of disability diversity on productivity in a work integration social enterprise." Manufacturing & Service Operations Management 22.6 (2020): 1112-1130.

Peltokorpi, J., Hoedt, S., Colman, T., Rutten, K., Aghezzaf, E. H., & Cottyn, J. (2023). Manual assembly learning, disability, and instructions: an industrial experiment. International Journal of Production Research, 1-19.

Qian, L. (2014). Market-based supplier selection with price, delivery time, and service level dependent demand. Int. J. Prod. Econ. 147, 697–706.

Rabelo, L., Helal, M., Jones, A., Min, H.S. (2005). Enterprise simulation: A hybrid system approach. Int. J. Comput. Integr. Manuf. 18, 498–508.

Rabiega, H. (2014). Jak kraje UE wspierają zatrudnianie osób niepełnosprawnych? GazetaPrawna.pl. https://serwisy. gazetaprawna.pl/praca-i-kariera/artykuly/ 808559,jak-kraje-ue-wspieraja-zatrudnianie-osob-niepelnosprawnych.html.

Ray, S. (2005). An integrated operations-marketing model for innovative products and services. IJPE. 95, 327–345.

Ritt M., Costa A. M. & Miralles C. (2016) The assembly line worker assignment and balancing problem with stochastic worker availability, International Journal of

Production Research, 54:3, 907-922, DOI: 10.1080/00207543.2015.1108534
Stadnicka, D., Litwin, P. (2019). Value stream mapping and system dynamics integration for manufacturing line modelling and analysis. IJPE. 208, 400–411.
Stadnicka, D., Litwin, P. (2017). VSM Based System Dynamics Analysis to Determine Manufacturing Processes Performance Indicators, in: DEStech Transactions on Eng. and Techn. Research. pp. 290–295.
Sweetser, A. (1999). A Comparison of System Dynamics (SD) and Discrete Event Simulation (DES), 17th Int. Conf. of the System Dynamics Society. pp. 20–23.
UN Convention on the Rights of Persons with Disabilities: initial report on how the UK is implementing it, https://www.gov.uk/government/publications/un-convention-on-the-rights-of-persons-with-disabilities-initial-report-on-how-the-uk-is-implementing-it
Venkateswaran, J., Son, Y.J. (2005). Hybrid system dynamic - Discrete event simulation-based architecture for hierarchical production planning. Int. J. Prod. Res. 43, 4397–4429.
Wagner, J., Schnabel, C., Kölling, A. (2001). Threshold Values in German Labor Law and Job Dynamics in Small Firms: The Case of the Disability Law. IZA Discuss. Pap. https://papers.ssrn.com/sol3/papers.cfm? abstract_id=288294 (accessed 4.12.21).

Links:

A More Accessible and Sustainable World: A Disability-inclusive Response to COVID-19. DECEMBER 1, 2020, https://www.worldbank.org/en/news/feature/2020/12/01/a-more-accessible-and-sustainable-world-a-disability-inclusive-response-to-covid-19
Convention on the Rights of Persons with Disabilities (CRPD), Department of Economic and Social Affairs, 6 May 2022, https://www.un.org/development/desa/disabilities/convention-on-the-rights-of-persons-with-disabilities.html
Convention on the Rights of Persons with Disabilities, 13 December 2006, Sixty-first session of the General Assembly by resolution A/RES/61/106, https://www.ohchr.org/en/instruments-mechanisms/instruments/convention-rights-persons-disabilities
Deloitte Insights, 23 August 2021, https://www2.deloitte.com/xe/en/insights/economy/global-labor-shortage.html
Disability and Development Report, Realizing the Sustainable Development Goals by,

for and with persons with disabilities, Department of Economic and Social Affairs, 2018, https://social.un.org/publications/UN-Flagship-Report-Disability-Final.pdf

Disability statistics, Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Disability_statistics

Disability in EU: facts and figures, https://www.consilium.europa.eu/en/infographics/disability-eu-facts-figures/Employment and disability in the European Union

EU Framework for the UN Convention on the Rights of Persons with Disabilities, https://fra.europa.eu/en/cooperation/eu-partners/eu-crpd-framework

The 2030 Agenda for Sustainable Development. A/RES/70/1. United Nations, https://sustainabledevelopment.un.org/

UK Initial Report On the UN Convention on the Rights of Persons with Disabilities, Office for Disability Issues, May 2011, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345120/uk-initial-report.pdf

Union of Equality: Strategy for the Rights of Persons with Disabilities 2021-2030, 03/03/2021, https://ec.europa.eu/social/main.jsp?catId=738&langId=en&pubId=8376&furtherPubs=yes

Vasilis Bouronikos, 30 July, 2021, The Status of Employment and disability in the EU in 2021, https://ied.eu/project-updates/the-status-of-employment-and-disability-in-the-eu-in-2021/

WHO (2021). Disability and health, https://www.who.int/ news-room/fact-sheets/detail/disability-and-health.