SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2024
ORGANIZATION AND MANAGEMENT SERIES NO. 209

SIMULATION MODELING IN THE STUDY OF MANUFACTURING ENTERPRISES' VULNERABILITY TO DISRUPTION

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Purpose: In recent years, manufacturing companies have been confronted with an increased incidence of disruptions affecting production processes. Finding approaches to effectively resist the occurrence of disruptions is crucial for enterprises. The development of Industry 4.0 technology enables the use of innovative tools to prepare for the unpredictable situations and ensure business continuity.
Design/methodology/approach: The aim of the manuscript is to investigate the possibility of using simulation modeling to study the vulnerability of production processes to disruptions. The research was limited to the study of internal disruptions occurring in a manufacturing enterprise. The manufacturing process performed at a mechanical engineering company was studied. A case study was conducted to investigate the process vulnerability to selected internal disruptions identified at the company. The research was performed in Tecnomatix Plant Simulation software. Three simulation experiments were performed for disruptions such as machine failure, decrease in employee efficiency, and delivery delay of materials.
Findings: The conducted research proved that simulation modeling can be applied to assess the vulnerability of the production process to selected disruptions. The benefits of the presented approach were indicated, especially in supporting the decision-making process.
Research limitations/implications: The research was conducted for selected internal disruptions. The focus of future studies was established by identifying and classifying disruptions suitable for simulation modeling, as well as outlining the application scope of simulation tools.
Practical implications: Simulation modeling can be applied by manufacturing enterprises to investigate the vulnerability of implemented processes to disruption. The case study was conducted in the mechanical industry. However, the presented approach can be applied to companies in various industries. A potential barrier is the lack of familiarity with simulation modeling tools. Nevertheless, the advantages of analyzing different event scenarios are substantial enough to justify overcoming this challenge.
Originality/value: The literature review found a deficiency of research on process vulnerability using simulation modeling. The research conducted indicates validation and application of the studied approach to manufacturing companies. A significant benefit is conducting analyses without interrupting the actual process, which is especially crucial for manufacturing operations.
Keywords: vulnerability, disruption, simulation modeling, production companies.
Category of the paper: research paper.

1. Introduction

Disruptions in production processes exist from the beginning of the realization of processes aimed at producing various types of products and services. Depending on the size of the disruption and the strength of its influence, the impact on the implementation of individual activities can be minimal, through partial disruption of their course up to even stopping the ongoing production process.

The effect of disruptions on the execution of the production process is particularly strong when crisis situations occur, such as the eruption of the Eyjafjallajokull volcano in Iceland in April 2010 (Harrison, Williams, 2016), which paralyzed the flow of goods through supply chains for several weeks, the blockade of the Suez Canal by the container ship Ever Given in March 2021, which caused delays in shipping products to customers around the world (Popkien, 2021) or the COVID-19 pandemic, which resulted in a massive damage and destruction to global supply chain operations (Sajjad, 2021). The described events have significantly affected manufacturing companies, limiting their operations in the short or longer periods. Most of them are classified as external disruptions, which are difficult for companies to predict and manage. In addition to external disruptions, companies also experience internal disruptions, which are closely related to the operations performed inside the organization and the resources it possesses. Some of the most common disruptions include: machine breakdown, reduced employee efficiency, lack of materials at the workstation, etc.

Disturbances, characterized by a high impact, are capable of interrupting the operation of the production process. Prof. Lis stresses that disruptions cause the course of production processes to deviate from initially accepted assumptions and plans, leading to a reduction in production efficiency and losses for the enterprise (Lis, 1982). Despite the significant negative consequences, many manufacturing enterprises do not focus appropriate attention on possible risks. Such an approach can expose companies to large losses, both financially (penalties resulting from orders not completed on time, reduced incomes resulting from fewer products sold), but also in terms of image (reduced value of the company in the perception of customers). Many enterprises are oblivious to the possible consequences. The companies also show an aversion to taking preventive activities, as they require ensuring an appropriate level of time and resource reserves for the processes in execution. Determining the size of these reserves is often based on the knowledge and experience of employees. Technologies used as part of Industry 4.0 (such as Internet of Things, Big Data, Machine Learning, etc.) can be extremely helpful for companies, however these solutions can most often be afforded by large companies with high investment capital. Most enterprises in Poland consider the mentioned solutions too expensive. When they successfully implement the proposed technologies, it is usually done in a selective and unsystematic manner in response to prevalent opportunities, such as funding from implementation projects. Identifying a tool that allows for straightforward research into the vulnerability of a process to disruptions is crucial for companies wishing to achieve resilience. A highly effective solution for this challenge is simulation modeling, originally utilized by experts to delve into specific topics across various disciplines. As the 1980s approached, modeling evolved to address unique engineering and design issues. By the early 21st century, its application expanded significantly, leading to the design of simulation-based systems. As of 2015, simulation has become a fundamental component of digital twins, revolutionizing how businesses manage and optimize their processes (Rosen et al., 2015).

The purpose of the presented manuscript is to present the possibility of using simulation modeling to study the vulnerability of manufacturing enterprises to disruption. Section 2 presents the results of literature research conducted in the area of susceptibility, disruptions occurring in manufacturing enterprises and the scope of application of simulation modeling. The research method is described in Section 3. Section 4 features a case study demonstrating the application of simulation modeling to investigate vulnerability in a chosen manufacturing process at a mechanical engineering company. The discussion of the obtained research results is presented in Section 5. Section 6 summarizes the manuscript and outlines potential future research directions.

2. Literature review

Process modeling involves creating a representation of a specific process implemented in the company. In engineering disciplines, mathematical models are often used to represent the real-world phenomena. They provide a simplified representation of the studied phenomenon, system or process using variables, parameters and constraints (or conditions imposed on the variables), or functions. The developed mathematical models can be inserted into dedicated computer software, which approximates the behavior of the analyzed phenomena. Constructed models do not perform successfully in supporting sophisticated processes. As a result, mathematical models are often represented in computer software, using simulation modeling (Smagowicz, Szwed, 2022). Prof. Beaverstock emphasizes that simulation modeling enables a manufacturing process to be constructed in a proper environment to reflect both the machine setup, the number of workers and the duration of each operation. (Beaverstock et al., 2017). Simulation modeling is a set of procedures used to represent the improvements implemented in a real system. The solution details enable a virtual representation of the production process, and concurrently, verify the system's behavior under different scenarios. This enables the results of specific modifications to be predicted, processes to be optimized, and costs to be minimized. (Bangsow, 2016). Simulation models, created with the help of IT tools, accurately reflect the real systems in a computer environment. Simulation allows providing information about, for example, the physical constraints present in the process under study (Rostek, Wiśniewski, 2020). It is important to noted that simulation models are often applied to projects where obtaining a solution through traditional analytical methods or direct experimentation is impossible. Simulation modeling also plays a crucial role in ensuring the continuity of production processes. It allows to visualize and analyze the production process without disrupting its stability. For instance, it enables to conduct research without the necessity of stopping the production or reduce labor productivity, making simulation modeling a valuable tool for conducting research.

Most of the production processes implemented are affected by major or minor changes. The changes resulting from intentional efforts can be resolved as part of the organization's continuous improvement. While the changes resulting from non-intentional performance must be adequately prepared for by the enterprise. The disruption in production area is defined as a change in the properties of the objects of the production system or its inputs, not resulting from an intentional behavior, causing undesirable deviations of the flow of the processes of this system from the planned course (Lis, 1982). A related definition is provided by N. Sticker and G. Lanza, who define production disruptions as undesirable, unpredictable and unplanned occurrences that lead to significant deviations between the realized and planned flow of the process (Sticker, Lanza, 2014). A. Ingemannson and G.S. Rolmsjo highlight that disruptions are destabilizing factors in the production process, causing poor performance of the production system (Ingemannson, Rolmsjo, 2004). The research team led by Y. Kim draws attention not only to some differences in the process flow, but even the possibility of a significant obstruction or interruption (Kim, Chen, Linderman, 2015).

Depending on the type of disruption, the enterprise is obliged to take different actions. The main classification of disruptions is the distinction between external disruptions - related to factors located in the system's environment - and internal disruptions - related to factors occurring inside the enterprise (Wirkus, Maciagowski, 2011). Regarding the source of disturbances, we can identify: (1) upstream disruptions (problems with material and semifinished goods shipment, quality, delays), (2) internal disruptions (problems in the flow of information and operation of the control system, operator errors, machine and equipment failures), and (3) downstream disruptions (sudden orders, changes in orders, seasonality of orders) (Matson, McFarlane, 1998). The MASCADA organization emphasizes the nature of disruptions that occurred: (1) abrupt and gradual disruptions, (2) random and systematic disruptions, and (3) time, quality, and cost disruptions (MASCADA, 1997). On the other hand (Kalinowski, Knosala, 2003), classified disruptions in terms of the resulting effects from their occurrence: (1) operation disruptions - preventing the execution of a given operation, but not excluding the possibility of carrying out other operations assigned to a given stand, (2) machine disruptions - eliminating the entire production stand from operation (e.g., due to machine failures, (3) process disruptions - causing immediate or gradual shutdown of the entire process (e.g., in situations of detection of a technological process defect).

Vulnerability is a concept that is particularly commonly referred to in risk management. It refers to the exposure level of a given system, its sensitivity to threats, and its capacity to adapt (Adger, 2006). The literature emphasizes that vulnerability is the probability degree at which a system, subsystem, or component is expose to harm from both external and internal hazards (Turner et al., 2003). This approach is essential for production systems, where disruptions are classified as external and internal factors affecting the system. Vulnerability is characterized by four main components: exposure (the range of risks to the system), susceptibility (the predisposition of risk elements to hazards), lack of resilience, and hazards to determine the risk of unexpected events (Birkmann et al., 2013). How is it possible to measure a system's vulnerability to undesirable incidents or disruptions? Most significantly, the assessment should be based on the primary factors constraining a given system's ability to respond to hazards, rather than on their adverse effects (Costa, Kropp, 2013). The measurement of vulnerability should focus on more than just identifying the number of elements prone to disruption due to their exposure or lack of sufficient adaptive capacity (Willroth, Massmann, Wehrhahn, Revilla Diez, 2012). It is important to conduct research to measure the ability of different elements to adapt to the changed circumstances or to redistribute risks in the environment (Adger, 2006).

As part of the literature research, the Scopus database was analyzed in search of publications addressing the study of manufacturing companies' vulnerability to disruption using simulation modeling. The concept of vulnerability is strictly related to the fields of risk management (Liu et al., 2012) or cybersecurity (Awotunde et al., 2023; Conti, Donadel, Turrin, 2021). A significant number of studies also emerge on critical infrastructure management (Ani, He, Tiwari, 2017; Chaudhry, Yousaf, Khan, 2020). However, the vast majority of them address the vulnerability to external factors of the organization, especially disruptions causing natural disasters like floods, fires or earthquakes (Ouma, Tateishi, 2014; Shao et al., 2015). Publications frequently present research in the form of case studies, suggesting that the topic remains new and underexplored. In recent years, a notable increase in publications on supply chain management was noticed (Hassija et al., 2021; Das et al., 2022; Vafadarnikjoo et al., 2022). However, these studies tend to focus more on external factors influencing companies rather than on internal hazards. The research did not identify any publications directly addressing the vulnerability of manufacturing enterprises to disruptions through simulation modeling. In recent years, studies of the resilience of manufacturing enterprises to disruptions have been occurring, and the possibility of applying the simulation method is indicated in some papers. However, these studies are described in general terms and often do not refer to identifying specific disruptions or implementing procedures.

Accordingly, the paper's aim of using simulation modeling to study the vulnerability of manufacturing companies to disruptions was considered a new topic and recommended for extensive studies.

3. Research method

The literature survey conducted indicated a lack of studies on the use of simulation modeling in investigating the vulnerability of manufacturing enterprises. However, experience indicates that such an effort can be successfully undertaken for implemented production processes. A case study research method was chosen for this study due to several key characteristics. This approach allows for the analysis of the phenomenon within its natural context, focuses on a contemporary issue, provides an in-depth examination of the complexities involved, and aims to explore the subject thoroughly (Benbast, Goldstein, Mead, 1987). Case studies exert a significant influence on the development of management theory (Eisenhardt, 1989). By leading to the observation and research of the phenomenon relevant to science, case studies enable to conduct a reliable description of its performance, that is, to investigate the real environment (Czakon, Glinka, 2012; Jarvensivu, Tornroos, 2010). The case study methodology is strictly established and homogeneous (Goffin, Ahlstrom, Bianchi, 2019). Although the case study method is well described in the literature, the approach to case study design still differs and is adapted to the individual line of research (Beverland, Lindgreen, 2010). The standard research procedure using the case study method is shown in Figure 1.

In the presented study an exploratory case study was conducted. It focuses on the exploration of the little-known and barely recognized phenomena, which are still in the early stages of recognition (Ellram, 1996).

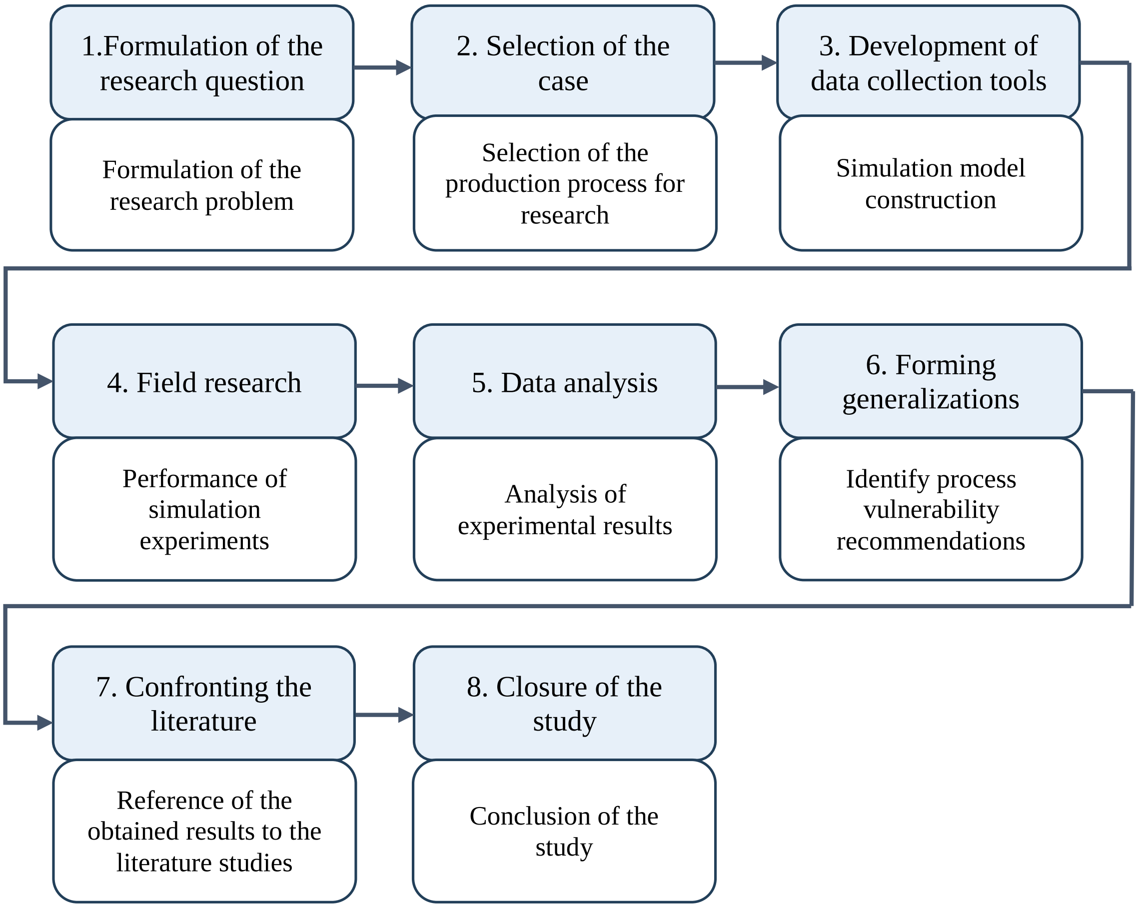

Figure 1. Applied research method.

Source: Czakon, 2006.

The implementation of the first five steps of the research methodology (formulation of research problem, selection of the production process, simulation model construction, performance of simulation experiments and analysis of experimental results) is presented in Section 4. The formulation of recommendations on the vulnerability of the process to disruption, reference of the obtained results to literature studies and conclusion of the study are presented in the discussion in Section 5.

4. Results

The subject under study was the production process conducted in the selected manufacturing company in the mechanical industry. The study was carried out in the form of a case study in according to the research methodology described in Section 3.

Formulation of the research problem

The research problem defined in the conducted study concerned the possibility of investigating the vulnerability of manufacturing enterprises using simulation modeling. According to the literature research performed, such a study has been conducted in a limited manner. Based on the experience of improving manufacturing processes with simulation modeling, it was decided to examine the applicability of simulation modeling tools in a different area.

Vulnerability refers to the susceptibility of a system to disruptions. In manufacturing enterprises, a distinction is made between external disruptions (caused by factors outside the organization) and internal disruptions (caused by factors originating within the organization). The research focuses on the study of selected internal disruptions of a manufacturing enterprise.

The selection was determined by factors that can be analyzed using simulation modeling software.

Selection of the production process for research

One of the core manufacturing processes implemented in the manufacturing enterprise under study was selected. The selection was performed on the basis of the criteria shown in Table 1.

Table 1.
Criteria for enterprise selection for case study research

Criteria	Characteristics
Business process type	Production process.
The implementation period of the process in the company	Process implemented at the company for at least 2 years; it is important to include a stabilized process in the study, after the first improvements have been made.
Cycle time	Short cycle time, less than 1 day, to ensure short simulation time.
Type of operations performed	Operations performed automatically and manually to maximize the number of disruptions possible for research.
Data availability	Ability to collect detailed process data (including measurements).

Source: own study.

The process is composed of thirteen workstations - five workstations require manual operation by an employee, the remaining eight are operated in automatic mode - and one belt feeder. The characteristics for the individual workstations are shown in Table 2.

Table 2.
Characteristics of the implemented process

Workstation	M1	M2	M3	M4	M5	M6	M7
Operation time [s]	180	78	97	121	80	72	117
Availability [%]	98	97	96	99	98	94	96
Operating mode	manual	automatic	automatic	automatic	automatic	manual	automatic
Workstation	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**C**
Operation time [s]	84	63	78	109	190	40	9
Availability [%]	95	93	99	97	96	98	99
Operating mode	automatic	automatic	automatic	manual	manual	manual	automatic

Source: own study.

At three workstations (M3, M6, M8), operations are carried out simultaneously on several semi-products at the same time. The enterprise operates in two-shift mode, with every work shift lasting 8 hours with two breaks of 15 minutes. In the production area, the company employs five workers, who are mostly assigned to operations on a particular machine.

Simulation model construction

The simulation model was built in Tecnomatix Plant Simulation (ver. 15.0.4) software. The model is composed of nearly 30 objects, derived from libraries such as Material Flow, Resources, Tools and User Interface. The used objects represent the operations performed on each workstation. The built digital model was validated, and the obtained results confirmed the correctness of its construction. The simulation was carried out for five working days and the result was 1171 manufactured products. The visualization of the production process in simulation model is shown in Figure 2.

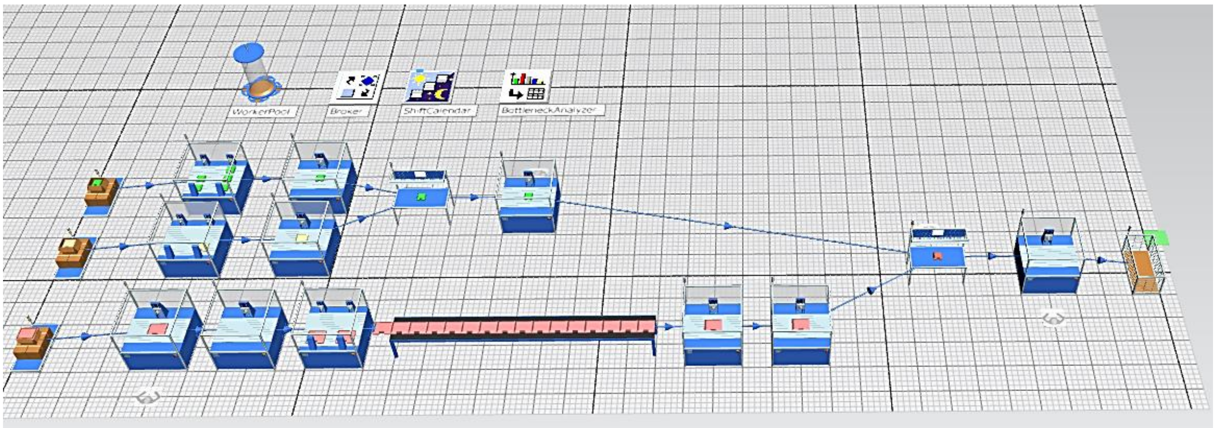

Figure 2. Visualization of the simulation model constructed.

Source: own study.

Performance of simulation experiments and analysis of results

The successful performance of simulation experiments is based on the definition of the assumptions and the purpose of the performed operations. The purpose of the conducted experiments is to investigate the vulnerability of the production process to selected disturbances. Making a selection of factors that are particularly relevant to the disruption of the process, and possibly to be mapped in the built digital model, is essential for the presented research. Table 3 presents the main assumptions of factors selected.

Table 3.
Assumptions for the selection of disruptions to be investigated

Assumptions	Detailed characteristics
Selection of the disruption classification	Classification of disruptions into external and internal. Considering the purpose of the research conducted, the study focused on the investigation of internal disturbances, which include: — in the area of equipment (machines/equipment failure, inappropriate maintenance of machines/equipment, inappropriate exploitation of machines/equipment, lack of appropriate equipment), — in the area of labor (high worker absence, decreased worker efficiency, unskilled workers, operators' errors, disorganization of work), — in the area of material resources (lack of materials, incorrect quality of materials, delayed deliveries, disruptions in material flow), — in the area of information resources (data loss, information system failure, cyberattacks, failure in the ICT system, incorrect internal communications), — in the area of energy resources (power outages, reduction of electricity supply, voltage fluctuations), — in the area of financial resources (disrupted cash flow, delays in repayment of debts, sudden changes in exchange rates).
Selection of factors that might be represented in a digital model	Disturbances possible to study within the simulation model constructed: — machines/equipment failure, inappropriate maintenance of machines/equipment, lack of appropriate equipment, — high worker absence, decreased worker efficiency, operators' errors, disorganization of work, — lack of materials, incorrect quality of materials, delayed deliveries, disruptions in material flow, — information system failure, incorrect internal communications, — power outages, reduction of electricity supply.
Selection of three disruptions from different areas, especially relevant to the process	1. Equipment area – machines/equipment failure. 2. Labor area – decreased worker efficiency. 3. Material resource area – delayed deliveries.

Source: own study.

Literature research indicates that the original sources of disruptions should be investigated in the unreliability of the primary factors of production, such as labor resources, work objects and employees. Based on the assumptions presented, it was decided to conduct a study for three selected disruptions (machine/equipment failure, decreased worker efficiency, delayed delivery). Simulation experiments were performed in a structured manner, according to the adopted procedure. Each experiment was characterized by features such as: (1) the purpose of the experiment, (2) the determination of the explanatory variables, (3) the determination of the values the explanatory variable adopts, (4) the determination of the response variable, and (5) the tools used to conduct the study. Detailed information about each of the experiments conducted is provided in Table 4.

Table 4.
Assumptions of the conducted experiments

Assumptions	Experiment 1	Experiment 2	Experiment 3
Purpose of the experiment	Verification of the impact of the machine failure on the process	Verification of the impact of employee efficiency on the process	Verification of the impact of delivery delay on the process flow
Determination of the explanatory variables	Availability of the M12 machine (process bottleneck)	Employee efficiency	Time of the delivery of materials to the M1 workstation
Determination of the values the explanatory variable adopts	Range 78-96 [%] (3 [%] increment)	Range 80-95 [%] (3 [%] increment)	Range 170-410 [s] (40 [s] increment)
Determination of the response variables	Number of manufactured products	Number of manufactured products	Number of manufactured products
Tool used to conduct the research	ExperimentManager	Manual simulation	ExperimentManager

Source: own study.

Experiment 1 examined the impact of the machine failure on process efficiency. The investigation was performed on workstation M12 - on which the operation of assembling semi-finished products, supplied from machines M5 and M11, is performed. The workstation was chosen for the experiment because it is the bottleneck of the process. The change in the value of the parameters at other workstations (outside the bottleneck) would not result in a variation in the value of the explanatory variable. Experiment 2 examined the impact of worker efficiency on the process efficiency. Workers perform randomly selected operations within a given production area. The change in efficiency applied to all employees (on both work shifts). Experiment 3 examined the impact of repeated supply delay on the process efficiency. The study was conducted on the supply source for the M1 workstation - because it indirectly affects the process bottleneck. The different ranges of value variations were determined on the data collected from the company. The measure investigated in all experiments was the process efficiency, determined by the quantity of products manufactured. The results derived from the experiments are shown in Table 5.

Table 5.
Results of the conducted experiments

Step of the research	Experiment 1		Experiment 2		Experiment 3	
	Value of the variable [%]	Research result [pc]	Value of the variable [%]	Research result [pc]	Value of the variable [s]	Research result [pc]
Simulation 1 (baseline)	96	1171	95	1171	170	1171
Simulation 2	93	1136	92	1136	210	1171
Simulation 3	90	1098	89	1096	250	1159
Simulation 4	87	1068	86	1063	290	1132
Simulation 5	84	1029	83	1026	330	1109
Simulation 6	81	992	80	987	370	1085
Simulation 7	78	957			410	980

Source: own study.

The experiments show that the analyzed production process is vulnerable to all factors leading to a disruption of the process. However, the strength of the impact varies depending on the disruption. The analyzed process is susceptible to machine failure at the M12 workstation, as already in the first simulation a decrease in the number of manufactured products can be observed (by about 3%). A similar trend occurs in the following simulations, reaching the greatest decrease (about 4% between simulation 5 and simulation 6). A similar susceptibility of the process occurs with a decreasing worker efficiency, where a marginal modification of the value results in a corresponding difference in the process efficiency - by 3-4% on average between following simulations. The delayed deliveries, on the other hand, revealed a varied impact on the process. The initial variation in the delivery of materials did not affect the level of capacity utilization. However, extending the delay time in the following simulations increasingly affected the process - achieving a reduction of nearly 10% in the quantity of products manufactured between simulation 6 and simulation 7.

5. Discussion

The literature analysis indicates that the primary sources of disruptions should be searched for in the unreliability of the basic factors of production, such as means of labor, work objects and workers (Lis, 1982). The research conducted focused on three main factors such as the failure of the machine used in the implementation of the process (Experiment 1), the efficiency of workers in the production area (Experiment 2) and the delay in the delivery of materials to the workstation (Experiment 3).

The second experiment, which examined the influence of a worker efficiency change on the process efficiency, showed the most significant impact on the production process under study. A minimal change in employee efficiency causes significant disruption to the enterprise. Therefore, the company is recommended to take efforts to adequately protect the process from possible negative consequences. It is particularly important to conduct systematic internal and external training for employees - in the area of assigned production operations. Employee efficiency is characterized by a downward trend, so reactions should be taken at the first symptoms.

The study also investigated the vulnerability of the process to the failure frequency of the machines used. Particularly important is the failure of the bottleneck of the production process, since the throughput of the bottleneck defines the throughput of the entire process (Goldratt, 2004). Even the lowest throughput constraint (for example, in the form of lower machine availability) will reduce the amount of products manufactured. Therefore, the machines should be systematically serviced and maintained to detect defects at an early stage. Employees should react at the first sighting of process anomalies in order to respond to the arising problem as soon as possible. For other workstations, a machine availability variation, at least to some extent, would not significantly affect the process. In the future vulnerability studies, selecting the bottleneck of the process when studying the impact of machine failures is advisable. This approach eliminates the possibility of a false negative vulnerability result.

A minimal increase in the delivery time of materials to the M1 workstation does not adversely affect the process. The delivery time variations within a specific range are acceptable to the company and do not require an immediate response. However, if there is a significant increase in delivery time—beyond 40%—the process becomes responsive to the modifications made. The analysis of the results indicates that as the magnitude of the delivery delay increases, the negative impact on the process under study significantly increases - this tendency is initially minor, and then significantly increases during the execution of the sixth experiment. Therefore, initially, the enterprise may take no action in response to the disruption noticed. However, observing a further increase in the delay between deliveries to the workstation, the situation will require an appropriate response. As a recommendation to the enterprise, it might be suggested to establish a buffer before M1 workstation, or to investigate operations at the component supplier to identify the problems and improve the implemented operations.

6. Conclusions

Simulation modeling can be applied to study the vulnerability of production processes implemented in the enterprise to disruption. Currently, there is a lack of the papers in this research area. However, with the growing impact of Industry 4.0 technology and the growing importance of enterprise resilience, the number of studies conducted will increase. Such studies provide potential practical benefits for the enterprise, especially in supporting the decision-making process. Simulation modeling provides a powerful tool for conducting analysis and research, enabling the right business decisions without disturbing the system in a real environment. As part of the presented paper, the results of a vulnerability study for typical disruptions occurring in the enterprise are presented. The direction of further work should be an attempt to identify the scope of the application of simulation modeling to the study of vulnerability, both in terms of the disruptions that can be investigated, as well as the identification of specific factors, in order to conduct detailed studies.

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