

BATCH PRODUCTION: AN EXPLORATION OF THE SENSITIVITY WITHIN THE PRODUCTION PROCESS

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Purpose: In recent years, manufacturing companies have been facing an increasing number of disruptions to production systems, as well as broader effects. This paper discusses the impact of disruptions on the batch production process.

Design/methodology/approach: This research paper aims to explore methods for analyzing the production process's sensitivity to disruptions without disrupting system functioning. The focus of the research is on batch production, specifically rhythmic production. The following research methods were employed at each stage of the study: (1) Data collection stage – continuous observation and interviews with employees; (2) Research stage – simulation modeling and simulation experiments; (3) Results analysis stage – rhythmicity index analysis. The manufacturing process at a company that produces valves for the water and sewage industry was studied. A case study was conducted to investigate the process sensitivity to selected internal disruptions identified at the company. The research was performed using Tecnomatix Plant Simulation software. Experiments were conducted on four selected disruptions, including limited station throughput, low employee efficiency, high machine failure rate, and quality defects in delivered materials.

Findings: The conducted research has shown that the rhythmicity index can be used to assess a process's sensitivity to internal disturbances. It is worth noting that it is possible to examine both positive and negative rhythmicity index indices, allowing for the assessment of the impact (both positive and negative) of a given parameter on the analyzed process.

Research limitations/implications: The study investigated specific internal disruptions in batch production processes, focusing on a selected manufacturing process for devices used in the water and wastewater industry. The conclusions derived from this research can be applied to manufacturing companies across various sectors.

Practical implications: Simulation modeling enables the sensitivity of the production process to disruptions to be examined. The proposed rhythmicity index provides a detailed analysis of the impact of a given disturbance on the process, divided into positive and negative impact analysis. Research has demonstrated that the effects of a disruption differ when viewed from these two perspectives. This method of assessing the sensitivity of the production process is essential for effective decision-making.

Originality/value: A review of the literature indicates limited research on the analysis of internal disruptions affecting the production process. No studies have specifically addressed batch production in this context. One key advantage of this approach is the ability to assess the

sensitivity of production processes using the rhythmicity index. This offers significant convenience to manufacturing companies when deciding which disruptions are critical to the production process.

Keywords: batch production, simulation modeling, sensitivity, disruption, rhythmicity index.

Category of the paper: research paper.

1. Introduction

In today's rapidly changing markets and increasingly complex manufacturing environments, the ability to respond effectively to disruptions has become a matter of strategic importance. Disruptions are no longer viewed merely as undesirable incidents but as valuable sources of insight into system vulnerabilities and opportunities for improvement (Klumpp, 2017).

Manufacturing companies experience various disruptions that can be classified into two primary categories: internal disruptions, arising from factors within the organization, and external disruptions, related to the organization's environment (Wirkus, Maciagowski, 2011). External disruptions have been extensively studied in the literature, with a noticeable increase in analyses following the COVID-19 pandemic and the war in Ukraine. In contrast, internal disruptions have received significantly less attention. However, organizations have substantial influence over these internal factors through careful observation, research, and the implementation of appropriate measures. It is important to acknowledge that disruptions in the production process are inevitable and can arise from various aspects of process execution.

The study focused on batch production, characterized by a certain level of process repeatability (production order schedule, range of possible operations), which enables the prediction of disruptions and helps mitigate their impact. However, batch production also presents challenges, particularly the need to adapt to changes in product ranges and irregularities in material deliveries—such as variations in types, quantities, and delivery dates. Due to frequent disruptions during the production process, it is challenging to identify which are most critical to maintaining production continuity. Therefore, it is essential to correctly identify and classify these disruptions based on their expected impact and scale. This impact is often determined by the vulnerability of the process under study to disruptions (Burggräf, Dannapfel, Hahn, Schulz-Isenbeck, 2022) and related factors, including its sensitivity.

Manufacturing companies face the challenge of measuring how disruptions impact the stability of their processes. While various risk assessment and scenario methods can be applied, finding a universal indicator remains difficult. Due to the study's limitation to batch production, it was decided to investigate the use of a rhythmicity index. This index evaluates production stability by quantifying both positive and negative deviations from an established production standard.

A systematic analysis of disruptions enables a more effective and efficient response to challenges in production processes. This approach also enhances an organization's flexibility by adapting to the actual conditions of process performance. Furthermore, it should be one of the essential elements of a manufacturing company's strategy, integrating technical, organizational, and human factors towards building a culture of continuous improvement.

The purpose of the presented manuscript is to explore the possibility of analyzing the sensitivity of the production process to disruptions without disturbing the functioning of the system. Section 2 presents the results of literature research on batch production characteristics, process sensitivity characteristics, and the feasibility of simulation modeling. The research method is described in Section 3. Section 4 features a case study demonstrating the process sensitivity investigations using the rhythmicity index in a chosen manufacturing process for devices used in the water and wastewater industry. 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 on the use of simulation modeling in the sensitivity analysis of manufacturing processes

Batch production is a type of production in which the number of products manufactured with a given machine setting is high (at least several dozen), and their diversity is low. There are several types of serial production: (1) non-repetitive production and (2) repetitive production (within a repetition period) – these periods may be the same or variable. In terms of production rhythmicity, the distinction between rhythmic and non-rhythmic production is used. The following section of the paper focuses on the characteristics of batch, repetitive production (Lis, 1982).

Batch (repetitive) production can be characterized in terms of six criteria: (1) tooling, (2) employee qualifications, (3) space planning, (4) materials, (5) planning, and (6) transportation. The tooling must ensure the unification of the operations performed, regardless of the employee's level of competence. The workstations are equipped with universal tools to a small extent, and the work is performed using specialized tools (often taken from the toolroom), made to order for the production of a given series of products. Employees involved in technological processes usually have average qualifications but are distinguished by their comprehensive knowledge of the operations they perform. Significantly higher qualifications are required for service personnel (toolroom/machine and equipment maintenance). Workstations are most often grouped into modular cell (multi-item) or production lines, where the assignment of operations changes rhythmically. The range of materials is adapted to the planned production tasks. Planning ensures the repeatability of operations at individual

workstations. Therefore, once the production cycle plan has been implemented, it is carried out in a repeatable manner, possibly incorporating adjustments due to delays in the work performed. Transport is carried out by using universal tools, but more often specialized tools dedicated to a given production process (Chambers, 2010).

The literature also refers to the layout of workstations used in batch production. Chambers distinguishes between functional and cellular layouts (Chambers, 2010). The functional layout focuses on the functions performed by the company's resources, grouping resources with similar functionality. This promotes better utilization of the potential of the accumulated machines. The material flow path is determined in accordance with technological requirements, with the material adapted to the capabilities of the operation. As a result, the material flow is complex and challenging to control. This system is characterized by high flexibility in product range, but the degree of infrastructure utilization is low. In a cellular system, the appropriate resources for operation are selected and grouped into a given cell. This system guarantees higher throughput and fewer errors. However, for the company, a larger number of resources is required, and any changes to the selected system will be costly (Chambers, 2010). The characteristics of the systems presented correspond to the previously described division into production lines and modular cells.

Defining the sensitivity of production systems to threats can be quite challenging. It is very often associated with system vulnerability analysis. To clarify this concept, it is useful to reference definitions of sensitivity provided by established figures in risk management and business continuity management. Sensitivity is considered a key element of vulnerability, as it helps determine a system's predisposition to specific events (Birkman, Cardona, 2013). Al-Khudhairy et al. define sensitivity as the degree to which a system is exposed to hazards. This exposure is one of three indicators of vulnerability, along with the degree of loss and impact caused by a hazard and the degree of resilience (Al-Khudhairy, Axhausen, 2012). According to Turner et al., vulnerability refers to the system-environment interface. It indicates that sensitivity is the degree to which a system maintains its ability in response to internal and external environmental factors. This implies that sensitivity influences the extent to which a system can adapt to changing conditions (Turner, 2003). A similar approach is presented by Adger, who points out that sensitivity to hazards defines a system's vulnerability, understood as the level of exposure to undesirable events (Adger, 2006). McEntire offers a more detailed definition, describing sensitivity as the degree of risk—specifically, the extent to which a disruption can negatively affect the object or system under study (McEntire, 2011). The literature on the subject also introduces the concept of production process resilience, defined as a system's ability to absorb disruptions and reorganize in response to changes while maintaining its function, structure, identity, and responsiveness (IPCC, 2012). Resilience is understood as the potential of a specific system configuration to maintain its structure and functionality during threats, as well as its ability to reorganize and adapt (Lebel et al., 2006). The definitions provided indicate that sensitivity is a key aspect of a process's vulnerability to

disturbances, making it a more specific concept. Both sensitivity and vulnerability, of which sensitivity is a part, examine how a given disruption affects the process and assess how much the process deviates from its expected course. In contrast, resilience focuses on a company's ability to implement actions that enable the process to respond effectively to disruptions and quickly return to normal operation.

The literature review revealed limited research on the sensitivity of production processes to disruptions through simulation modelling. The research was conducted by searching the Scopus database for publications matching the specified search criteria. In the following stages of the study, the range of keywords entered became increasingly detailed to refine the analysis results. The results obtained in the subsequent steps of the study are presented in Table 1.

Table 1.
Results of literature review

Used keywords	Res. #1	Res. #2	Res. #3	Res. #4	Res. #5	Res. #6	Res. #7
Production / Manufacturing	⊕						
Production companies / Production enterprises / Manufacturing companies / Manufacturing enterprises /	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Production process / Manufacturing process		⊕	⊕	⊕	⊕	⊕	⊕
Sensitivity	⊕						
Sensitivity research / sensitivity study / sensitivity analysis		⊕	⊕	⊕	⊕	⊕	⊕
Simulation modeling / simulation modelling			⊕		⊕		
Batch production				⊕	⊕		
Production process sensitivity/ Manufacturing process sensitivity						⊕	
Process sensitivity							⊕
Results	2116	173	8	2	0	0	0

Source: own study.

The results indicate that research on the sensitivity of production processes is reported in scientific publications. However, a closer analysis of the manuscript revealed that the study focuses on the chemical properties of the substances used in the process or on the strength of the materials. On the other hand, narrowing the analysis to keywords such as mass production or simulation modeling significantly reduced the number of publications. However, the few identified publications highlight the growing opportunities to study the sensitivity or vulnerability of production processes to disruptions.

Sensitivity analysis plays a vital role in assessing the robustness of production systems and understanding how variations in key parameters influence operational performance. Studies have demonstrated that even minor fluctuations in factors such as processing times, machine availability, or capacity constraints can significantly affect scheduling efficiency and production outcomes (Yang, 2012; Dhand, Singla, 2016). Research in this field has employed both analytical and simulation-based approaches to evaluate the stability of production schedules and optimization models under uncertain conditions. Analytical methods, including the dual-phase simplex approach, enable determination of parameter ranges within which an optimal solution remains valid, while simulation models allow exploration of nonlinear relationships and interdependencies in complex manufacturing environments (Grznár et al., 2024). In recent years, the scope of sensitivity analysis in manufacturing has expanded beyond traditional scheduling problems to include evaluating system adaptability and structural flexibility. Burggräf, Dannapfel, Hahn and Schulz-Isenbeck (2022) applied local sensitivity analysis to assess how the definition and weighting of layout changeability metrics influence their reliability and interpretability in automated production evaluation. Similarly, Grznár et al. (2024) demonstrated that global and variance-based sensitivity methods applied to simulation models enhance understanding of system behavior under uncertainty and support the development of more resilient and adaptive production systems. Collectively, these studies highlight the strategic importance of sensitivity analysis as a foundation for process optimization, informed decision-making, and continuous improvement in modern manufacturing environments.

3. Methodology

A literature review found a lack of studies on the use of simulation modeling to analyze the sensitivity of production processes (in batch production) to disruptions. Accordingly, this paper applied the presented approach, using an exploratory case study as the research method. This method is used to study little-known and poorly defined phenomena that are in the early stages of recognition (Ellram, 1996). The research procedure used is presented in Figure 1.

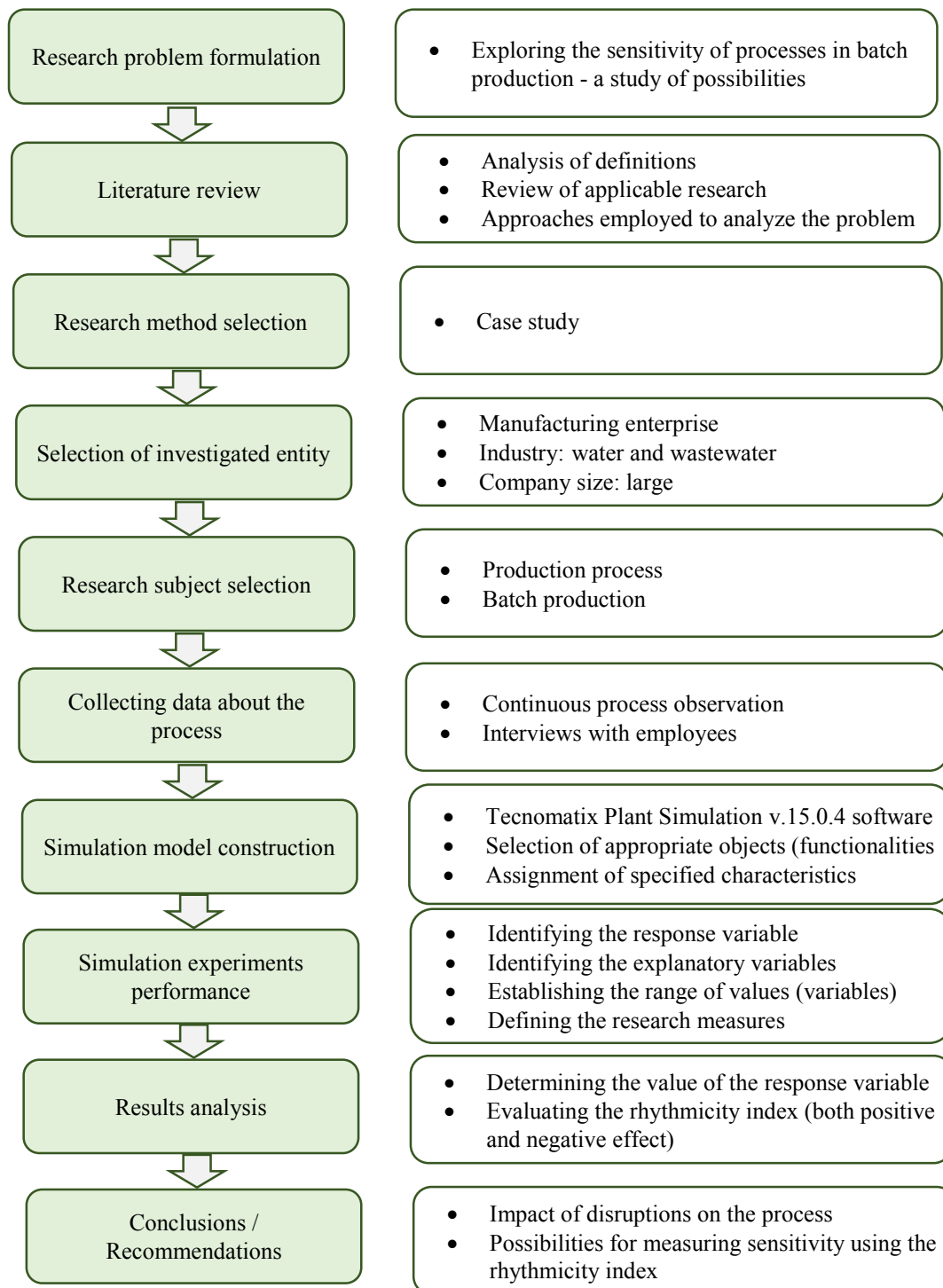


Figure 1. Research methodology.

Source: own study.

The initial stages of the procedure, namely the formulation of the research problem and the literature review, are presented in the “Literature review” section. The “Methodology” section presents the research method employed and describes its selection. The “Results” section characterizes the production process under analysis, constructs a simulation model, and then conducts simulation experiments. The results analysis and recommendations for the studied process are presented in the “Discussion” section.

4. Results

The subject under study was the production process conducted in the selected manufacturing company in the water and wastewater industry. The study was carried out in the form of a case study.

The research problem addressed in the study concerned the feasibility of investigating the sensitivity of manufacturing processes through simulation modeling. According to the literature review, such a study has been conducted only in a limited manner. Attempts to address the topic of process vulnerability to disruptions have been made in (Smagowicz, 2024). This study focuses on batch production, which is characterized by unique data characteristics, and examines sensitivity analysis as a measure of vulnerability.

Section 2 defines sensitivity as the extent to which a disturbance affects the object under study. In manufacturing companies, it's important to differentiate between external disruptions—those caused by factors outside the organization—and internal disruptions, which originate from within the organization. This research examines specific internal disruptions experienced by manufacturing enterprises.

Characteristic of the process selected for study

The study focused on a specific stage in valve production for the water and wastewater industry. This stage consists of three parts: washing semi-finished products (M), verifying their dimensions (W), and conducting leak tests (T). Detailed characteristics of the selected process, the subject of the study, are presented in Table 2.

Table 2.*Characteristics of the process selected for study*

Characteristics	Description
Type of production	Batch (repetitive) production.
Form of production organization	Line production (rhythmic).
Type of equipment	Universal tooling – to a small extent; specialized tooling – to a large extent.
Employee qualifications	Average level of employee competence; some employees specialized in specific tasks.
Transport	Transport performed manually or using dedicated equipment.
Type of operations performed	Operations performed automatically and manually to maximize the number of disruptions possible for research.
Capacity constraints	The bottleneck of the process at the ‘Housing cleaning’ station by using an advanced BottleneckAnalyzer tool.
Working hours	The production process is performed in two shifts. Each shift lasts 8 hours. There are two breaks of 5 minutes each and one break of 15 minutes.
Number of employees	There are 2 employees in the examined area who move freely around workstations.
Standardization of processes within the company	The production process under review has been implemented at the company for 5 years.

Source: own study.

The process is composed of 24 workstations – 21 workstations require manual operation by an employee; the remaining 3 are operated in automatic mode. The production parameters for the individual workstations are shown in Table 3.

Table 3.*Characteristics of the implemented process*

Name	Operation	Average operation time [s]	Availability [%]	MTTR [s]	Operating mode
M1	Loading of housings	270	90	60	Manual
M2	Layout check	30	90	60	Manual
M3	Basket insertion	15	90	60	Manual
M4	Basket retrieval	15	90	60	Manual
M5	Washing and rinsing	900	90	60	Manual
M6	Drying	300	90	60	Manual
M7	Additional drying	-	-	-	Automatic
M8	Receiving housings from conveyor	15	90	60	Manual
M9	Housing cleaning	90	86	90	Manual
M10	Housing positioning	30	86	60	Manual
M11	Preliminary operation WP1	45	86	60	Manual
M12	Measurement check	15	86	60	Manual
M13	Housing unloading	15	86	60	Manual
M14	Report generation	-	-	-	Automatic
M15	Setting aside defective housings	8	86	60	Manual
M16	Passing correct housings	8	86	60	Manual
M17	Placement in holder	30	80	120	Manual
M18	Device sealing	90	80	120	Manual
M19	Table positioning and rotation	30	80	120	Manual
M20	Operation T1	45	80	120	Manual

Cont. table 3.

M21	Transition to stage T1	-	-	-	Automatic
M22	Transport to assembly	15	80	120	Manual
M23	Transport of parts	15	80	120	Manual
M24	Transport of defective parts	15	80	120	Manual

Source: own study.

The analysis focused on a selected production area, where significant productivity decreases and frequent disruptions were observed, resulting from irregularities in component cleaning quality, metrological measurements, and housing strength tests.

Simulation model development

The simulation model was built using Tecnomatix Plant Simulation (ver. 15.0.4). The model is composed of 38 objects, assigned to libraries such as Material Flow, Resources, Tools, and User Interface. The used objects represent the operations performed on each workstation. The model was validated. The model results confirmed the correctness of the constructed model. The visualization of the production process in the simulation model is shown in Figure 2.

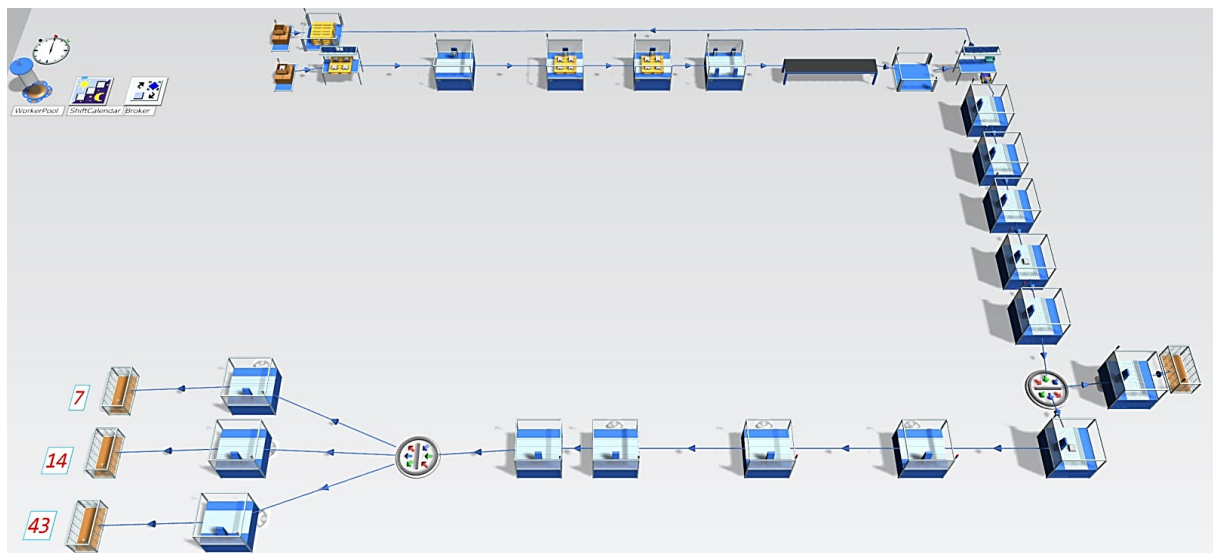


Figure 2. Visualization of the simulation model constructed.

Source: own study.

The simulation was carried out for 1 working day, and the result was 64 manufactured products – 43 products were approved for correct manufacturing, 7 products were specified as spare parts, and 4 products were identified as defective. To conduct further research on the impact of disruptions on process execution, a process bottleneck was identified using the advanced BottleneckAnalyzer tool integrated into Tecnomatix Plant Simulation. The results indicated a bottleneck at station M9 - these findings were confirmed by the station's workload and participant observation conducted in the production area under study. Long execution times at workstations M5 and M6 suggest a possible bottleneck. However, work at these stations

involves several semi-finished products simultaneously, indicating that station M9 is the limiting factor in the process's throughput.

Disruptions identification

A production disruption refers to unintended changes in the properties of production system objects, leading to undesirable deviations from the planned sequence. The study divides production disruptions according to the area in which they are observed. Table 4 presents the main production disruptions identified for batch production. This production is performed in a line production (rhythmic) form.

Table 4.
List of disruptions occurring in batch production

Area of occurrence	Type of disruption
Supply	• Delays in workstation deliveries • Quality defects in delivered materials/semi-finished products • Damage to materials/semi-finished products during transport • Delivery of incorrect materials/semi-finished products • Lack of availability of key components • Incorrect order specifications • Inappropriate safety stock management
Production	• Unstable operation of machines/equipment, leading to increasing operation times • Problems with maintaining machine operating parameters (equipment calibration) • Incorrect execution of operations • High frequency of changeovers • High machine failure rate • Lack/Damage of tooling • Limited throughput of workstations • Increase the cost of resources used • Inappropriate planning of the sequence of operations • Low quality of technical supervision • Lack of standardisation of work activities
Employees	• Insufficient number of employees • Low employee efficiency • Overloading of employees with tasks • Low/inadequate employee qualifications • Conflicts in interpersonal relations • High staff turnover • Lack of motivation/ commitment • Failure to comply with health and safety rules
Storage	• Lack of permanent storage areas for materials/semi-finished products • Lack of local warehouses at workstations • Frequent movement of materials/semi-finished products around storage locations • Excessive production inventory • Damage to materials/semi-finished products during storage • Incorrect labelling or marking of batches • Inappropriate storage conditions (e.g. temperature, humidity)
Transport	• Faulty transport equipment • Long transport routes around workstations • Inappropriate organisation of material flow • Lack of internal transport resources • Interruptions in the material flow (congestion, downtime)

Cont. table 4.

Supporting processes	• Incorrect control of tasks being performed • Variability of production plans • Incorrect production order • Incorrect environmental conditions • Incorrect batch marking • Incorrect production planning/scheduling • Changes in norms/standards/regulations • Lack of up-to-date technical instructions • Inconsistency between production planning and implementation
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Source: own study based on Gaschi-Uciecha, 2015, pp. 136-139.

The identified disruptions are closely related to the nature of batch production, which, on the one hand, has the characteristics of mass production with an organized and repeatable (to a certain extent) flow. Therefore, the selected disruptions significantly impact the implementation of the production plan. For example, a machine failure causes downtime because it is not possible to quickly transfer the order to another workstation, as would be the case in unit production or in a specific technological cell, with redirection of operations to another available machine.

On the other hand, the flow is not constant, and the production of a given batch lasts for a limited time, after which the range of manufactured components changes. This means, among other things, that employees must have the appropriate skills to adapt to changes in the range of manufactured products and that it is difficult to quickly replace one employee with another.

Conducting the study

The evaluation of the course of batch and repetitive production can be based on a range of metrics. The choice of metric depends on the objectives set during the design or investigation of the system and on the feasibility of performing appropriate measurements or calculations. Natural metrics are always of fundamental significance, although their direct use is difficult due to the diversity of the subject matter. In terms of the research, it is crucial to determine the sensitivity of the production process to disturbances, i.e., the degree to which a given factor influences the planned course of the process. The analysis will be based on the measurement of the production rhythmicity index. Production rhythmicity can be measured in two ways: (1) by comparing actual production performance with plan assumptions, and (2) by comparing actual production performance records in the analyzed time intervals. In the further part of the study, it was decided to measure the rhythmicity index, which allows for the examination of deviations in production volume from the planned volume, thereby enabling the analysis of the stability, consistency, and regularity of the production plan's implementation. The rhythmicity index K accounts for both positive and negative deviations from the planned production plan. It is defined as the sum of the positive (K_d) and negative (K_n) deviation indices:

$$K = K_d + K_u \quad (1)$$

The partial factors are calculated according to the following formulae:

$$K_d = \frac{\sum P_{fi}^r}{\sum P_{pi}^r} - 1, K_u = 1 - \frac{\sum P_{fi}^r}{\sum P_{pi}^r} \quad (2)$$

where:

P_{fi}^r – actual production volume in the analysed time interval,

P_{pi}^r – planned production volume in the same interval.

The summation in the above formulas includes, respectively:

- in the case of K_d – intervals in which positive deviations occurred (production exceeded the plan),
- in the case of K_u – intervals in which negative deviations occurred (production was lower than planned).

A K value > 0 indicates the occurrence of variances and deviations in the implementation of the analyzed production process.

Four key process disruptions were selected for further analysis in the study. These include: (1) limited throughput of the M9 station identified as a process bottleneck, (2) low employee efficiency, (3) high failure rate of the M9 workstation, and (4) the occurrence of quality defects in the delivered materials, which delays the start of the process. For each disruption, the main characteristics of the study were determined, including the initial value of the explanatory variable, the range of change in the explanatory variable, and the measured values (the response variable). It should be noted that the process sensitivity study took into account changes that had negative and positive effects on the value of the response variable – the number of products manufactured. A detailed summary of the parameters is presented in Table 5.

Table 5

List of characteristics of disruptions subject to examination

Disruption	Characteristic	Range of examined values	Measured value
Limited throughput of M9 workstation M9	Operation time – 90 seconds	Range: 75-110 [s] (12 [s] increment)	Number of manufactured products
Low employee efficiency	Employee efficiency – 80%	Range: 60-100% (4 [%] increment)	Number of manufactured products
High failure rate of the M9 workstation	Availability level – 86%	Range: 71-100% (3 [%] increment)	Number of manufactured products
Quality defects in delivered materials	Operation time – 270 seconds	Range: 210-330 [s] (12 [s] increment)	Number of manufactured products

Source: own study.

Performance of simulation experiments and analysis of results

The results obtained in the experiments are presented in Table 6. For each disruption examined, the explanatory variable and response variable values are presented. It should be noted that 40 observations were made in each experiment (to obtain reliable results for the number of manufactured products, taking into account the assumed percentage availability of machines and the introduced failure rates).

Table 6.
Summary of experimental results

No.	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11
Disruption #1											
Explanatory variable	110	106	102	98	94	90	86	82	78	74	70
Response variable	61	61	63	63	64	64	65	67	68	68	70
Disruption #2											
Explanatory variable	60	64	68	72	76	80	84	88	92	96	100
Response variable	56	58	62	63	64	64	67	67	69	71	72
Disruption #3											
Explanatory variable	71	74	77	80	83	86	89	92	95	98	100
Response variable	61	62	62	63	63	64	65	65	66	68	68
Disruption #4											
Explanatory variable	330	318	306	294	282	270	258	246	234	222	210
Response variable	60	61	62	62	64	64	65	66	66	67	69

Cont. table 6.

Experiment 6 outlines the values of both the explanatory and response variables in their initial state, reflecting the current production process. The other experiments show results consistent with the values assumed for the individual characteristics listed in Table 5. Figure 3 illustrates these results by graphing the range of values that the response variable can take.

The results indicate that the widest range of values for the response variable occurs in disruption #2, which describes employee efficiency. Furthermore, in the study of selected disruptions, the impact of changes in the explanatory variable differs between positive and negative changes. The predominance of a positive effect is evident in three of the four disruptions studied, with the most significant difference observed in disruption #1, which characterizes the M9 workstation's throughput.

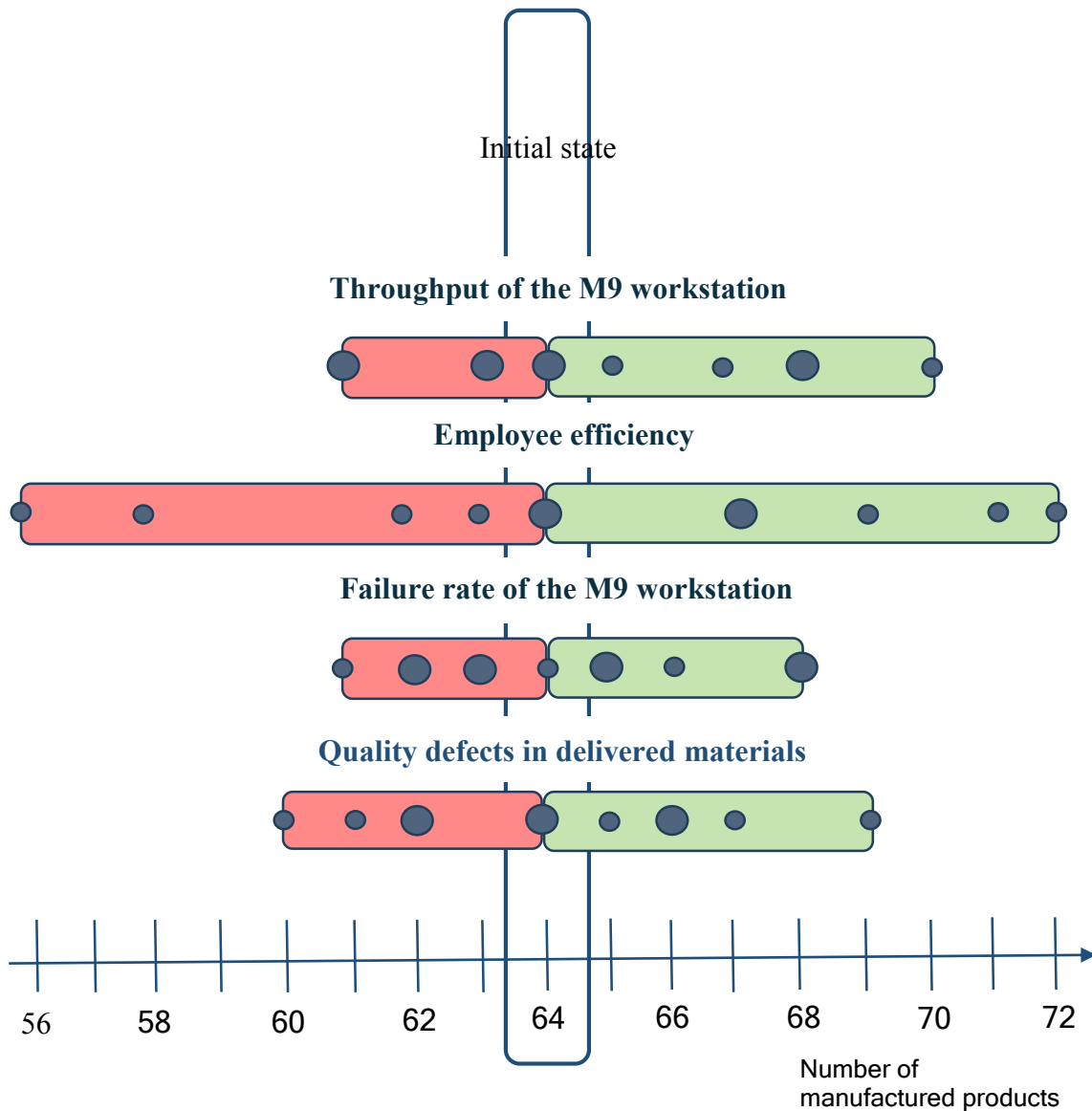


Figure 3. Results obtained in the experiments.

Source: own study.

Based on the results, a rhythmicity index was calculated for each disruption using formula (1). The measurements of rhythmicity show both positive and negative deviations for individual disruptions. The overall value of the rhythmicity index, which is the sum of these deviations, is summarized in Table 7.

Tabel 7.
Results of the rhythmicity index

	Disruption #1	Disruption #2	Disruption #3	Disruption #4
Rhythmicity index	0,08125	0,134375	0,065625	0,075

Source: own study.

The rhythmicity index values obtained for individual disruptions were above 0. This means that each disruption affects the implementation of the examined process. The highest index value was obtained for disruption #2, related to employee productivity. On the other hand, disruption #3, the failure rate of workstation M9, had the least influence on the process. These results confirm the conclusions drawn from the experiments.

5. Discussion

As part of the study, an analysis of four selected disruptions classified as disruptions occurring in batch production was carried out. The results of the experiments and the determined rhythmicity index indicate that the most significant impact on the production process is due to changes associated with disturbance #2, which concerns employee efficiency. This situation may arise when an employee is unsure how to execute tasks correctly during a change in the product assortment, which may require proper machine retooling or workstation preparation. Additionally, consistently performing a specific set of activities for a given batch of products can lead to fatigue from the monotony of the work. While employees may not have specialized knowledge, they possess a wide range of competencies related to the operations they perform. This scenario can increase stress and require more careful consideration when carrying out tasks, potentially extending the duration of operations to avoid mistakes. It should be noted that achieving the learning curve effect is challenging in batch production. The study of the process's sensitivity to the analyzed disruption was based on findings from participant observation. Additionally, employees' stress levels and job monotony were assessed on a broad scale. As a result, it is challenging to draw general conclusions from the findings, which represents a limitation of the study.

The results indicate that the response variable exhibits a similar range of positive and negative changes as the explanatory variable varies. However, the results indicate that the negative rhythmicity index takes higher values than the positive one.

A further disruption impacting the production process (to a lesser extent) was the throughput of workstation M9. This workstation was identified as a bottleneck in the process, which is why changes to the operational parameters affect the production result. An increase or decrease in throughput at the bottleneck directly impacts the throughput of the entire production process under study. Therefore, from a process-flow perspective, it is crucial to keep the M9 workstation continuously engaged in production tasks, as even a momentary downtime will reduce productivity. The experiments show that the range of changes in the response variable is smaller as the explanatory variable increases and larger as it decreases. The results were also confirmed during the study of the rhythmicity index: the negative rhythmicity index takes smaller values than the positive one.

Quality defects in the delivered materials were another disruption affecting the production process. The materials are strictly assigned to a given production order, leading to discrepancies in the quality, quantity, or type of materials ordered. At the same time, control of the delivered components may take longer due to changes in the product range, so the employee may not remember the specific delivery conditions. The results of the experiments indicate that the range of changes in the response variable is greater when the explanatory variable decreases. This phenomenon is also confirmed by the results of the rhythmicity index – the positive rhythmicity index is higher than the negative one.

The least impact on the process is caused by phenomena related to disruption #3, characterized by the failure rate of machine M9. In batch production, due to specialized tools and tooling changes depending on the products manufactured, more frequent failures may occur at the workstation. Equipment failure may also be caused by a lack of specialist knowledge of tool use, which increases the likelihood of damage or improper operation. The experiments indicate that the range of changes in the response variable is greater when the explanatory variable increases and smaller when it decreases. The results were also confirmed during analysis of the rhythmicity index - the positive rhythmicity index takes higher values than the negative one.

The rhythmicity index examined in the experiments proved essential for analyzing disruptions in production processes. It allows evaluation of the impact of unwanted actions and identification of which disruptions are significant for ensuring production continuity and achieving planned results. It is crucial to examine this factor when the range of parameters changes across the experiments is similar. The values of the positive and negative rhythmicity index enabled the determination of which changes (positive/negative) have a greater impact on the process being carried out.

Conclusions

The presented research examined the sensitivity of the production process as one element of studying the system's vulnerability to disruptions. The use of simulation modeling enabled the digital representation of the production area under study and the conduct of experiments without disrupting system performance. Additionally, it enables simultaneous answers to various questions, such as the type or extent of a given disruption's impact. In future research, the feasibility of verifying solutions that minimize the impact of disruptions on the system under study will be investigated.

The rhythmicity index utilized in this research is an important tool for assessing the effects of individual disruptions. A key advantage of this factor is its capability to analyze impacts separately, distinguishing between positive and negative deviations. This allows verification of

how each change affects the process and confirms that the impacts are not equal. By systematically monitoring the rhythmicity index, we can enhance the stability of production processes, ultimately increasing productivity. The objective of this paper was to verify the impact of specific disruptions on the production process under study. As part of future research, the authors plan to adopt a broader approach to analyzing the combined effects of multiple disruptions simultaneously to determine which concurrent disruptions reinforce one another and exacerbate the negative impact on the process. This would also enable verification of a potential cascade effect in the analyzed process, allowing for the implementation of appropriate preventive measures in the future.

The approach presented in this paper is constructive for decision-making in manufacturing companies and can be adapted by companies across any industry.

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