

Article

An Assortment–Quantity Optimization Problem in Printing Industry Using Simulation Modelling

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Abstract: This paper presents a method for assortment–quantity production scheduling in a printing company. The company uses specialized machinery to make prints on clothing. The method is based on a study of the company’s practical operations and the production technologies used. It involves the construction of simulation and optimization models of the process. The simulation models reflect the technical aspects of the production process and the business requirements. Optimization models provide solutions that balance product sales revenue with appropriate production schedules. On this basis, managers can make resource-balanced decisions on the implementation of selected production plans, taking into account the current economic conditions of the company. The experiments used the FlexSim simulation program (by FlexSim Software Products, Inc., Orem, UT 84097 USA; v. 20.1.3.1) and the OptQuest optimization package (embedded in FlexSim), resulting in a cost-effective solution in a short time. The proposed method, thanks to the optimization of the production program, provides savings in the use of materials for production, as well as water and energy savings in the production process. Thanks to the possibility of analyzing the process without interfering with it, provided by simulation modelling, the method practically eliminates the costs and time needed to prepare the execution of new production orders. This contributes to the sustainable development of the company and provides an opportunity to assess the impact of potential business decisions in the company prior to their implementation. The method has been directly applied in a company to improve its performance. The method is scalable and can be applied to problems of varying complexity and production systems of different types and sizes. This is especially true for small- and medium-sized companies that use discrete manufacturing in the textile, metal, and furniture industries.

Keywords: sustainable production; simulation modelling; optimization algorithms; integrated approach; printing industry



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1. Introduction

The market’s demands for individualized customer needs require companies to diversify their range of manufactured products. This necessitates that companies offer at least several assortment items. Moreover, companies must meet additional requirements in the area of operational management. This necessitates agile and sustainable decision making. From a management perspective, it is essential to focus on maintaining a consistent level of income and profits. Similarly, production process management should prioritize continuous improvement. This is especially important for small- and medium-sized enterprises, which often have limited resources and lack appropriate production management tools.

The printing industry is one of the sectors where these conditions are particularly crucial. Printing is a technology that deals with the processes of print production, including the development of templates for original texts and drawings and the printing of copies on various materials, usually based on individual customer orders. From a manufacturing

process perspective, printing can be defined by the technologies used, the characteristics of the products produced, and the applied manufacturing knowledge. The enterprise discussed in this article decided to standardize the production process due to the large number of possible solutions and the constant need to fulfil accepted orders. It was also assumed that the process could be improved by making changes to the way individual manufacturing operations were performed, particularly in their duration.

The enterprise faces a challenge in processing incoming orders in the order they are received. Currently, orders are processed with a delay of at least one day. The enterprise registers all orders placed on the previous day and then manually divides them according to the material used. The organization of production mentioned was time-consuming and did not meet the customer's needs for prompt delivery. The enterprise aims to maintain high customer satisfaction by offering the option of printing within a few hours of placing an order, even allowing for same-day collection at a designated point. This strategy is expected to provide a competitive advantage. Due to the current work organization, it is challenging to group individual printing orders based on lead time or printing material. It is necessary to ensure that this requirement is compatible with a production plan that maximizes profit and optimizes resource and energy consumption in the process.

After operating in the printing industry for over a year, the enterprise also considers the differentiation of prices for individual products as an equally important element. Currently, due to the instability of the process and the possibility of differentiation depending on the type of material used, the prices of all products offered are the same. However, research on the market suggests that customers expect price differentiation based on the materials used, due to the possibility of a shorter service life after purchase. The enterprise agrees with these recommendations, as research on potential technologies to be used indicates that reducing the duration of selected activities in the majority of implemented processes does not affect the final product quality.

This study aims to address the primary issue faced by the enterprise, which is the optimization of the assortment–quantity production program through the economic decision-making process. Simultaneously, this issue will be examined from two perspectives. In the first cross-section, the advantages of adjusting the parameters of the process to the materials used will be explored, particularly in relation to varying operation times for different materials. The second cross-section pertains to the possibility of price differentiation for individual products based on market research results. The enterprise is interested in acquiring and implementing methods to optimize the production plan. In the production area, the enterprise aims to improve the processes. In the initial state, the main constraint for the enterprise is the available working time of the machines and equipment located in the production area. The number of manufactured products is fixed, and all machines are fully dedicated to the production process under study. The presented research problem examines the possibility of using an additional machine in a parallel system. The aim of this study is to identify and eliminate the bottleneck in the process flow and examine its impact. Various machine utilization scenarios will be considered, including using the machine full time or dividing it for alternative processes. The operation of the machines is carried out by a fixed number of employees. Furthermore, this paper explores the potential of the proposed approach to address similar issues in other industries and enterprises.

Due to the disruptions in supply chains, the lack of repeatability of the material ordered from suppliers has become another variable in the process under consideration. The reduction in production in many European and global markets means that the materials previously used for the process are no longer available in sufficient quantities. Furthermore, when placing an order with a supplier, the enterprise is notified that if the specified material (with proven technological parameters, reproduced in the production process) is unavailable, only materials with similar parameters will be provided. Therefore, it was decided to operate under uncertain conditions regarding the composition and parameters of the supplied printing material. This situation introduced additional variability to the production process and requires further research beyond the scope of this publication.

The objective of the additional work is to select process parameters based on the supplied material's different parameters to optimize production volumes.

This paper presents a research approach that combines simulation modelling and mathematical programming to solve the addressed problem. A multi-stage method is proposed, starting with the identification of the problem's characteristics using techniques applied in production management. The problem is then analyzed in depth using the developed simulation model and by solving the mathematical programming task. Finally, this paper discusses the quantitative and qualitative results obtained from the proposed method. The novel approach of this paper is to comprehensively address the issues of business decision making at the level of production preparation, evaluation of production revenues and costs, and consumption of production resources, materials, and energy. The method integrates the possibility of assessing the course of the production process, outside the real system—based on the results of simulation experiments—and selecting optimal business decisions, using special mathematical programming problems solved by an optimization solver. To remain competitive in the market, it is essential to plan, control, and optimize production. According to Reta et al. [1], production planning and control (PPC) are necessary to produce high-quality goods at reasonable prices in a systematic manner. The optimization problem of product planning/mix of 49 textile and apparel industrial units was addressed using quantitative decision-making tools such as linear programming (LP), queuing models, critical path, and PERT methods. The LINGO 16.0/Matlab software was used to solve the model. The study's results indicate that the enterprise's profit can be improved by almost 50 percent. The authors tested eight hypotheses using data from 186 manufacturing firms and concluded that flexibility in manufacturing promotes efficiency and novelty-oriented business model designs, subsequently improving firm performance. Competitive intensity strengthens this effect, while demand heterogeneity weakens it [2]. Due to the complexity of production planning and scheduling, which involves unpredictable scenarios and overlapping requirements, metaheuristic algorithms are commonly used to solve this problem. These algorithms optimize product selection, production line assignment, and production sequencing to maximize overall company profit and customer satisfaction while satisfying given constraints. Kunapareddy et al. [3] presented an alternative approach to integrating production planning and scheduling using an improved genetic algorithm (GA) with variable chromosome length and parameters tuned by Taguchi experiment design.

The Theory of Constraints (TOC), based on the application of concepts of experimental science in organizations, was conceived by physicist Goldratt [4]. Naor et al. [5] concluded that the TOC is not only a formal operations management theory, but it also explains phenomena in many domains. Its concepts, relationships, and logic are relatively simple, and its innovative relationships and logic are fruitful for hypothesis development. The TOC is internally consistent, and its core statements are not self-verifying but are conceptually subject to disconfirmation. Furthermore, its theoretical statements have evolved to higher levels of abstraction. According to Pacheco et al.'s literature review [6], most of the literature on the TOC fails to establish a direct connection between each competitive dimension, its implications, and the set of TOC elements that enable performance improvements in the operations strategy. The TOC can help achieve continuous improvement and enhance organizational performance in various business contexts, such as healthcare, services, retail, and manufacturing. Pacheco et al. [7] demonstrated that the TOC and Lean are complementary approaches, with the individual gaps of each approach being balanced by the merits of the other.

The article explores the integration of Customer Relationship Management (CRM) and PPC approaches to improve the utilization of job shop manufacturing resources. In [8], a Simulated Annealing-based simulation optimization approach was proposed to make near-optimal strategy decisions in terms of machine-based dispatching rules and the number of equivalent sub-lots for products. The authors concluded that integrating the CRM and pay-per-click PPC approaches in job shop systems enables more effective resource utilization

for customer satisfaction. In their systematic literature review, Trost et al. [9] examined existing review papers that can be assigned to a sustainable PPC, focusing mainly on the scheduling level and the ecological dimension. The authors concluded that the papers strongly focus on the environmental dimension, particularly on energy and CO₂ emissions. They suggest that existing and future approaches at individual planning levels should be integrated to form holistic approaches across the entire PPC, addressing both ecological and social dimensions for a comprehensive sustainability approach.

Rossit et al. [10] conducted a study on the impact of Cyber-Physical Systems (CPSs) and Industry 4.0 technologies on scheduling problems. They reviewed the main contributions, distinguishing between works in which scheduling is part of a higher level of planning and those that address scheduling directly. Among the contributions on planning problems, they found that the main approaches are agent-based or simulation-based. When directly addressing scheduling, many contributions aim to generate rescheduling strategies using real-time information. It is important to note the need for benchmark instances and standard scenarios to compare and assess different contributions.

Dealing with a lack of homogeneity in the product (LHP) can make the management system more challenging. This can increase both the information volume and the uncertainty in the system. Improper handling of LHP can have negative effects on stocks, customer service levels, and supply chain efficiency. Production planning is essential for meeting customer requests in terms of ordered quantities, due dates, and homogeneity specifications [11]. The authors have proposed an analysis framework that characterizes the inherent uncertainty of LHPs based on the environment (sector and LHP characteristics), uncertainty, and modelling approaches. The study's conclusions suggest that certain sectors, such as agri-food and remanufacturing, consider LHP to be an inherent uncertainty in the planning process. However, in other sectors that are heavily affected by LHP, such as mining, wood, ceramic, textile, jewel, or leather, there is a lack of existing literature. It was concluded that the most widely used modelling approach is stochastic programming and the most common method for modelling uncertainty is the scenario-based approach. Additionally, it was found that current production planning models do not provide adequate decision support for modelling uncertainty in LHP characteristics.

Textile printing is the process of applying color to fibers in specific patterns or designs with sharp outlines. The color is applied to limited sections according to a specific design, making it similar to a dyeing operation. The color is bound to the fiber to protect against washing and crocking. Modern advances in printing technology, including machinery, thickening agents, and fixation methods, have made printing a significant process in textile coloration. The main distinction between textile dyeing and printing operations lies in the method of applying color to fabric. During the dyeing process, the fabric is immersed in a diluted solution of the dye bath and excess dye solution is squeezed out. In contrast, printing involves incorporating dyestuff into a thickener paste along with other auxiliaries. The resulting printing composite, which includes dyestuff, thickener, and other auxiliaries, is known as printing paste. After preparing a printing paste with the appropriate components, it is applied to the substrate using various techniques such as block printing, stamping, photographic printing, batik printing, screen printing, metography, machine printing, and spray printing. However, resist and discharge printing, as well as screen printing, are considered the most significant techniques in the industry [12].

Direct printing involves applying a dye-containing paste to specific areas of the fabric, followed by dyeing, steaming, and washing to remove any residue. Pigment printing, on the other hand, involves applying pigments and a cured binder film directly to the fabric surface, with no further treatment required. Direct printing and pigment printing are two methods of applying designs to textile fabrics. Direct printing is generally considered the more important of the two methods. Textile fabrics can be made from natural or artificial fibrous materials. Textile fibers are classified into two types: natural fibers (animal, mineral, vegetable) and cotton fibers [13]. Dyeing can be achieved through direct dyeing, dyeing with a soluble dye precursor, direct dyeing followed by chemical reaction of the dye, or

adhesion of the dye or pigment to the fiber surface. Dyeing can be either a discontinuous exhaust process or a continuous impregnation and fixation process. Post-dyeing treatments may include washing in detergent, treatment with chemicals, or application of simple finishing chemicals [14]. Additive Manufacturing, also known as 3D printing, is a technology used in various manufacturing sectors to create 3D objects by depositing successive layers of material. Spahiu et al. [15] studied the effect of 3D printing parameters on textile fabric. They changed the parameters and performed adhesion tests according to [16] and evaluated the results using [17].

To optimize production, it is recommended to model and simulate the production process to obtain the best solution based on the chosen criteria. The field of optimization simulation has seen significant development in recent years [18]. Various algorithms and simulation tools have been combined in different ways to tackle complex problems. In 1998, Åström et al. [19] presented a discussion on the historical development of modelling and simulation. In [20], the authors provide a critical review of three simulation techniques (system dynamic (SD), discrete-event simulation (DES), and agent-based simulation (ABS)) and their application to eight topics related to PPC: facility resource planning, capacity planning, order planning, process planning, scheduling, inventory management, production and process design, and purchasing and supply management. The authors aim to provide a clear and concise overview of these techniques and their potential applications in PPC. The study concluded that the SD application is commonly used for capacity planning, inventory management, and purchasing and supply management problems that require continuous-time simulation modeling. In contrast, DES and ABS applications are evenly distributed across PPC problems, with scheduling and process design problems having a high percentage of DES applications. Yang et al. [21] proposed a method for simulating PPC systems that visualizes the production process, compares Key Performance Indicators (KPIs), and optimizes PPC parameters under various uncertainties to mitigate potential risks and reduce time and effort. The study concluded that accounting for uncertainties enables companies to design more feasible production plans in less time and meet their production requirements more flexibly.

Kutin [22] proposed a simulation modelling method for assembly processes in digital manufacturing. The method considers the influence of intersections of main material flows of different products at the same workstations, interruptions in component supply, and unproductive time losses due to organizational or technical causes on the performance parameters of assembly processes. Missbauer [23] analyzed the production planning algorithms that iterate between the planning and scheduling levels, based on LP-simulation algorithms for order release planning. Based on the Theory of Constraints and complemented by the Simplex method, Onofrejova et al. [24] present a quantitative approach for management decisions developed through a simulation study and a what-if analysis with the aim of increasing productivity, optimizing production time, defining the optimal number of operators, achieving high utilization of machinery and equipment, and maximizing sales profit.

The simulation tools are based on mathematical models and algorithms. Emami et al. [25] integrated short- and medium-term decisions in manufacturing systems using a mathematical model for the production planning and scheduling problem. To maximize the gain, they presented a mixed-integer programming (MIP) model implemented in the software environment GAMS. An MIP-based optimization was formulated to select the best pollution control strategies for an oil refinery, given specific values of emission reduction targets. Binary variables were used to select the ideal pollution control strategies from three mitigation options, and the optimal set was chosen to meet a given emission reduction target with the minimum annual cost minus export revenue, while ensuring the satisfaction of demand levels and quality specifications [26].

Joseph et al. [27] conducted a simulation study to analyze the performance of a flexible manufacturing system (FMS) operating under different decision rules and production manager objectives. Based on their findings, the appropriate planning rule can be selected

for implementation. Schweiger et al. [28] systematically compared modelling paradigms for large-scale system modelling and simulation. Experts consider acausal modeling techniques suitable for large-scale systems modeling, while causal techniques are considered less suitable. Additionally, many experts noted that causal methods are already well developed with little room for improvement. The market offers a wide range of DES software used in industries such as manufacturing, logistics, warehousing, and packaging. According to a study by [29], the most popular simulation tools in alphabetical order are AnyLogic, Arena, AutoMod, Emulate3D, FlexSim, OPS, ProModel, SimEvents, and Witness. The study found that FlexSim was the best software of 2018, being the most capable, universal, easiest to use, and most actively developed.

The challenge of designing a manufacturing system that meets production and market demands is increasing due to demand variability and short lead times. Manufacturing flexibility is a widely recognized solution for achieving and maintaining strategic and operational objectives in the face of global competition. Luscinski et al. [30] assumed this and developed a simulation model of a flexible manufacturing system using FlexSim 3D software and the ontology of flexibility. The model's flexibility was evaluated using the flexibility ontology approach. Wang et al. [31] used a temporal Petri net model and FlexSim simulation model to simulate manufacturing logistics, analyze results, identify bottleneck problems, and propose targeted optimization methods to improve efficiency. FlexSim has been used not only for manufacturing simulation and optimization but also for warehouse operation and logistics. It can identify bottlenecks and simulate optimized plans [32,33].

Simulation allows for unlimited opportunities to test different scenarios by altering decision variables, objective functions, and constraints and repeating experiments [34]. Simulation software packages available in the market provide a tool to prepare scenarios and run experiments automatically. The main challenge is to find the best set of model specifications to obtain optimal simulation results. Optimization packages, such as AutoStat, Extend Optimizer, OptQuest, SimRunner2, Technomatix Optimizer, Witness Optimizer, and others, are commonly used for this purpose. The study conducted by [35] compared the Taguchi method and OptQuest for the performance optimization of a flexible manufacturing system using simulation. The conclusion was that the OptQuest optimization platform outperforms the Taguchi optimization method. OptQuest employs three heuristic search methods, namely scatter search, tabu search, and neural networks. It can handle both linear and nonlinear constraints, including uncertainty and risk. Simulation modeling is a valuable research method that can be used to optimize problems encountered with constraints. It can be employed as an optimization package in a variety of simulation programs [29,34,35].

The results of the research are important both from the perspective of the enterprise—the economic impact and value of the enterprise, as well as the efficiency of management processes in the enterprise—and from the broader socio-economic perspective—satisfying consumer needs for goods and services, while reducing negative impacts on the environment and using its resources efficiently. In this context, attention should also be paid to the increase in air pollution caused by economic activity, which is worsening in many cities [36], and the need to take various measures to reduce it [37]. These include the creation of a good production environment and ecological production [38], as well as the reduction in negative environmental impacts, such as in dismantling lines [39].

Based on the literature review, many authors have demonstrated the usefulness of simulation modeling in obtaining the most suitable results while considering constraints without affecting actual production. Based on the literature, the FlexSim simulation program with the OptQuest optimization package was chosen for simulation modeling in the printing industry.

2. Materials and Methods

Within the framework of this paper, an assortment–quantity optimization of a selected printing process realized in a printing enterprise has been carried out using simulation

modeling, with particular emphasis on mathematical modeling. The proposed method aims to develop an efficient system to support economic decision making in enterprises. The method comprises six stages (refer to Figure 1):

1. Identification of the research problem;
2. Analysis of the manufacturing process;
3. Simulation model building;
4. Mathematical models definition;
5. Experiments;
6. Carrying out simulations.

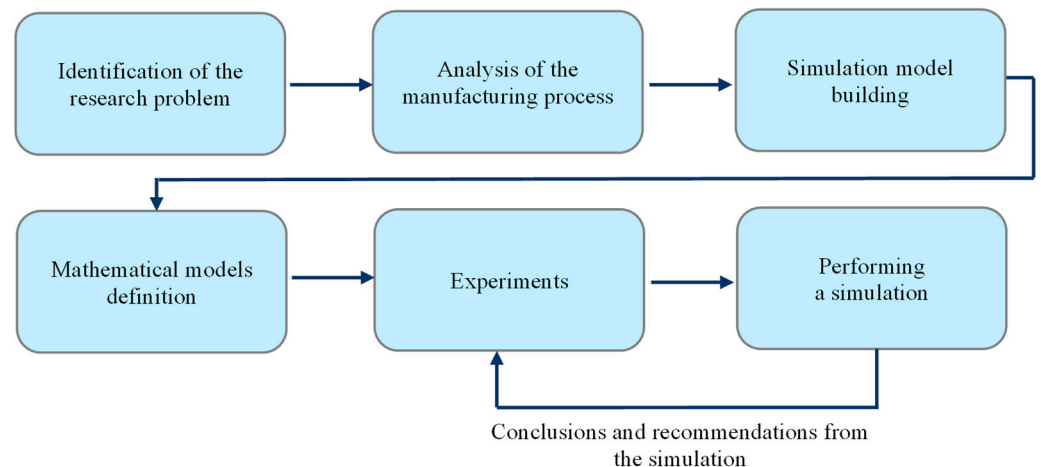


Figure 1. Diagram of solution method.

The following section outlines the individual stages of the research process:

Stage 1. Identification of the research problem. This requires becoming familiar with the enterprise's implemented process and conducting talks or interviews with senior management to identify key issues that require solutions and the scope of expected process improvements. It is important to note that the company may have the option to select or change the parameters of the applied technology. The main research problem, which will be the subject of the study, should be formulated.

Stage 2. Analysis of the manufacturing process. The manufacturing process should be analyzed using methods that provide a detailed insight into the process. This section refers to the analysis of documentation, such as process maps, workstation instructions, and machine and device documentation. Additionally, continuous observation of the process is necessary, which can be achieved through the video recording of all activities performed within the process. Finally, interviews with employees operating individual machines should be conducted. The activities should be identified in detail for each workstation, including their correct sequence, relations between them, and duration.

Stage 3. Simulation model building. A simulation model must be built using an appropriate tool. During this stage, the main objective is to accurately represent individual technological operations in the construction of simulation models. Each program contains multiple objects with assigned functionalities. In FlexSim, it is also possible to modify selected attributes of objects to align with the material flow within the process. In the production system model, the objects mainly represent machinery and transport equipment. Independent variables are defined for the objects, describing their parameters, which are not subject to change in a specific experiment. The dependent variables represent the production of individual products, the value of which is the result of the experiment. After selecting the appropriate objects, it is necessary to input quantitative data into the model. This includes the duration of specific operations, the availability of machines and equipment used in the process, and the availability of employees. Recreating the flow of materials, parts, or semi-finished products within the implemented process, as well as

setting flow limitations, presents a certain challenge. Special functionalities of objects often perform these activities. The simulation model is completed by comparing the obtained results with the actual process (model validation). The validation criteria used were the total production volume of products in a given planning period, the volumes of products processed on individual machines in a given time, and the execution times of individual technological operations and transport operations.

Stage 4. Definition of mathematical models. The mathematical model must be formulated in a way that is suitable for implementation in an optimization algorithm used in a simulation program or an external optimization algorithm, provided that it is possible to export data and import results from the external program. In general, the model can be multi-criteria and nonlinear and may contain random variables. Solution methods are typically approximate (heuristics or metaheuristics). The model construction should begin by defining the decision variables and their types, introducing quality criteria, and specifying the direction of optimization for each criterion. Next, appropriate equations and inequalities should be used to impose constraints on the decision variables. The resulting model can then be searched for the best solution or optimized if the algorithm allows for it. For metaheuristic algorithms, the problem's constraints can be obtained from the simulation model. For the proposed method, the decision variables are integers, the mathematical model of the original problem is MIP, and the relaxation of the problem is LP (continuous variables). A heuristic algorithm (solution space search) was implemented in the optimization solver, including tabu search and GA.

Stage 5. Experiments. The research's final stage involves conducting experiments to evaluate the best solutions for various process realization scenarios. Initially, the state representing the current course of the analyzed process is determined. This fragment serves as a reference point for subsequent experiments' results. The model modifies one selected process characteristic (often described by several variables) to determine its impact on the process implementation. The characteristics may result from parameters that describe the process, which are crucial from both the company's and process's point of view. These parameters may include the following:

- Way of business transactions performed—determining the scope and size of orders executed within the analyzed process (individual customers, business customers);
- Price of products—determining the size and variation of the price for each of the manufactured products;
- Time of operations—differentiating the duration of individual operations depending on the type of manufactured product;
- Use of additional resources—specifying the possibility of using additional machinery, employees, or equipment;
- Taking into account the cost of lost profits due to involvement of additional resources;
- Process improvement—identification of bottlenecks in the process, determination of the maximum capacity of the process, and searching for a dependence of the production program on the change in the location of the bottleneck.

As part of the experiments, objective functions are developed to consider economic indicators such as income and opportunity cost. This ensures that activities support the economic optimization of the company's production.

Stage 6. Carrying out simulations. The experiments conducted in step 5 identified the best solutions based on the defined criteria. The results are presented as objective function values and a set of values for the decision variables. While optimization provides a quick review of acceptable solutions, it does not always allow for the verification of the feasibility of the best solution. After conducting optimization experiments, it is necessary to perform simulations on the obtained solution. Simulations help determine the machine workload, identify process limitations such as bottlenecks according to the Theory of Constraints, or establish a schedule for the production process. In addition, it is possible to track the movement of materials, semi-finished products, and products through the various stations of the examined process. Creating a schedule can be especially important when

implementing a parallel layout for workstations or when dealing with a complex process structure. Following each optimization experiment, simulations are conducted and their results are interpreted. The process outlined in stages 5 and 6 is followed until a solution to the research problem is achieved.

The proposed method can be directly applied to discrete production problems in flow lines, with serial, parallel, or mixed production organization. It is possible to represent different parameters of machines (product processing time, resource and energy utilization, machine setups) and transport equipment (transfer rate, capacity). The method can easily be adapted to continuous production (bulk materials, liquids, volumetric materials). In this case, the Fluid Library of FlexSim can be used. The model will then have a computationally simpler form, with continuous variables. The limitation of the proposed method is the lack of direct ability to solve nonlinear problems. FlexSim allows you to model objects with nonlinear transition characteristics, but you would need a specialized external tool to solve the mathematical programming problem. In this case, communication should be provided by the Python/C API supported by FlexSim. However, this was not investigated in this paper.

3. Results

Stage 1. The research problem was identified within the framework of the cooperation with the studied enterprise. The solutions implemented are derived from various areas of production management, with a focus on modern production management concepts such as Kaizen, Lean Management, and Theory of Constraints. The company has decided to implement a new production process that involves printing on various materials. This process requires the use of new technology and the adjustment of process parameters to ensure the profitability of the solutions. The company initially decided to stabilize the implemented process and determine the appropriate parameters for the activities to ensure the quality of the manufactured products. The same parameters were used for all materials and products offered at the same price.

However, during research conducted by another team and improvements made to the printing technology, it was discovered that certain parameters of the process could be altered (such as reducing the duration of operations) while maintaining the appropriate level of product quality. Implementing these solutions could increase the production capacity of the process. Another consideration is the pricing of individual products. Initially, all products were priced the same due to the use of the same printing technology without the differentiation of materials. However, market analyses, including competitive research, social media analysis, and direct customer feedback, revealed that customers were willing to pay more for a product with an additional service compared to a competitor's product. Currently, the enterprise should consider diversifying prices based on the products manufactured.

The company's introduction of B2B activities in other areas has led to the signing of long-term contracts in the newly applied technology sector. While this solution guarantees a steady income, it also restricts the ability to make changes to the project. For instance, it may require the production of a specific number of units of a product, regardless of its profitability. Minimum production programs have been established for a given product. The research problem addressed in this paper is the optimization of the assortment–quantity production program, analyzed in the area of management decision support.

Stage 2. The production process analysis involves six workstations, each assigned to specific technological operations (Figure 2). The stations work sequentially.

The production process starts with collecting material dedicated to printing one of the three products. This material must be appropriately prepared for production to ensure the highest possible quality of the printed image. The material is impregnated by the M1 machine, which coats it with a special reagent. Next, the material is cleaned using special equipment on the M2 machine. The surface on which the print is applied must be smoothed to ensure optimal bonding between the ink and the material.

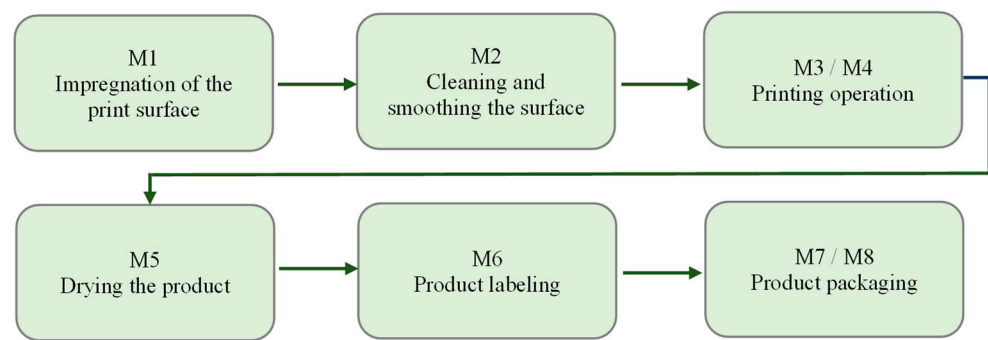


Figure 2. Diagram of printing process.

The printing process is carried out by machine M3, which is fully dedicated to production. However, analysis has revealed that machine M3 is a bottleneck in the process. The company is therefore considering adding an additional printer, the M4 machine. The research should consider the possibility of limiting the use of machine M4, as it may be used in another process. Technologically, the decision to direct the product to the next machine, whether it be machine M3 or machine M4, will be based on the lack of occupation of the next station. The duration of a technological operation on the M4 machine is shorter than that on the M3 machine, regardless of the product type, due to the greater single coverage of the print surface. Additionally, the M4 machine consumes fewer material resources during the operation. This paper will not address this element as a research problem.

The M5 machine is a tunnel with a moving belt inside, where the print is thermally cured onto the material. This study assumed the flexible adjustment of the tunnel's operating parameters, including belt speed and internal temperature. After manufacturing, each product is labelled using the M6 machine. At the end of the process, the product is divided into two possible paths, and the allocation of semi-finished products is determined after the operations on M6, which runs parallel to machines M7 and M8. The assignment of the operation to the workstation is determined by the type of order, whether it is an individual order or subject to picking with other products. To maintain focus on the topic, we assume an allocation with statistical distribution of orders to machines M7 and M8.

As part of the process analysis, subsequent experiments will aim to check how the proposed solutions affect the production capacity of the process and the profitability of its execution, while adhering to the Theory of Constraints. The machines are operated by four workers (E1-E4). This quantity of workers enables the operation of all machines, considering the simultaneous initiation of operations on each machine. Production can be carried out in two modes: B2B and B2C. In the B2B mode, production is carried out according to the enterprise's business partner's order. In this case, the expected production volume for each product is known. In the B2C mode, the production volume of each product is not specified and should be determined by optimizing a defined quality criterion while satisfying the problem's constraints. The unit profits from the sale of each product are known. The processing times for each product on each machine are known, as well as the availability of both machines and employees during the planning period.

The production process takes place on seven to eight machines, with the duration of each operation depending on the surface of the material to which the ink is applied. The enterprise manufactures three different products. In the initial state, the lead times of operations on individual machines are the same for each product (see Table 1a).

When looking for ways to improve the process, it was found that these times could be reduced. Table 1b shows the duration of each operation for each machine depending on the product after a process improvement (excluding the tunnel improvement). The table also shows the duration of the operations on the M4 machine when it is used to run the process.

An additional improvement that was investigated was to reduce the tunnel operating time while increasing the temperature inside the tunnel (Table 1c).

Table 1. (a) Duration of machine operations for each product. (b) Duration of machine operations after improvements excluding tunnel improvement. (c) Duration of machine operations after improvements including tunnel improvement.

(a)			
Machine	Duration of Machine Operations [s/pc]		
	P1	P2	P3
M1	35	35	35
M2	52	52	52
M3	150	150	150
M4	131	131	131
M5	638	638	638
M6	47	47	47
M7	93	93	93
M8	93	93	93
(b)			
Machine	Duration of Machine Operations [s/pc]		
	P1	P2	P3
M1	30	32	35
M2	44	47	52
M3	125	134	150
M4	110	118	131
M5	638	638	638
M6	47	47	47
M7	93	93	93
M8	93	93	93
(c)			
Machine	Duration of Machine Operations [s/pc]		
	P1	P2	P3
M1	30	32	35
M2	44	47	52
M3	125	134	150
M4	110	118	131
M5	319	319	319
M6	47	47	47
M7	93	93	93
M8	93	93	93

Each machine in the printing process studied has been allocated an hourly fund (availability), which can be used to perform the assigned technological operations. Due to the introduction of a single-shift working system, each machine works 8 h a day as a standard, but this time must be reduced by the time spent on preparing the machine for work (setting the machine parameters, adjusting the machines to the set working conditions, completing the tooling, completing the materials for the implementation of the process) and the activities carried out at the end of the work (cleaning individual elements of the machine in order to extend its life and ensure uninterrupted work on the following day). A

summary of the working time available for the machines studied is given in Table 2. These values were determined for an 8 h working day.

Table 2. Machine availability.

Machine	Availability [s]	
	Without Additional Printer M4	With Additional Printer M4
M1	27,600	27,600
M2	27,900	27,900
M3	27,000	27,000
M4	-	27,600
M5	27,000	27,000
M6	28,200	28,200
M7	27,600	27,600
M8	27,600	27,600

Within the framework of the simulation model, the technological operations performed at each workstation were represented in terms of the duration of a single operation and the availability of a given machine. It should be noted that due to the adopted simplifications in the construction of the model, the object representing an employee operating machines was not introduced. However, the allocation of tasks related to the operation of a machine to a limited number of workers was represented in the available working time fund of the workers (the sum of the time of the machine operation and the average time of the transition between stations—from the center of the area to the station). The working time fund allocated to an individual employee is 8 h; however, this should be reduced by the period of breaks—resulting from the applicable provisions of the legislation and the internal rules of the enterprise. In the analyzed case, each employee is entitled to a 40 min break included in the working time (15 min resulting from the provisions of the Labor Code and 25 min imposed by the employer to increase the comfort of the employee's work). Therefore, the scope of activities assigned to each employee should not exceed 440 min. Table 3 shows the amount of work assigned to each employee.

Table 3. Duration of employee operations.

Employee	Machine [s/pc]								Employee Availability [s]
	M1	M2	M3	M4	M5	M6	M7	M8	
E1	27	34	0	0	0	0	0	0	26,400
E2	0	0	34	29	12	0	0	0	26,400
E3	0	0	0	0	0	47	93	93	26,400
E4	0	0	0	0	0	47	93	93	26,400

The search for an optimal assortment quantity program is based on the constraints introduced into the system (in the problem studied, this constraint is the available machine time) and on the different sizes of the benefits of producing the products in question. Initially, the unit price of all three products is the same (Table 4). Eventually, the price of each product will vary according to its quality and the customer's expectations. In the B2B mode, the demand for each product is given in Table 5.

Table 4. Unit income value for individual products (initial state).

Product	P1		P2		P3	
	Initially	Finally	Initially	Finally	Initially	Finally
Unit income [EUR/pc]	12	case A: 10 case B: 8	12	10	12	12

Table 5. Product requirements in the B2B mode.

Product	P1	P2	P3
Demand [pc]	20	30	50

The unit opportunity cost of using the M4 machine in the process analyzed varied from EUR 0.05 to 0.2. Within the analyzed variants of the implementation of the printing process, possible improvement actions should be considered. In such situations, the concept of the Theory of Constraints can be applied, which focuses on finding the main bottleneck of the process and then, through selected actions of exploitation of the bottleneck, subordinating all resources to the activities performed at the bottleneck or strengthening the bottleneck, leading to an increase in production capacity.

Stage 3. The analyzed manufacturing process was modelled in FlexSim version 20.1.3. The simulation model was built from fourteen standard objects belonging to the library of fixed process resources (i.e., Processor, Queue, Source, Sink). Quantitative data about the process being run (such as operation durations, machine time funds) were presented in tables that were constructed, and then references to the individual values in the objects representing each machine were entered. The material flow logic was also set up in each object according to the way the printing process was implemented. On the basis of the simulation experiments carried out as part of this study, elements were introduced into the model to enable their future implementation (e.g., continuous identification of the number of semi-finished products passing through the machines working in parallel). The developed model of the investigated overprinting process is shown in Figure 3.

The model was successfully validated using data provided by the company. The simulation was set for 8 h, corresponding to one working shift. The process produced 180 pieces of product (60 pieces of product P1, 60 pieces of product P2, and 60 pieces of product P3). Note that the simulation ended earlier than the predicted simulation time due to the exhaustion of the available working time on the M3 machine. In the built model, such a situation means closing the output port on the given machine (the product cannot leave the given machine and be transported to the next one) and it is equivalent to the end of the realization of the given process.

As was shown in the literature review, on the basis of the created simulation model it is possible to carry out a detailed analysis of the considered production process. The main advantage of this approach is that there is no interference with the real production system. The simulation experiments made it possible to analyze a whole range of different situations that occur in the real system. These included observing the flow of a piece of product through the whole system, analyzing the load on individual machines, analyzing the duration of the whole process, and checking whether it was possible to execute a given production plan. The analysis was facilitated by the visualization of the process, the speed of which was adapted to the actual needs. On this basis, it was possible to make assumptions about which elements of the problem would be reflected in the optimization model.

The inclusion in the optimization model of the unit times of execution of individual technological operations on individual machines, the time of availability of machines in the entire planning period, the time of execution of operations by individual workers on individual machines (the same for each type of product), and the time of availability of workers was considered crucial. Machine set-up times were not taken into account. This is due to the fact that, at the moment the product appears on the machine, it is necessary to

carry out preparatory activities for the operation, while the scope of the activities carried out is the same for each product, differing only in their duration. In order to simplify the simulation model to be analyzed, it was decided to include the time required to adapt the workstation to the production of a product in the duration of a single operation.

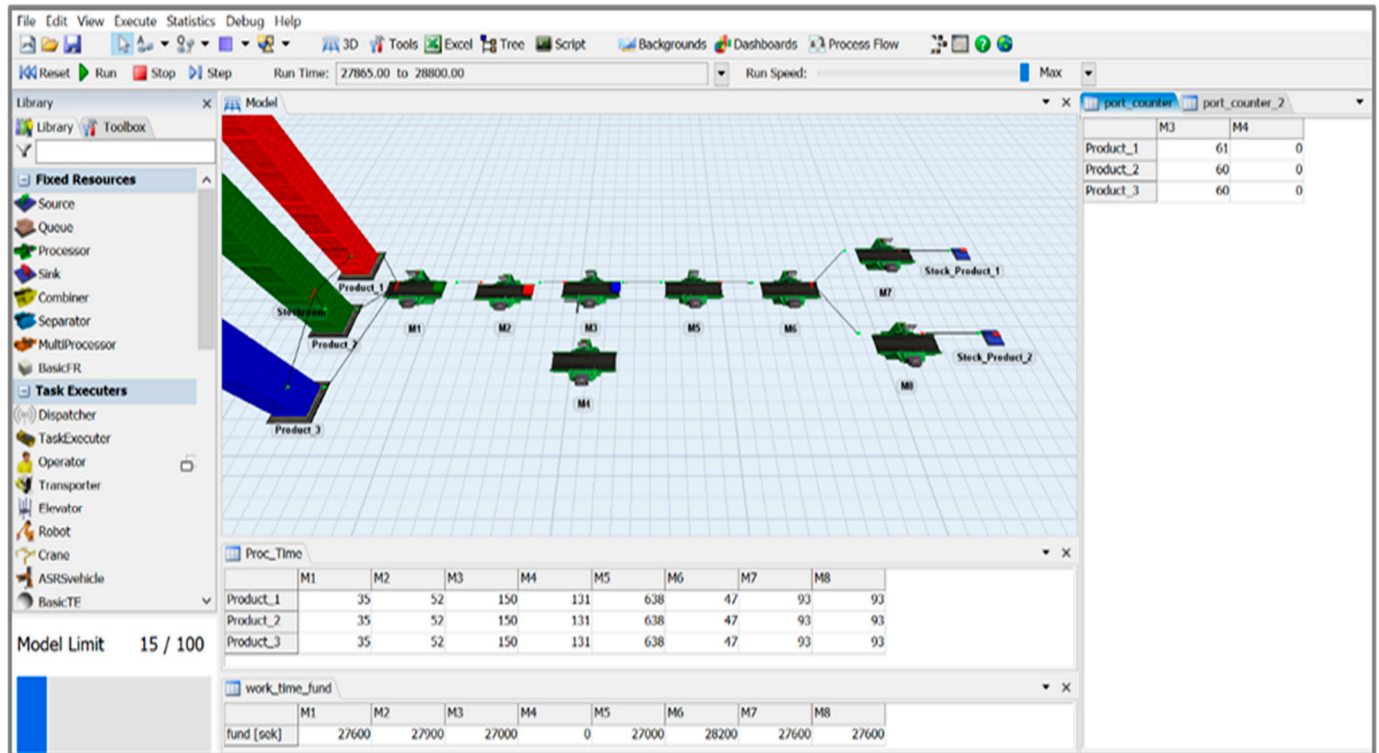


Figure 3. The developed model of the printing process.

The model also takes into account the allocation of individual operations to a given worker. In the process analyzed, the work is carried out by four people, and the first two employees carry out activities directly related to the realization of the technological process—therefore an appropriate level of competence and skills is required. Two other employees perform activities mainly related to the marking and packing of finished products; therefore, the activities performed by them are the same and do not require high qualifications from the employees. At the same time, they are interchangeable in any configuration.

For the B2B order model, the number of units of each product ordered was determined. It was also decided to include the unit profit for each product in the optimization model. It was decided to use the total profit of a given production plan as a quality criterion. It was also decided to check how the inclusion of the cost of using an additional printer (M4 machine) in the quality criterion affects the solution.

Stage 4. The mathematical model was formulated as an MIP. The relaxation of the problem is formulated as an LP.

The following indexes are introduced:

- i —product index, $i \in \{1 \dots I\}$, where I —number of products;
- j —machine index, $j \in \{1 \dots J\}$, where J —number of machines;
- k —employee index, $k \in \{1 \dots K\}$, where K —number of employees;
- p —index of individual pair of machines working in parallel, $p \in P$;
- P —the set of indexes of all pairs of machines working in parallel;
- J_k —set of machines $\{ \dots, j, j+1, \dots \}$ operated by employee k ;
- J_p —the pair p of machines $\{j, l\}$ working in parallel.

There are three groups of objects in the problem under study: machines, workers, and products. For each group, an appropriate index is assigned and the specific sets necessary to implement the constraints of the problem are defined.

The following decision variables are defined:

x_i —number of products i ;

x_{ij} —number of products i processed on machine j .

Two types of decision variables have been defined—variables representing the number of pieces of each product produced during the planning period and decision variables representing the number of pieces of each product produced on each machine belonging to a pair of parallel machines. Both types of variables are integers in nature.

The following parameters are introduced:

a_{ij} —processing time of product i on machine j ;

dk_j —processing time of employee k on machine j ;

u_i —unit profit for product i ;

c_{M4} —opportunity unit cost of using the M4 machine;

b_j —availability of the machine j during the planning period;

e_k —availability of the employee k during the planning period;

R_{iB2b} —requirements for product i in the B2B production mode, during the planning period.

For the problem description, parameters were introduced according to the analysis carried out in the previous section. The parameters describe the operating times of the machines and labor units, the availability of the machines and labor in the planning period, the profits and costs associated with the process, and the production volume requirements.

The following quality criteria have been defined:

(I) U —profit on all products sale, $U = \sum_i u_i x_i$;

(II) C —total opportunity cost of using the M4 machine, $C = \sum_i c_{M4}(a_{i4} x_{i4})$.

The quality criterion (I) represents the sum of the profits from the sale of all the products produced. This criterion is maximized. Quality criterion (II) represents the total opportunity cost of using the M4 machine. This criterion is minimized. Because the two quality criteria have the same label [EUR], it has been assumed in the computational experiments that the objective function is always a single function and that no weights are assigned to the quality criteria.

The following constraints are introduced:

(1) $\sum_i a_{ij} x_i \leq b_j \forall j$;

(2) $\sum_i \sum_{j \in Jk} dk_j x_i \leq e_k \forall k$;

(3) $x_i \geq R_{iB2b} \forall i$;

(4) $x_i = \sum_{j \in Jp} x_{ij} \forall p, \forall i$;

(5) $x_i \in \text{Integer}, x_i \geq 0$;

(6) $x_{ij} \in \text{Integer}, x_{ij} \geq 0$.

Constraint (1) ensures that for each machine, the sum of the processing times of each product on that machine does not exceed the total available time of that machine during the planning period. Constraint (2) ensures that for each operator, the sum of the operator's run times on each machine to which the operator is assigned does not exceed the operator's total availability time during the planning period. Constraint (3) ensures that at least the expected number of units of each product is produced in the B2B production mode. Constraint (4) ensures the correct balance of production of each product for each pair of machines running in parallel in the production system. Constraints (4) and (5) ensure that the decision variables are integers (the problem is a discrete one). The various mathematical models of the problem studied in this paper have been constructed using the elements defined above, as assumed for each experiment in the next section.

Stage 5. The main objective of the presented paper is to determine the optimal size of the assortment quantity program of the investigated printing process. After positive verification of the simulation model, it was necessary to carry out a series of experiments.

The experiments were prepared in the Experimenter tool, which allows the study of a given process through the execution of several well-defined scenarios, or by using an OptQuest algorithm implemented in the FlexSim program. Therefore, the objective function of the model, decision variables, parameter values, and constraints were entered into the Experimenter tool. A description of the experiments performed is given in Table 6.

Table 6. Description of performed experiments.

No.	Quality Criteria	Constraints	Values of the Parameters	Description
1.	max U	(1), (2), (5)	Table 1a. Table 2 (without M4). Table 3. Table 4 (initially).	B2C case; printers: M3; profit maximization; the same machine operation lead times; the same unit prices for each product
2.	max U	(1), (2), (3), (5)	Table 1a. Table 2 (without M4). Table 3. Table 4 (initially). Table 5.	B2C case; B2B case; printers: M3; profit maximization; the same machine operation lead times; the same unit prices for each product
3.	max U	(1), (2), (3), (5)	Table 1a. Table 2 (without M4). Table 3. Table 4 (finally). Table 5.	B2C case; B2B case; printers: M3; profit maximization; the same machine operation lead times; the different unit prices
4.	max U	(1), (2), (3), (5)	Table 1b. Table 2 (without M4). Table 3. Table 4 (finally). Table 5.	B2C case; B2B case; printers: M3; profit maximization; machines improvement (the different machine operation lead times); the different unit prices
5.	max U	(1), (2), (3), (4), (5), (6)	Table 1b. Table 2 (with M4). Table 3. Table 4 (finally). Table 5.	B2C case; B2B case; printers: M3, M4; profit maximization; machines improvement (the different machine operation lead times); the different unit prices
6.	max (U – C)	(1), (2), (3), (4), (5), (6)	Table 1b. Table 2 (with M4). Table 3. Table 4 (finally). Table 5.	B2C case; B2B case; printers: M3, M4; profit maximization; opportunity costs minimization; machines improvement (the different machine operation lead times); the different unit prices
7.	max (U – C)	(1), (2), (3), (4), (5), (6)	Table 1c. Table 2 (with M4). Table 3. Table 4 (finally). Table 5.	B2C case; B2B case; printers: M3, M4; profit maximization; opportunity costs minimization; machine and tunnel improvements (the different machine operation lead times); the different unit prices
8.	max (U – C)	(1), (2), (4), (5), (6)	Table 1c. Table 2 (with M4). Table 3. Table 4 (finally).	B2C case; printers: M3, M4; profit maximization; opportunity costs minimization; machines and tunnel improvement (the different machine operation lead times); the different unit prices
9.	max U	(1), (2), (4), (5), (6)	Table 1c. Table 2 (with M4). Table 3. Table 4 (finally).	B2C case; printers: M3, M4; profit maximization; machines and tunnel improvement (the different machine operation lead times); the different unit prices

Each experiment corresponded to a real decision problem defined by the company's management. When defining the models, the management distinguished between the

usefulness of the models for the B2C situation only (Experiments 1, 8, 9) and the usefulness for B2C including B2B (Experiments 2–7). In this sense, the B2C case was more general than the B2B case. Each decision problem differed from the others by a specific configuration of criteria, variables, and parameters, as expected by the company. In this respect, the research carried out was also utilitarian in nature.

The following assumptions were made in carrying out the experiments:

1. Maximum number of iterations of the algorithm: 1000.
2. Maximum computing time: 900 s.
3. Single-criteria optimization (one or two components of the objective function).
4. Standard parameters for invoking the optimization algorithm.

During the experiments, two criteria were decisive in determining the number of solutions—the duration of the simulation and the maximum number of iterations of the algorithm. In most of the experiments, the key criterion was to obtain as many feasible solutions as possible, even if it meant extending the duration of the experiments.

For each experiment, the value of the objective function (both components where applicable), the computation time, and the values of the decision variables in the best solution were recorded. All computations were performed on an ASUS Intel® Core™ i5-7200U CPU @2.50 GHz under Windows 10 Home edition and the FlexSim version of 20.1.3.1 along with the OptQuest package. Each optimization experiment is followed by a simulation experiment, and conclusions are drawn for use in subsequent optimization experiments.

Experiment 1. As a result of the optimization, 995 feasible solutions including 944 optimal solutions with the same objective values were obtained from 1000 simulations performed, and the sum of decision variables x_1 , x_2 , and x_3 was equal to 180. Any combination of values of decision variables x_1 , x_2 , and x_3 that satisfies the constraints of the problem is acceptable in the general case. Among the results, a numerical variation in the production volume of each product was observed. None of them is a preferred product in the implementation of the production program. The described situation results from the same process parameters in terms of the duration of operations or profits from the sale of individual products. Therefore, the company can freely formulate its policy on the recommended production volume of each product. The situation described provides good flexibility in decision making. However, with reference to the Introduction of this paper, it is necessary to take measures that will allow the company to better adapt its production capacity to market expectations and production profitability.

The simulation of the production process showed a high degree of flexibility in the design of the material flow through the individual machines. This situation is related to the lack of preference for the production of a certain number of selected products.

Experiment 2. As a result of the optimization, 147 feasible solutions, including 140 optimal solutions, were obtained out of 1000 simulations performed, and the sum of decision variables x_1 , x_2 , and x_3 was equal to 180. Any combination of values of decision variables x_1 , x_2 , and x_3 that satisfies the constraints of the problem ($x_1 \geq 20$, $x_2 \geq 30$) is acceptable in the general case. Among the results, a numerical variation in the production volume of each product was observed. None of them is a preferred product in the implementation of the production program. The described situation results from the same process parameters in terms of duration of operations or profits from the sale of individual products. Therefore, the company can freely formulate its policy on the recommended production volume of each product. The situation described provides good flexibility in decision making. However, with reference to the Introduction of this paper, it is necessary to take measures that will allow the company to better adapt its production capacity to market expectations and production profitability.

The simulation shows that the flow of materials and semi-finished products within the analyzed process depends on the assumed volume of orders in the B2B cooperation. The flow flexibility within the process was reduced compared to Experiment 1.

Experiment 3. Two special cases were made in this experiment. Case A, where $u_1 = u_2 = 10$ EUR/pc and $u_3 = 12$ EUR/pc, and case B, where $u_1 = 8$ EUR/pc, $u_2 = 10$ EUR/pc,

and $u_3 = 12$ EUR/pc. In case A, the optimization process yielded 76 feasible solutions out of 1000 simulations. Among the feasible solutions, one optimal solution was found with an objective function of EUR 2060. Based on the results obtained to maximize the objective function, it is necessary to produce as much of the product P3 as possible. However, below the size of 97 units of the production program for product P3, more flexibility was observed in the production program for the other two products. In case B, 159 feasible solutions were obtained in the optimization process out of 1000 simulations performed. Among the feasible solutions, one optimal solution was found with the objective function of EUR 2020. As in case A, the objective function was to maximize the production of product P3.

The simulation made it possible to observe changes in the size of the buffer capacity between workstations. This study also makes it possible to study the rotation of materials and semi-finished products contained in the buffers dedicated to certain machines. This condition is related to the different duration of the operations carried out on different products.

Experiment 4. There were also two special cases in this experiment. Case A, where $u_1 = u_2 = 10$ EUR/pc and $u_3 = 12$ EUR/pc, and Case B, where $u_1 = 8$ EUR/pc, $u_2 = 10$ EUR/pc, and $u_3 = 12$ EUR/pc. In case A, the optimization process yielded 86 feasible solutions out of 1000 simulations. Among the optimal solutions, one optimal solution was obtained with a value of the objective function of EUR 2080. To maximize the objective function, as much as possible of the product P3 should be produced. The key constraint is to determine the minimum number of products P1 and P2 resulting from B2B orders. As the amount of product P3 decreases, more flexibility in the production program is obtained. In case B, the optimization performed yields 128 feasible solutions out of 1000 simulations performed. Among the feasible solutions, two optimal solutions were found with an objective function of EUR 2094. The production of each product differs by ± 2 units between the optimal solutions.

The simulation identified a bottleneck in the process on machine M3. Therefore, in subsequent experiments, an improvement was introduced in the form of an additional printer (machine M4). It should be noted that machine M4 is more efficient than machine M3.

Experiment 5. The optimization performed yielded 694 optimal solutions out of 1000 simulations performed. On the basis of the results obtained, it was concluded that in order to maximize the objective function, as much product P3 (161 pieces) as possible should be produced. The production of P1 and P2 should meet the requirements of the B2B mode: 20 units of P1 and 30 units of P2. Thus, the main constraint in this case is to determine the minimum number of products P1 and P2 resulting from the fulfilment of B2B orders. In the experiments presented, the value of the objective function is EUR 2392. All solutions with the optimal value of the objective function are characterized by different production distributions per machine M3 and M4. An arbitrary flow distribution is observed among these solutions—neither of these two machines is preferred.

There is a large variation in the flow of materials and semi-finished products over time. The main criterion for the flow distribution at the printing stage is the availability of a particular machine. It was found that the bottleneck in the process was removed at the printing stage.

Experiment 6. This experiment included the additional costs associated with using the M4 machine as part of the process under investigation. There were four special cases in this experiment (see Table 7 for details). According to the information received from the company, the M4 machine can be used to perform an alternative printing process. The alternative process is carried out for other products on a different production line. The use of the M4 machine for the investigated process partially excludes the use of this machine from the execution of the alternative processes. This gives rise to an opportunity cost, which is estimated from the profits generated by the alternative products. Depending on the type of alternative process in which the M4 machine can be used, the unit cost parameter takes values in the range (0.05–0.2 EUR/s).

The value of the objective function increases up to EUR 2231.5 as the value of the C_{M4} parameter decreases. The increase in the objective function is mainly due to the increase

in the number of products produced on the M4 machine. The results obtained indicate that only at a value of the C_{M4} parameter not greater than 0.1 EUR/s is it advantageous to introduce the machine into the process at the expense of reducing its share in the implementation of alternative processes. At the C_{M4} parameter value of 0.05 EUR/s, the maximum number of manufactured products was obtained—211 pieces. The size of the production program was designed to meet the requirements of the B2B mode for products P1 and P2 and then to maximize the production of product P3. The maximum utilization of the M4 machine is over 53 min.

Table 7. Results of Experiment 6.

	Values of the C_{M4} Parameter			
	A: 0.05	B: 0.1	C: 0.15	D: 0.2
Computation time [s]	965	827	883	417
Numbers of best results	1	1	2	2
$U - C$ [EUR]	2231.5	2095	2094	2094
U [EUR]	2392	2128	2094	2094
C [EUR]	160.5	33	0	0
Number of products [pc]	211	189	187	187
Quantity of Product 1 (P1) [pc]	20	20	20/21	20/21
Quantity of Product 2 (P2) [pc]	30	30	35/33	35/33
Quantity of Product 3 (P3) [pc]	161	139	132/133	132/133
Quantity of products on M3 [pc]	186	186	187	187
Quantity of products on M4 [pc]	25	3	0	0
Working time—M4 [s]	3210	330	0	0

As part of the simulation carried out, a process bottleneck was identified on machine M5. Therefore, in the subsequent experiments carried out, an improvement was introduced on machine M5, which involved a reduction in the duration of the operations carried out on this workstation.

Experiment 7. This experiment also included the additional cost of using the M4 machine as part of the process under investigation. There were four special cases in this experiment (see Table 8 for details). The value of the objective function increases up to EUR 2694.75 as the value of the C_{M4} parameter decreases. The results obtained indicate that only at a value of the C_{M4} parameter not greater than 0.1 EUR/s is it beneficial to introduce the machine into the process. At the C_{M4} parameter value of 0.05 EUR/s, the maximum number of manufactured products was obtained—246 pieces. The size of the production program was designed to meet the requirements of the B2B mode for products P1 and P2 and then to maximize the production of product P3. The maximum utilization of the M4 machine is almost 4 h.

In the experiment carried out, it was also necessary to increase the maximum number of solutions examined in the calculations carried out to 1500. With the previous value of 1000 solutions, the value of the objective function increased significantly in the following solutions. Within the results obtained with two values of the parameter C_{M4} (0.15 and 0.2 EUR/s), it was noticed that the OptQuest program reached the limit of sensitivity for proving the fulfilment of the constraints of the problem. Therefore, more than 40% of the solutions were infeasible.

The simulation carried out allowed the removal of the bottleneck from the M5 machine. Individual simulations showed a variable distribution of the flow of materials and semi-finished products in the process, depending on the unit cost of using machine M4 in the realization of the alternative process.

Table 8. Results of Experiment 7.

	Values of the C_{M4} Parameter			
	A: 0.05	B: 0.1	C: 0.15	D: 0.2
Computation time [s]	853	888	1295	855
Numbers of best results	1	1	2	2
$U - C$ [EUR]	2694.75	2095	2094	2094
U [EUR]	3412	2128	2094	2094
C [EUR]	717.25	33	0	0
Number of products [pc]	286	189	187	187
Quantity of Product 1 (P1) [pc]	20	20	21/20	20/21
Quantity of Product 2 (P2) [pc]	30	30	33/35	35/33
Quantity of Product 3 (P3) [pc]	246	139	133/132	132/133
Quantity of products on M3 [pc]	186	186	187	187
Quantity of products on M4 [pc]	110	3	0	0
Working time—M4 [s]	14,345	330	0	0
Number of feasible solutions	1500	1500	894	825
Number of infeasible solutions	0	0	606	675

Experiment 8. This experiment also included the additional cost of using the M4 machine as part of the process under investigation. There were four special cases in this experiment (see Table 9 for details). The value of the objective function increases up to EUR 2792.2 as the value of the C_{M4} parameter decreases. The results obtained indicate that only at a value of the C_{M4} parameter of 0.05 EUR/s is it advantageous to introduce the machine into the process. The maximum number of manufactured products was equal to 296 pieces. The size of the production program was maximized by the production of product P3. The maximum use of the M4 machine is over 4 h.

Table 9. Results of Experiment 8.

	Values of the C_{M4} Parameter			
	A: 0.05	B: 0.1	C: 0.15	D: 0.2
Computation time [s]	432	431	441	457
Numbers of best results	1	1	1	1
$U - C$ [EUR]	2792.2	2160	2160	2160
U [EUR]	3552	2160	2160	2160
C [EUR]	759.8	0	0	0
Number of products [pc]	296	180	180	180
Quantity of Product 1 (P1) [pc]	0	0	0	0
Quantity of Product 2 (P2) [pc]	0	0	0	0
Quantity of Product 3 (P3) [pc]	296	180	180	180
Quantity of products on M3 [pc]	180	180	180	180
Quantity of products on M4 [pc]	116	0	0	0
Working time—M4 [s]	15,196	0	0	0

The simulation confirmed the results of the optimization and indicated the execution of one product—P3. The size of the unit cost of using the M4 machine in carrying out the alternative process affects the schedule of the flow of materials and semi-finished products.

The lower the value of the parameter, the higher the share of the M4 machine, which results in directing a certain number of semi-finished products to this machine.

Experiment 9. This experiment gave the best results in absolute terms due to the assumptions made. Based on the results obtained, it was concluded that in order to maximize the objective function, it is necessary to produce as many P3 products as possible (296 units) and to limit the production of P1 and P2 products to zero units. In the experiment presented, the value of the objective function is EUR 3552. All solutions with the optimal value of the objective function are characterized by different production distributions per machines M3 and M4. An arbitrary distribution of flows is observed among these solutions. Neither of the two machines is preferred.

In addition, in Experiment 9, the performance of the optimization algorithm was studied in two scenarios. The first scenario (Experiment 9A) assumes an increasing number of iterations, with 3000 iterations and a computation time of 3600 s (extension of the scope of the algorithm execution). The second scenario (Experiment 9B) assumes the rejection of the constraints on the type of decision variables (problem relaxation).

In case A, no improvement in the objective function was observed. The same values were obtained as with the basic algorithm settings. In case B, the upper constraint of the objective function was found to be EUR 3561.29 with a production of product P3 of 296.7742 units. The difference is only 0.26%. The largest integer not greater than the production value of product P3 in the solution of the relaxed problem is equal to the solution of the mixed integer problem. This means that the solution of the MIP is optimal.

The simulation carried out confirmed the results obtained in the optimization—maximizing the production of product P3. It was also found that the timing of the flow of materials and semi-finished products through the M3 and M4 machines varied for equivalent optimal solutions. The overall results of all the experiments are shown in Table 10.

Table 10. Overall results of the experiments.

No.	Quality Criteria for the Best Solution [EUR]	Computation Time [s]	Quantity of Products P1, P2, and P3 in the Best Solution [pc]
1	2160	697	Any combination for which the sum of P1, P2, and P3 is equal to 180
2	2160	49	Any combination for which the sum of P1, P2, and P3 is equal to 180 and $P1 \geq 20$, and $P2 \geq 30$, and $130 \geq P3 \geq 0$
3	A: 2060 B: 2020	A: 41 B: 51	A: $P1 = 20, P2 = 30, P3 = 130$ B: $P1 = 20, P2 = 30, P3 = 130$
4	A: 2080 B: 2094	A: 76 B: 42	A: $P1 = 20, P2 = 30, P3 = 135$ B: $P1 = 20, P2 = 35, P3 = 132$ or $P1 = 21, P2 = 33, P3 = 133$
5	2392	860	$P1 = 20, P2 = 30, P3 = 161$
6	A: 2231.5 B: 2095 C: 2094 D: 2094	A: 965 B: 827 C: 883 D: 417	A: $P1 = 20, P2 = 30, P3 = 161$ B: $P1 = 20, P2 = 30, P3 = 139$ C: $P1 = 20, P2 = 35, P3 = 132$ or $P1 = 21, P2 = 33, P3 = 133$ D: $P1 = 20, P2 = 35, P3 = 132$ or $P1 = 21, P2 = 33, P3 = 133$
7	A: 2694.75 B: 2095 C: 2094 D: 2094	A: 853 B: 888 C: 1295 D: 855	A: $P1 = 20, P2 = 30, P3 = 246$ B: $P1 = 20, P2 = 30, P3 = 139$ C: $P1 = 20, P2 = 35, P3 = 132$ or $P1 = 21, P2 = 33, P3 = 133$ D: $P1 = 20, P2 = 35, P3 = 132$ or $P1 = 21, P2 = 33, P3 = 133$
8	A: 2792.2 B: 2160 C: 2160 D: 2160	A: 432 B: 431 C: 441 D: 457	A: $P1 = 0, P2 = 0, P3 = 296$ B: $P1 = 0, P2 = 0, P3 = 180$ C: $P1 = 0, P2 = 0, P3 = 180$ D: $P1 = 0, P2 = 0, P3 = 180$
9	A: 3552 B: 3561.29	A: 2952 B: 504	A: $P1 = 0, P2 = 0, P3 = 296$ B: $P1 = 0, P2 = 0, P3 = 296.7742$

4. Discussion

The computational experiments have shown that it is possible to achieve the company's business objectives. If the prices of the products are the same, the company has full flexibility to choose its production mix according to the volume requirements in the B2C and B2B cases. If only the prices of the products produced in the B2B case change, the distribution of production changes and the total profit decreases. A process improvement that reduces the execution time of some technological operations on some machines increases the production volume and the total profit. The addition of machine M4 in a B2B case, without taking into account the opportunity cost of its use in other processes, also increases the production volume and the total profit by more than 10%. Machine M3 is the bottleneck of the process and determines the maximum throughput of the whole production process. Therefore, by increasing the production capacity of the printing stage, the production capacity of the entire production process is increased.

If lost benefits are taken into account, production volume and profit are reduced. The degree of reduction increases as opportunity costs increase. The improvements in this case are a result of the tunnel improvement. The best results are obtained when an additional printer is used as dedicated to the process (without considering opportunity costs) and all improvement possibilities are used. The profit increases by around 65%. If the lost benefits are considered at the lowest level considered, the profit increases by less than 30%. For reasons of commercial confidentiality, the company did not provide the value of profit on all product sales for comparison. However, the information showed that the results of the work were much more favorable than the status quo. The criterion of the total opportunity cost of using the machine M4 was defined during this study, and the company had no comparative results.

Achieving business objectives requires actions to improve the production process. Some of these measures can be implemented at low cost on certain machines (taking advantage of the possibility to reduce the operating time of these machines). Tunnel rationalization should be carried out with great care, as it may affect the quality of the products manufactured. Adding resources to the process (an additional printer) will increase the operating costs of the process. The economic decision-making process in this regard should concern the balance of profits and losses for the company, taking into account other processes.

The proposed method for solving the problem proved to be effective and efficient. The method can be applied in the case of assortment quantity planning for similar classes of production problems. In this case, it is necessary to know the structure of the production system, the principles of the flow of discrete products through the system, and the basic parameters of technological operations, as well as parameters describing the availability of resources necessary for the implementation of the process. From a business point of view, it is necessary to know the quality criteria used by the company. The variables and parameters of the problem should be linear or can be linearized within the analyzed scope. The model parameters should be deterministic or analyzed for fixed values of random variables. The method makes it possible to define and analyze various quality criteria that can be defined at the company level and that reflect the economic environment in which the company operates.

Within the framework of the applied method, a study of the production process has been carried out in various company cross-sections, which allows for its comprehensive improvement. The conditions of process implementation were taken into account, such as the time of operation, the use of additional resources, and the application of modern concepts of production management. These measures make it possible to examine the changes introduced during the process. The economic viability of the process is also examined on the basis of resource consumption. Transaction methods, product prices, and opportunity costs are analyzed. These criteria make it possible to assess which of the actions undertaken will bring the greatest benefit to the company. The results can be used directly to support business decisions.

The identification and analysis of the problem can be carried out using tools and techniques known and used in production management. The construction of a simulation model requires the availability of an appropriate computer program and the ability to use it. Building optimization models requires knowledge of mathematics and basic knowledge of optimization and solving mathematical programming problems. Conducting experiments and analyzing the results requires experience in conducting research. Due to the above requirements, the method has an interdisciplinary character. It combines the knowledge and skills of production management, computer science, and mathematics and relates the results obtained to financial measures, thus supporting the economic optimization of the company. Its application requires good skills in the above-mentioned fields.

As the results obtained show, despite the relatively high requirements, the proposed method can be used as an effective research tool in production management. The advantages of its application are related to the possibility of an in-depth analysis of the problem under consideration. This is possible thanks to the use of simulation modelling, which provides a broad knowledge of the problem through the possibility of carrying out different experiments. On this basis, it is possible to look for areas where the analyzed process can be improved. Optimization, on the other hand, makes it possible to map the business expectations of a company and to search for the best possible solutions in the area analyzed. The combination of simulation modelling and optimization creates a synergy effect, which is most visible in showing how certain actions in the production process translate into the possibility of realizing the company's business objectives in an economic environment. In this respect, the method has a very practical character from the point of view of the company and its results have an implementation meaning. The method is fully scalable and can be used to solve problems of varying size and complexity. It is clear that the execution time will be longer for larger problems.

In technical terms, the whole process requires time to gather information from the business, build models, and run experiments. The timing of these activities depends on both the company and the research team. In practice, several weeks are needed. Running the experiments themselves takes no more than a few days. Single optimization experiments for relatively simple models take from a few tens of seconds to a few minutes. As the size of the problem increases, they become longer. The optimization algorithm for the problem investigated proved to be very effective, providing at least feasible solutions in every case.

The multidisciplinary nature of the method makes it possible to consider different aspects of the problem. The method can be developed in terms of improving its steps, including the additional quality criteria, as well as the methods and tools used to carry out the analyses. As directions for the development of this work, one can indicate the testing of the method on other production problems (different structure, different size) and the use of other programs for simulation modelling (comparison of time and efficiency of work) and other optimization algorithms (possibility of solving other types of mathematical programming tasks). The use of production management concepts proposed in the literature to improve production processes can also be considered. The proposed method responds to the business needs of companies to make decisions on the preparation of production plans based on economic indicators. The proposed method can be used for solving similar problems in enterprises using discrete production in the textile, metal, and furniture industries and in other industries with a similar type of production. A limitation of the size of the solved problems may be the efficiency of the optimization solver (in general, the problem is *NP-hard*). The verification of the effectiveness and efficiency of the solver would require separate studies. For this reason, the method is recommended for production processes in small- and medium-sized industrial enterprises.

5. Conclusions

The research problem presented in this paper has been solved. A problem-solving methodology has been proposed and successfully applied to solve a real production problem. The IT and optimization tools used have confirmed their usefulness. The results

obtained have both a research character and can be directly implemented in the analyzed company. All the stated requirements of the problem were addressed and successfully verified by this study. This applied to both elements of the production process and its business aspects. The final results indicate a significant increase in the production volume and increase in the achieved profit. The proposed method is of a practical nature and can support managers in their decision-making process. The proposed method has been critically analyzed. The conclusions indicate that a relatively high level of knowledge in various subject areas is required from its users. The method can be applied to other production problems of a similar nature. From a research point of view, the added value of this work is the integration of simulation modelling and mathematical programming to improve the quality of solving decision problems in the area of production management. By optimizing the production program, savings can be made in the use of production materials, in the water and energy used in the production process, and in the resources used in production preparation. This improves the sustainability of companies and their financial efficiency.

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