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OPTIMIZING SUPPLY CHAIN IN A FOUNDRY THROUGH COMPUTER SIMULATION USING FLEXSIM – A CASE STUDY

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Abstract: The article presents the optimization of supply chain management in a foundry using computer simulation with the FlexSim program. The authors analyze collaboration with external entities in the production process, focusing on the settlement of raw materials, transportation services, and storage costs. Special attention is given to the production plans of subcontractors integrated into the operational production schedule. Utilizing the 3D FlexSim environment, they showcase a simulation model optimized for minimizing the costs of production, transportation, and storage of alloying elements essential for iron casting production. The case study illustrates the effective use of computer simulation in refining supply chain management within the context of the foundry production process.

Keywords: supply chain management, optimization, computer simulation, FlexSim

1. INTRODUCTION

Supply Chain Management (SCM) is a key area for the effective functioning of companies, enabling the optimization of processes related to sourcing raw materials and delivering finished products or services. In the context of manufacturing and distribution enterprises that collaborate with external entities, it becomes crucial to focus on cooperation aspects, starting from settlements related to raw materials and semi-finished products, up to the final production stage delivered by subcontractors (Kot, 2023; Dadi et al., 2021; Drljača, 2019; Ulewicz, 2018, Borkowski et al., 2012, Ingaldi et al., 2021).

In the realm of collaboration in supply networks, an increasing number of distribution companies recognize the opportunity to better adapt to dynamic market changes, especially in environments with variable demand and short product life cycles. Shifting the final production stage to distribution enterprises becomes a strategic choice for efficient product distribution (Drljača et al., 2020; Knop, 2023; Umam and Sommanawat, 2019).

In the context of supply chain planning, developing a set of measures monitoring efficiency, costs, quality, and customer value plays a significant role (Ulewicz et al., 2016). In supply chain management processes, key aspects such as pricing, supplier selection, payments, as well as monitoring and improving relationships with suppliers should be considered. Inventory management processes, including receiving, checking deliveries, transferring them to production, and approving supplier payments, are also essential (Adeyeri and Ayodeji, 2022; Nguyet et al., 2020; Saragih et al., 2020, Deja et al., 2023).

Recent advancements in computer technology and production engineering have allowed the virtual representation of real production processes using advanced IT tools such as Technomatix Plant Simulation, Matlab/Simulink, Enterprise Dynamics, Arena, FlexSim, Vensim, Excel/Solver, and others. These tools enable the modeling, simulation, and optimization of manufacturing processes, especially in the context of mass production (Krynke, 2021). Currently, IT tools are increasingly used for tracking, monitoring, and visualizing production processes in real-time (Beaverstock et al., 2011; Schmid, 2022). Crucial elements of effective production planning are appropriate mathematical models and optimization algorithms, particularly important in the simulation stage of virtual production system models (Castane et al., 2019; Daroń, 2022; Krynke and Klimecka-Tatar, 2022; Vanko et al., 2023).

Computer modeling and simulation are effective tools supporting decision-making, especially when analytical solutions are difficult or time-consuming (Gołda et al., 2019; Siwiec et al., 2022).

The presented approach becomes particularly useful after an appropriate reduction of the dimensionality of the problem (Skrzypczak-Pietraszek and Pietraszek, 2014; Pietraszek and Skrzypczak-Pietraszek, 2015), also using fuzzy approaches (Pietraszek et al., 2017a). It may also be inspiring in areas that use similar optimization mathematical models (Radek et al., 2021), including DOE (Radek et al., 2014; Pietraszek et al., 2017b).

The article discusses a collaboration model in the context of manufacturing and distribution enterprises, focusing on the comprehensive fulfillment of orders in the foundry industry. The study addresses the problem of choosing suppliers of alloy additives for iron production within the production and logistics network context. Using the methodology applied in transport-production issues, the focus is on efficiently planning the production process, especially in situations where the goods have not yet been produced, and decisions regarding production location and distribution to recipients are crucial for minimizing the total costs of production, transportation, and potential storage of surplus (Krynke et al., 2019). In this concept, the FlexSim simulation environment with the embedded optimization module OptQuest was used to solve the problem (Laguna, 2011; Pawlewski and Anholcer, 2019).

2. CONSTRUCTION OF THE SIMULATION MODEL – CASE STUDY

A consortium of companies specializing in the production of alloy additives is faced with the need to construct a production and raw material supply plan for foundries, aiming to maximize profits by minimizing delivery-related costs. The suppliers for these companies are three production facilities (designated as M_i), supplying alloy additives to four different foundries (designated as N_j). The production capacity coefficients of individual facilities (A_i), demand submitted by the foundries (B_j), unit transportation costs (t_{ij}) from the facilities to the foundries, and unit production costs of alloy additives in individual facilities (p_i) [in monetary units per ton] are presented in Table 1.

Furthermore, it is assumed that the facilities will utilize their production capacities, and any excess production will be stored for future export. The unit storage costs in individual facilities are respectively: 5, 5, 6 monetary units per ton of alloy additives.

Table 1
Production companies capacities (A_i), demand reported by foundries (B_j), unit transport costs (c_{ij}) from companies to the foundry, and unit costs of production of alloying additives in individual companies (p_i)

Suppliers (Companies)	**Recipients (Foundries)**				**Storage**	**A_i [Mg]**	**p_i [monetary units/Mg]**
	N_1	**N_2**	**N_3**	**N_4**	**N_5**		
M_1 [monetary units/Mg]	50	40	50	20	5	100	1080
M_2 [monetary units/Mg]	40	80	70	30	5	50	1060
M_3 [monetary units/Mg]	60	40	70	80	6	80	1100
B_j [Mg]	40	60	50	50	30	Σ230 Σ200	

Source: own study

The goal is to create a comprehensive plan for the production, transportation, and storage of alloy additives, so that the total costs of these processes are minimized. This problem falls into the category of open problems, where the sum of the production capacities of the facilities (ΣA_i) is 230, exceeding the sum of the demand submitted by the foundries (ΣB_j), which is equal to 200. The introduced decision variables x_{ij} represent the quantity of alloy additive production in the i-th facility (where $i = 1, 2, 3$) delivered to the j-th foundry (where $j = 1, 2, ..., 5$), with x_{i5} specifying the quantity of castings that will remain in the inventory of the i-th supplier. The ultimate goal is to optimize these variables in such a way that the costs of the entire process are minimized.

The optimization task can be described using boundary equations (1), constraint conditions (2), and the objective function (3). Decision variables, representing the quantity of production for each product, are denoted as x_{ij}, where the index i specifies the type of product, and the index j denotes the type of machine on which the production of the given product is conducted. The matrix of total production, transportation, and storage costs is denoted as $c_{ij} = t_{ij} + p_i$.

$$\sum_{i=1}^{3} x_{i1} = 40,\ \sum_{i=1}^{3} x_{i2} = 60,\ \sum_{i=1}^{3} x_{i3} = 50,\ \sum_{i=1}^{3} x_{i4} = 50,\ \sum_{i=1}^{3} x_{i5} = 30 \tag{1}$$

$$\sum_{j=1}^{5} x_{1j} \leq 100,\ \sum_{j=1}^{5} x_{2j} \leq 50,\ \sum_{j=1}^{5} x_{3j} \leq 80 \tag{2}$$

$$F(x_{ij}) = \sum_{i=1}^{3} \sum_{j=1}^{5} (c_{ij} \cdot x_{ij}) \rightarrow min, \tag{3}$$

The objective function (3) encompasses optimization criteria related to the quantity of products x_{ij}. The task involves finding values for the variables x_{ij} for which the objective function achieves the minimum value within the set of permissible decision values.

In every optimization task, it is crucial to construct a correct simulation model that allows for an accurate representation of the real process. In the FlexSim simulation environment, it is necessary to select appropriate elements from the object library available on the left side of the main program window. These elements serve the function of "mimicking" machines, raw materials, or products produced in reality. The logic of the flow of the examined process is created by adding relevant connections that enable the movement of flow elements, such as the production of raw materials in this case. An exemplary simulation model for addressing the discussed problem is presented in Figure 1.

In the simulation model, we distinguish 15 sources, representing quantities of products x_{ij}, 4 processors *N1* to *N4* representing 4 foundries, 1 processor *N5* responsible for production in the warehouse, and 3 processors *p1* to *p3* representing individual suppliers. Additionally, there are outputs (*Sinks*) for each supplier, tallying the production of delivered raw materials. The quantity of delivered raw material for each recipient and to the supplier's warehouse is simulated through flow elements generated by one of the 5 sources, operating in *Arrival Sequence* mode. It is worth noting that this model takes into account different suppliers, and the quantity of delivered raw materials is a key variable for the optimization process. The optimizer generates results from successive iterations at the location where this flow element is defined.

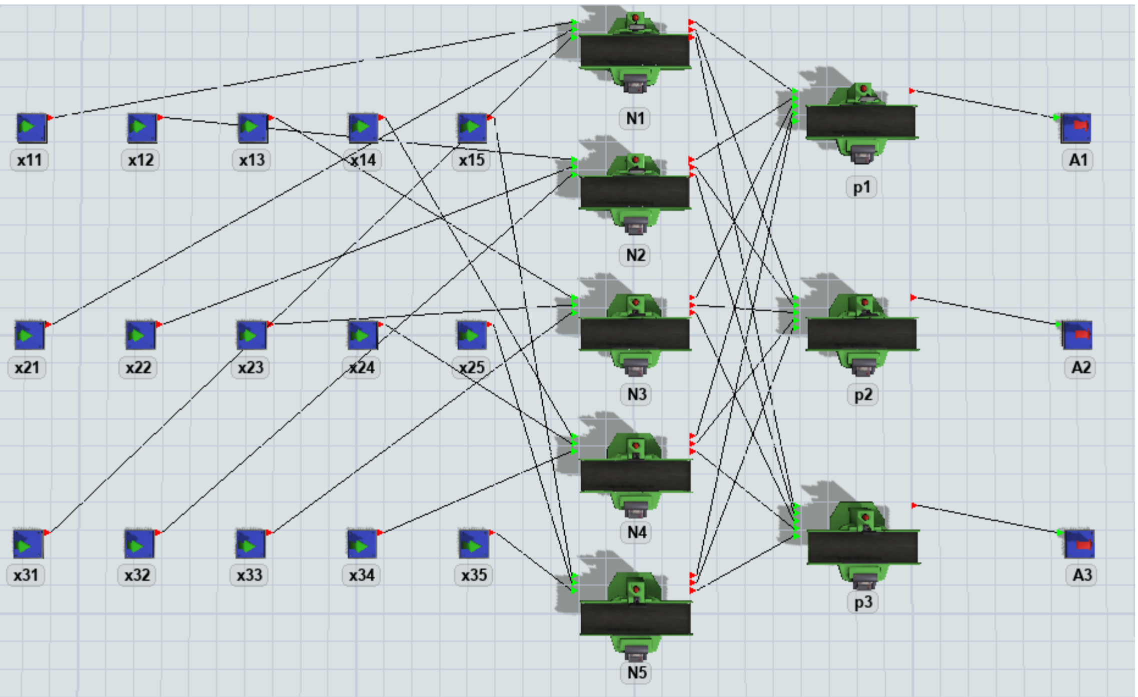
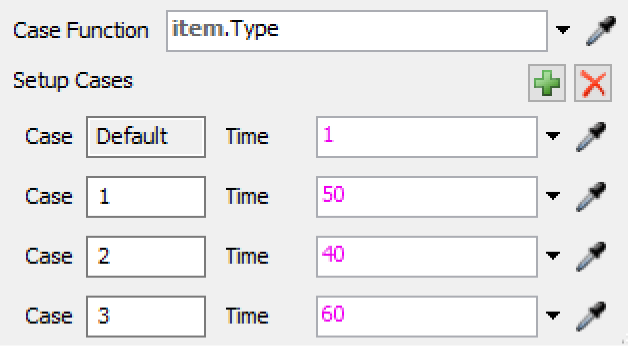


Fig. 1. Simulation model for the discussed problem

Source: own study

Each source is connected to the respective processor simulating the type of recipient. Each recipient is then connected to a processor representing individual supplier facilities. Due to the varied costs of different deliveries, the efficiency of processors is set based on the type of delivery. Therefore, it is necessary to account for this in the working time configuration for each processor. The *Values By Case* function is used for this purpose, where the durations of individual operations are set, depending on the input ports for the processor. An example of such settings for processor *N1* is presented in Figure 2.



Case Function: item.Type

Setup Cases

Case	Default	Time	1
Case	1	Time	50
Case	2	Time	40
Case	3	Time	60

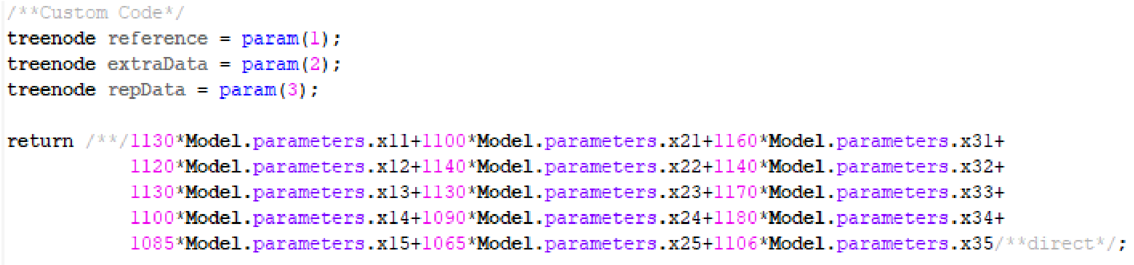
Fig. 2. Configuration of work time for the first workstation (efficiency) for individual suppliers

Source: own study

To ensure that the finished units from individual suppliers leaving the processors reach the appropriate output ports based on their types, it is necessary to configure the flow logic in the *Output* tab accordingly. Using the *By Expression* function, you can sort the types of suppliers according to their types, as defined in the configuration of the *Source* objects.

In the analysis of this problem, the *OptQuest* optimizer embedded in the FlexSim platform was utilized. Its operation is based on neural networks and metaheuristic algorithms (Laguna, 2011).

The objective function is based on the variable costs associated with the working time of individual processors representing suppliers and recipients. In the analyzed case, the working time for each workstation was set at a constant level according to Table 1 and is 1 currency unit/ton per second. This parameter should be defined by adding it from the Toolbox library as a *PerformanceMeasures* variable. Custom code should be used here (see Figure 3).

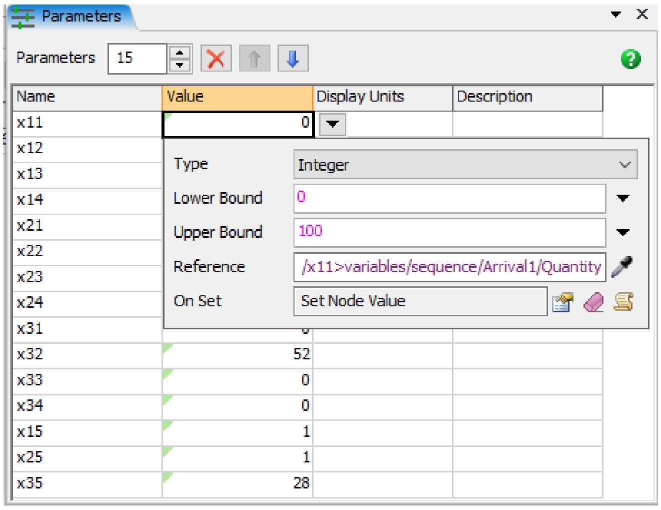


```
/**Custom Code*/
treenode reference = param(1);
treenode extraData = param(2);
treenode repData = param(3);

return /**/1130*Model.parameters.x11+1100*Model.parameters.x21+1160*Model.parameters.x31+
           1120*Model.parameters.x12+1140*Model.parameters.x22+1140*Model.parameters.x32+
           1130*Model.parameters.x13+1130*Model.parameters.x23+1170*Model.parameters.x33+
           1100*Model.parameters.x14+1090*Model.parameters.x24+1180*Model.parameters.x34+
           1085*Model.parameters.x15+1065*Model.parameters.x25+1106*Model.parameters.x35/**direct*/;
```

Fig. 3. Objective function defined as a performancemeasures variable
Source: own study

To enable the optimizer to determine the optimal production and delivery plan, it requires certain parameters specifying the quantity and location of delivered raw materials. These parameters need to be defined by adding them from the Toolbox library. In this model, it is assumed that the minimum order quantity is 1 ton of raw material; hence, in the *Value* column, the variable type should be selected as *Integer* (see Figure 4). The boundary values should be set according to the logic of the task, taking into account the production capacities of the suppliers. The optimizer settings are shown in Figure 5.

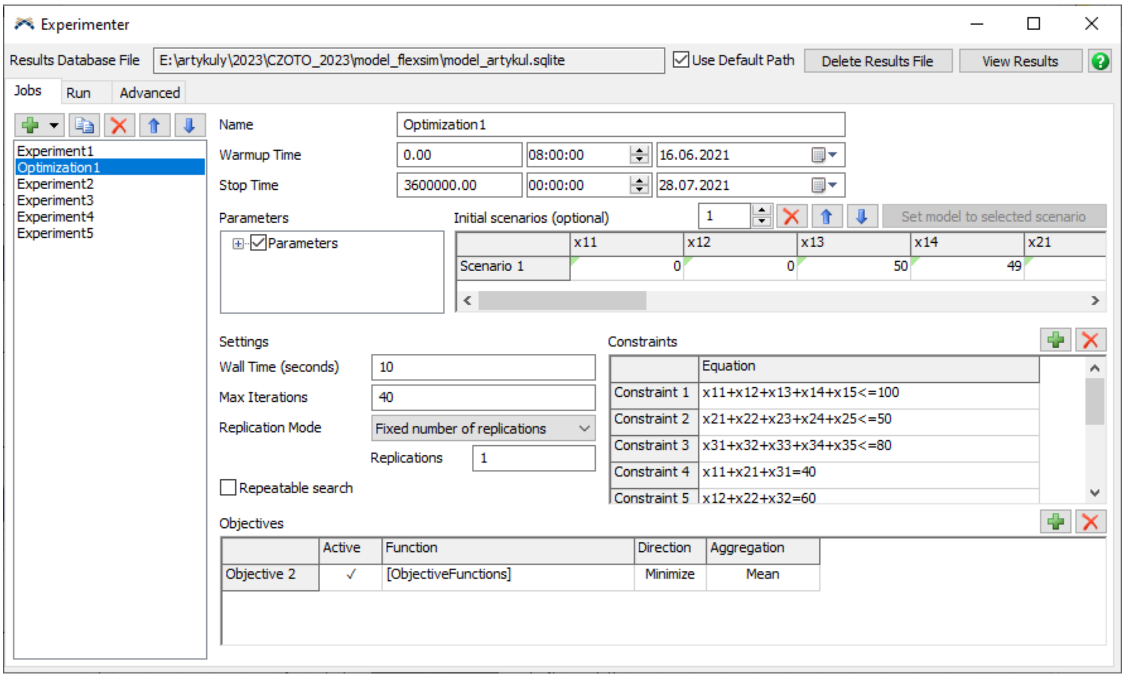


Type: Integer
Lower Bound: 0
Upper Bound: 100
Reference: /x11>variables/sequence/Arrival1/Quantity
On Set: Set Node Value

Name	Value	Display Units	Description
x11	0		
x12			
x13			
x14			
x21			
x22			
x23			
x24			
x31			
x32	52		
x33	0		
x34	0		
x15	1		
x25	1		
x35	28		

Fig. 4. Definition of variables determining the quantity and location of delivered raw materials
Source: own study

The optimizer settings are shown in Figure 5. The objective of this task is to minimize the objective function since the consortium of suppliers aims to reduce production and delivery costs. The FlexSim optimizer will adjust the values of the defined parameters until it finds optimal values where production and delivery costs reach the lowest level.



Results Database File: E:\artykuly\2023\CZOTO_2023\model_flexsim\model_artykul.sqlite ☑ Use Default Path

Experiment1
Optimization1
Experiment2
Experiment3
Experiment4
Experiment5

Name: Optimization1
Warmup Time: 0.00 08:00:00 16.06.2021
Stop Time: 3600000.00 00:00:00 28.07.2021
Parameters: ☑ Parameters
Initial scenarios (optional): 1

	x11	x12	x13	x14	x21
Scenario 1	0	0	50	49	

Settings
Wall Time (seconds): 10
Max Iterations: 40
Replication Mode: Fixed number of replications
Replications: 1
☐ Repeatable search

Constraints

	Equation
Constraint 1	x11+x12+x13+x14+x15<=100
Constraint 2	x21+x22+x23+x24+x25<=50
Constraint 3	x31+x32+x33+x34+x35<=80
Constraint 4	x11+x21+x31=40
Constraint 5	x12+x22+x32=60

Objectives

	Active	Function	Direction	Aggregation
Objective 2	✓	[ObjectiveFunctions]	Minimize	Mean

Fig. 5. Configuration of the flexsim Optimizer

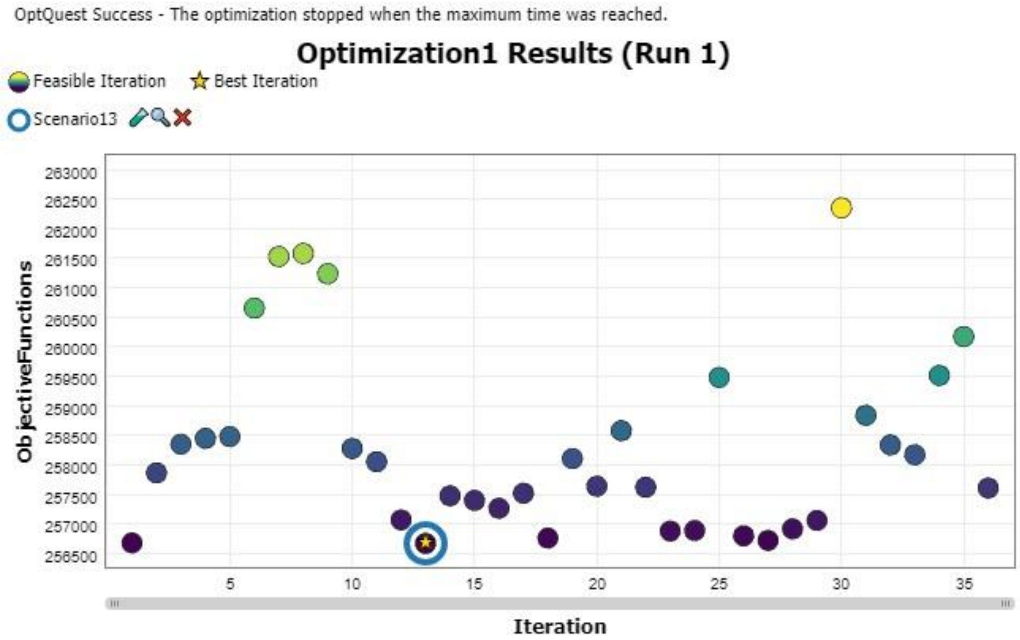
Source: own study

3. RESULTS ANALYSIS

As a result of the optimizer's work, essential data is obtained, serving as input information for various scenarios in the analyzed model. The optimizer's constraints are captured in equations (1) and (2). The objective function (3) represents a single-criteria optimization task aiming for minimization. Under the assumed conditions, the program searches for the optimal solution within the set of permissible decisions. The input variable type for all cases is set as *Integer*.

The set of solutions generated by the optimizer is presented in Figure 6, where permissible solutions are limited to 40 results, marked as points. Among them is the optimal solution, indicated by a star, with a value of 256,670 monetary units. This represents the minimum value of the objective function (production and delivery cost) within the constraints of this task.

Table 2 presents the allocation of suppliers and foundries along with the quantities of deliveries, assuming that the facilities producing alloy additives utilize their production capacities, and the excess production is stored in warehouses for future export. The minimum costs of the planned production and delivery will reach their optimum when Plant *M1* supplies raw materials for Foundries *N3* and *N4*, Plant *M2* for Foundry *N1*, and Plant *M3* delivers alloy additives for Foundry *N2*. Additionally, Plants *M2* and *M3*, to efficiently use their production capacities, should produce products in Warehouse *N5* with future export in mind.



OptQuest Success - The optimization stopped when the maximum time was reached.

Fig. 6. Wyniki rozwiązań zwróconych przez optymalizator

Source: own study

Table 2

Optimal Allocation of Suppliers *M* to Individual Foundries *N*, in a situation where the facilities producing alloy additives will utilize their production capacities and store excess production

Suppliers (Companies)	**Recipients (Foundries)**				**Storage**	**Total Cost**
	N_1 [Mg]	**N_2 [Mg]**	**N_3 [Mg]**	**N_4 [Mg]**	**N_5 [Mg]**	**c_i [monetary units]**
M_1	0	0	50	50	0	111500
M_2	40	0	0	0	10	54650
M_3	0	60	0	0	20	90520
Σ	40	60	50	50	30	256670

Figure 7 illustrates the total cost of order fulfilment for two extreme scenarios. The first case corresponds to the optimal solution where costs are minimized. For comparative purposes, the second scenario presents a situation where costs have been maximized.

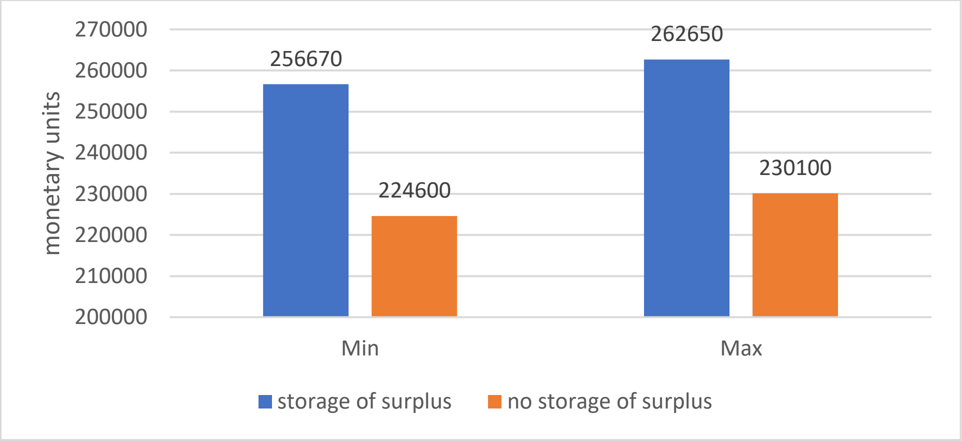


Fig. 7. Total costs of order fulfilment in the case of minimizing and maximizing cost criteria

Source: own study

The comparative analysis shows that in the case of the most unfavorable choice of suppliers, this leads to an increase in costs by almost 6 thousand monetary units when the facilities utilize their production capacities and store excess production in the warehouse, and by 5.5 thousand monetary units when the facilities are not fully utilized, and the production of alloy additives is in line with the foundries' demand. The obtained results were verified using the glpk Solver tool in the Octave environment (Krynke, 2020).

5. CONCLUSION

The proposed analysis forms the foundation for an effective business planning process, integrating information from the areas of operations, sales, marketing, and business partners. A modern approach to improving production processes must take into account innovative management trends in a market economy.

Computer simulation with process optimization becomes a crucial tool, enabling not only problem identification but also the discovery of optimal solutions. The presented model can be easily adapted to different scenarios, considering a greater number of suppliers, recipients, and breaking down the analysis into various stages of production.

In the context of improving manufacturing processes, modern tools such as 3D simulation environments, like FlexSim, become a key element of planning. They offer higher-quality simulation models and enable their optimization. Real-time visualization of the analyzed phenomenon allows for a better understanding of production processes.

The application of computer simulation with process optimization becomes a practical tool for strategic planning. It allows for the incorporation of the company's strategies, identifying the most efficient solutions to minimize production costs and maximize profits.

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