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ANALYSIS AND IMPROVEMENT OF GEARBOX MANUFACTURING PROCESS USING SIMULATION MODELLING

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ABSTRACT

Industrial valves, which control the flow of fluids such as liquid, gas or vapor, are an essential part of modern industrial processes. The gearboxes used in industrial valves are critical components that optimize power transmission and control. Design and quality of gearboxes have a great impact on efficiency and safety of the processes. In this concern, analyzing gearbox manufacturing processes and carrying out process improvement studies will provide advantages to manufacturers in terms of time, cost and quality. This study aims to analyze and improve the gearbox manufacturing process of an industrial valve manufacturer. To this aim, the current gearbox manufacturing process was simulated and the bottleneck station was identified. In order to overcome the bottleneck, alternative production scenarios such as contract manufacturing and new machine investment were proposed. Afterwards, simulation models for alternative scenarios were developed, taking into account the quality problems that may occur in alternative scenarios and the investment cost associated with the new machine investment. Finally, all alternative production scenarios were compared with the current situation in terms of production quantities, makespan and profit. The results revealed that investing in a new machine is more profitable for the company than contract manufacturing.

Keywords: Gearbox manufacturing, Simulation modelling, Process improvement.

1 INTRODUCTION

Industrial valves are used to control the flow of liquids, gases and vapors in many different industrial processes. The main functions of these valves can be stated as changing the

direction of fluids, providing flow control, balancing pressure and ensuring process safety. The gearbox used in industrial valves is the mechanism that allows valves to be opened and closed manually. It plays an important role especially in applications requiring high torque, in cases where large and heavy industrial valves are used, and in difficult operating conditions such as high temperature or pressure.

The design and manufacturing processes of gearboxes vary depending on the place and purpose of use. However, these processes usually include material selection, design, production, assembly and testing stages. Each stage is critical to ensuring properties such as high durability, corrosion resistance, sealing, efficient torque transmission, and resistance to high temperatures. There are various studies in the literature on design and mechanical analysis of gearboxes. For instance, Dalbiçer focused on the design of a gearbox housing that reduces vibration in his study [1]. Mousavi conducted a study on the design of a new magnetic gear that can be used in wind turbines [2]. Suresh et al. carried out a simulation study on the design of the gearbox used in stone crushing ball mill [3]. In addition, Mujiburrahman et al. used simulation in their study to select the gearbox housing material [4]. In another study, Kumar et al. aimed to create a design that reduces the weight of the gearbox by saving material [5].

From another point of view, in today's industrial markets, ensuring customer satisfaction plays a major role in achieving sustainable competitive advantage. However, customer expectations are increasing rapidly and companies are trying to meet these expectations with limited resources. For this reason, companies need to analyze their production processes and carry out studies that will increase production efficiency, reduce costs and improve quality. At this point, simulation appears to be a powerful tool in predicting the potential effects of process improvement efforts [6]. Thus, many alternatives that are costly and time-consuming to test on a real system can be easily tested on a digital copy of the system. In this regard, researches addressing process improvement and simulation modelling issues in production systems were examined. It is concluded that most of the studies in this field focused on bottleneck detection, reducing manufacturing lead times and costs, increasing production and resource utilization efficiency [7] - [17].

Bottlenecks play an important role in production systems as they determine the maximum capacity of the entire system. Besides this, bottlenecks have significant impacts on system performance such as throughput, cycle time, makespan, lead times, work-in-process inventories etc. In this concern, many studies have been conducted on the detection and resolution of bottlenecks in production systems. The reader may refer to Tang et al. and Skoogh

et al. for a detailed review of the studies on bottleneck detection methods and bottleneck elimination strategies [18], [19]. The most commonly used bottleneck detection methods can be stated as analytical methods, time-based methods, simulation-based methods and data-driven methods. Among these methods, simulation modelling is a powerful diagnostic tool that makes bottleneck detection faster, safer and without disrupting operations. When bottleneck resolution approaches are evaluated, it can be concluded that bottlenecks can be eliminated by increasing the number of the bottleneck machines, increasing the buffer size in front of the bottleneck machine, or reducing the processing time of the bottleneck machine. Herein, we have investigated the studies focusing on bottleneck detection using simulation. In one of these studies, Velumani and Tang considered a tire manufacturing system and detected bottlenecks based on the utilization rate of machines. They focused on throughput performance and tried to resolve bottlenecks by adjusting buffer sizes and rerouting batches [20]. Krishnan et al. also focused on the throughput performance and detected bottlenecks by considering average queue waiting time. They eliminated the bottleneck by reducing the processing time of the bottleneck machine [21]. Similarly, Thürer et al. overcame the bottleneck problem by reducing the processing time of the bottleneck machine. They considered both throughput and lead time objectives and used five different bottleneck detection methods [22]. In another study, Li et al. handled utilization rate and four other bottleneck detection methods and evaluated the effect of increasing the number of machines in a bottleneck station on makespan performance [23]. Mousavi et al. conducted a study on bottleneck detection in mining production. They identified bottlenecks based on the utilised capacity and analyzed the effect of increasing the fleed size on production quantity [24].

These studies show us that the utilization rate is a widely used method in bottleneck detection, and increasing the number of machines at bottleneck stations is a common bottleneck resolution approach. However, increasing the number of machines in a production system has a cost. Therefore, cost-benefit analysis should be performed in case of new machine investments. On the other hand, new machines can sometimes create uncertainties about product quality due to lack of historical performance data, calibration issues, operator inexperience, material incompatibility and unforeseen interactions with the existing system. That’s why, possible quality changes should also be taken into account. To the best of our knowledge, these two important issues have not been considered in the previous studies on bottleneck detection and resolution using simulation.

In the light of all this information, this study aims to analyze and improve the gearbox manufacturing system of an industrial valve manufacturer. For this purpose, firstly the current gearbox manufacturing process is simulated using ARENA software and the bottleneck station is detected. Accordingly, two bottleneck resolution alternatives such as contract manufacturing and new machine investment are proposed. Then, production scenarios were developed considering the possible product quality problems related to bottleneck resolution alternatives. Finally, effectiveness of alternative production scenarios was evaluated in terms of makespan, production quantities and profit by using simulation modelling. In addition, a break-even analysis of the new machine investment was performed.

The remainder of this study is organized as follows. Section 2 presents the brief information on simulation modelling, simulation model of the current gearbox manufacturing process and model validation. Bottleneck detection and alternative production scenarios are explained in Section 3. In addition, the comparison of the alternatives with the current situation and research findings are also included in the same section. Finally, conclusions and future research directions are given in Section 4.

2 MATERIAL AND METHOD

In this paper, simulation modelling is used to analyze and improve the gearbox manufacturing process of an industrial valve manufacturer. Simulation modelling is a technique that aims to analyze the behaviour of real-world systems or processes by creating a mathematical model of these systems. In simulation modelling, a digital copy of the real system is created in a virtual environment. In this way, experiments that are costly, time-consuming and sometimes impossible to perform on the real system can be easily performed and the results can be compared. Simulation modelling is especially successful in understanding complex, dynamic and stochastic systems and is frequently used in design, redesign and improvement of these systems [25]. When we consider the production systems, it is seen that simulation modelling technique is used especially in bottleneck detection, layout design, inventory management, production scheduling, capacity planning of resources such as labor, machines and transporters [26] - [29]. On the other hand, simulation of complex systems may require large volumes of data and computational power. In addition, creating simulation models requires deep knowledge and modeling skills.

2.1 Simulation Model of the Gearbox Manufacturing System

In this study, we handled the gearbox used in butterfly valves. This type of gearbox consists of 14 components as it is presented in Table 1 and Figure 1.

Table 1. Components of gearbox.

Component no	Component name	Component no	Component name
C1	Main body	C8	Bushing
C2	Worm wheel	C9	Helical gear bottom
C3	Main body cover	C10	Helical gear top
C4	Adjustment cover	C11	Helical pinion
C5	Gearbox body	C12	Pinion
C6	Gearbox cover	C13	Top flange
C7	Worm shaft	C14	Coupling

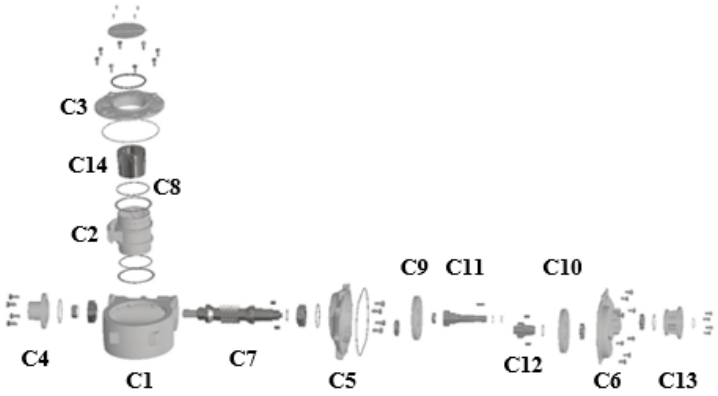


Figure 1. Exploded view of gearbox assembly.

In the simulation model of the system shown in Figure 2, 14 components are supplied in raw form and stored into the input warehouse for the operations. Some of these operations are carried out inside the company, while others are carried out by subcontractors outside the company. There are 13 stations in the simulation model, S1 represents the input warehouse, stations S2-S10 represent operations such as CNC turning, gear cutting etc., S11 represents the semi-finished goods warehouse, S12 represents the assembly station and S13 represents the paint shop station. The components go through operations in their processing routes and become ready for assembly. It should be noted here that each component has a different processing route as it is presented in Table 2. Then, the components that are ready for assembly are collected in the semi-finished goods warehouse and when all components required for a gearbox assembly are ready, they are sent as a set to the assembly station. This set also includes materials such as

gaskets, bolts, bearings and o-rings needed for assembly. In the assembly station (S12), the components are assembled and the gearboxes are produced. These gearboxes are then painted at the paint shop station (S13) and become ready for use. On the other hand, the quality of the components is checked after each operation and the components that do not meet the quality expectations are scrapped. The performance measure of the problem is determined as the minimization of makespan, which is equal to the completion time of 100 gearboxes.

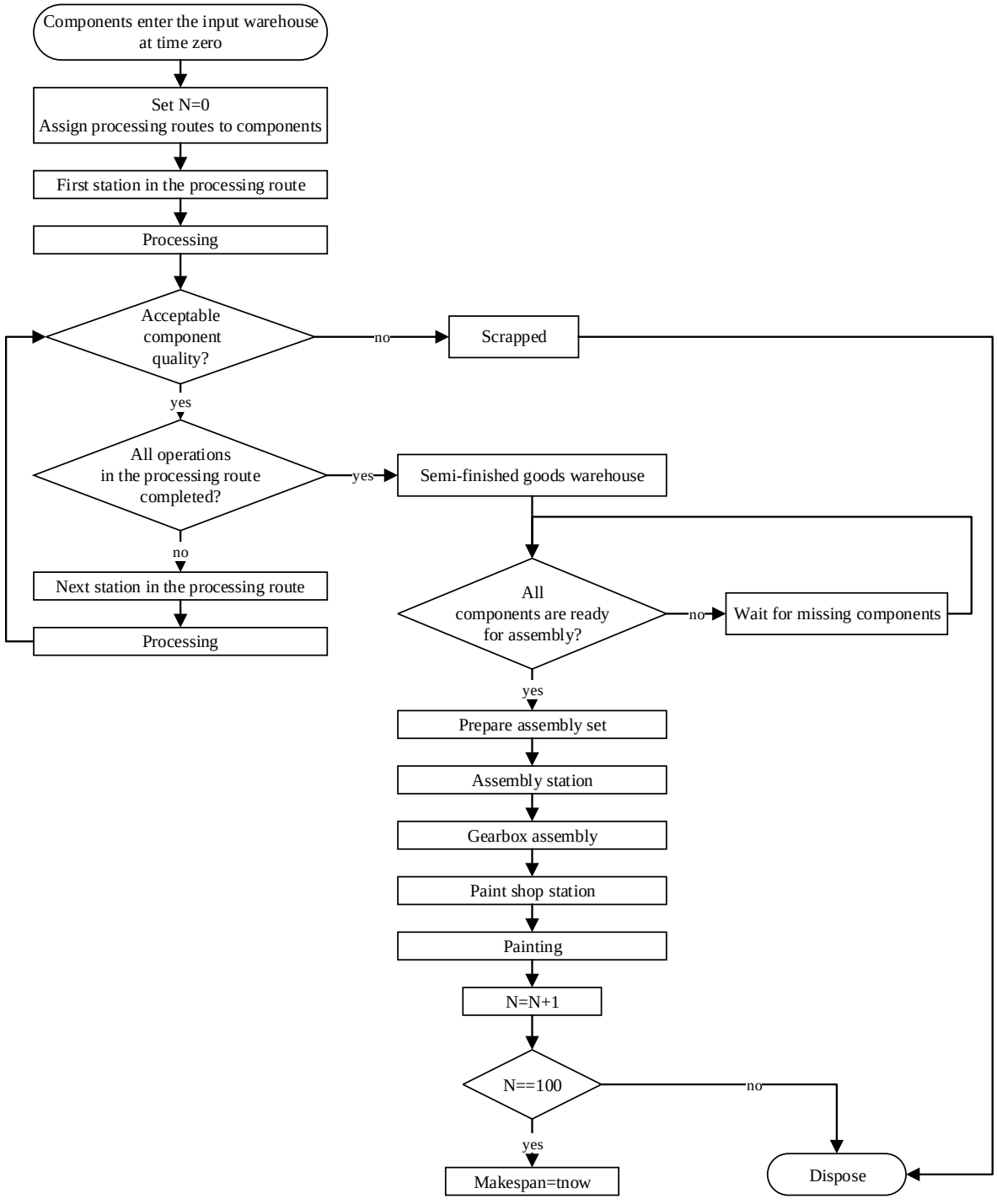


Figure 2. Flow of the simulation model.

Table 2. Processing routes.

Component no	Processing route	Component no	Processing route
C1	***S1***-S2-S5-***S11***	C8	***S1***-S3-***S11***
C2	***S1***-S2-S6-S8-***S11***	C9	***S1***-S2-S3-S4-S8-***S11***
C3	***S1***-S2-S7-***S11***	C10	***S1***-S2-S3-S4-S8-***S11***
C4	***S1***-S2-S3-S4-***S11***	C11	***S1***-S9-S8-S10-***S11***
C5	***S1***-S2- S4-***S11***	C12	***S1***-S3-S8-***S11***
C6	***S1***-S2- S4-***S11***	C13	***S1***-S2-S3-S4-***S11***
C7	***S1***-S3-S8-***S11***	C14	***S1***-S6-S8-***S11***

The underlying assumptions of the problem can be stated as follows: (i) machines are always in a good condition; (ii) processing routes are known and dependent on the component type; (iii) processing times are stochastic and vary depending on the component and station; (iv) input warehouse and semi-finished goods warehouse have sufficient capacity to store items; (v) gaskets, bolts, bearings and o-rings needed for assembly are always available; (vi) components are processed on a first-come-first-served (FCFS) basis; (vii) all components are ready in the input warehouse at time zero; (viii) the setup operations are negligible; (ix) travel times between stations are negligible and (x) buffer spaces are unlimited.

2.2 Model Validation

In simulation studies, it is very important to validate that the simulation model runs correctly and generates accurate results. In this regard, trace report of the model should be examined to determine whether the model flow is progressing correctly or not. In this context, simulation model of the current gearbox manufacturing process was run for the completion of two gearbox assemblies. Before this, input analysis was performed on the historical data and the distribution of processing times was determined using chi-square goodness of fit test, as presented in Table 3. Since no operations are carried out at input warehouse (S1) and semi-finished goods warehouse (S11), there is no processing time for these stations. On the other hand, assembly time of components is normally distributed with a mean of 150 minutes and a standard deviation of 2 minutes, while painting time of a gearbox assembly is normally distributed with a mean of 5 minutes and a standard deviation of 1 minute. Herein, it is assumed that there will be no quality problems in the components to ensure the assembly of two gearboxes.

Table 3. Processing times.

Component	Processing times (min)
C1	5+2.73*BETA (0.451, 0.869) -- 295+18*BETA (0.829, 0.847)
C2	5+2.73*BETA (0.451, 0.869) -- NORM (210,2.74) -- 475+16*BETA (0.623,0.353)
C3	5+2.73*BETA (0.451, 0.869) -- TRIA (92.5, 95, 98.5)
C4	5+2.73*BETA (0.451, 0.869) -- 36.5+9*BETA (1.11, 1.32) -- 17.5+WEIB (4.24, 1.88)
C5	5+2.73*BETA (0.451, 0.869) -- 48.5+10*BETA (1.08, 1.23)
C6	5+2.73*BETA (0.451, 0.869) -- 41.5+6*BETA (1.51, 1.66)
C7	NORM (99.7, 2.75) -- 350+21*BETA (0.552, 0.702)
C8	15.5+5*BETA (1.73, 1.47)
C9	5+2.73*BETA (0.451, 0.869) -- NORM (60.4, 2.65) -- NORM (15.2, 1.31) -- 97.5+WEIB (5.38, 1.63)
C10	5+2.73*BETA (0.451, 0.869) -- NORM (60.4, 2.65) -- NORM (15.2, 1.31) -- NORM (107, 4.27)
C11	37.5+WEIB (3.68, 1.85) -- 31.5+GAMM (1.67, 2.16) -- TRIA (7.5, 10, 12.5)
C12	31.5+5*BETA (1.74, 1.39) -- 37.5+WEIB (2.8, 1.73)
C13	5+2.73*BETA (0.451, 0.869) -- TRIA (31.5, 35.5, 37.5) -- TRIA (9.5, 15, 16.5)
C14	TRIA (99.5, 105, 121) -- NORM (160, 3.07)

In order to validate the model for completion of two gearboxes, two of each component were sent to the system at time zero and the flow of these components within the model was observed. Completion times of the components are recorded as presented in Table 4 and the processing sequence of the components through the stations is also illustrated in Figure 3. When the results given in Table 4 are evaluated, it is revealed that the last completed component is the helical gear top (C10) and the completion time of this component plays a major role in the gearbox manufacturing time.

Table 4. Completion time of components.

Component	Completion time	Component	Completion time
C1-1	315.48919	C8-1	221.69162
C1-2	618.65849	C8-2	240.89964
C2-1	1848.6274	C9-1	1359.2099
C2-2	2537.9538	C9-2	1946.4947
C3-1	134.8535	C10-1	**2053.1385**
C3-2	230.44833	C10-2	**2643.8302**
C4-1	502.42076	C11-1	93.087591
C4-2	540.01146	C11-2	137.10531
C5-1	123.03831	C12-1	1209.7095
C5-2	180.4142	C12-2	1251.3404
C6-1	269.54607	C13-1	700.02794
C6-2	269.54607	C13-2	736.44875
C7-1	486.94433	C14-1	647.73049
C7-2	1007.8708	C14-2	1170.0957

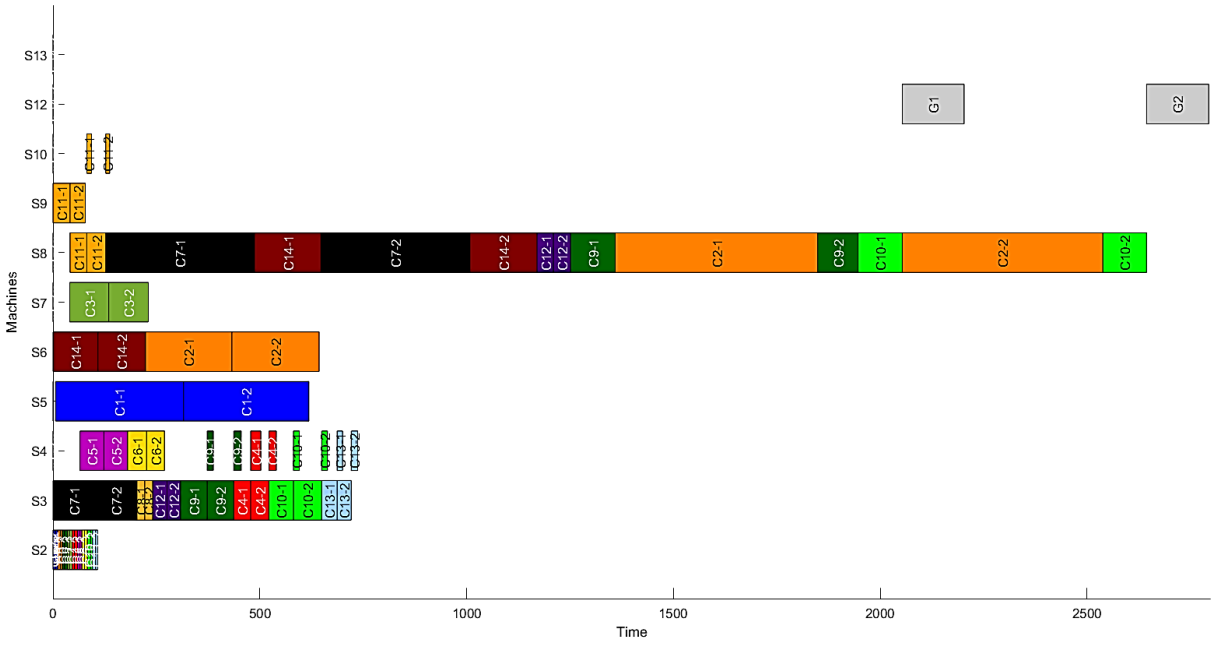


Figure 3. Gantt chart of two gearbox assemblies.

After the processing of the components, the assembly and painting of the gearboxes were carried out within the times given in Table 5. When the results obtained are evaluated, it can be concluded that the model runs correctly.

Table 5. Completion time of gearboxes.

Gearbox	S12 entry time	S13 entry time	Completion time
G1	2053.1385	2202.8152	2207.6698
G2	2643.8302	2794.2017	2799.3271

3 RESULTS AND DISCUSSION

This section consists of three subsections. In the first subsection, bottleneck stations are detected based on utilization rates of machines and bottleneck solution alternatives are proposed. In the second subsection, simulation models of the current situation and solution alternatives are run and the results are evaluated in terms of makespan, production quantities and profitability. In the last subsection, solution alternatives are compared in terms of makespan performance using paired t-test.

3.1 Bottleneck Detection and the Alternative Solutions

The simulation model of the current gearbox manufacturing process is run for the completion of 100 gearbox assemblies. In this context, 100 pieces of each component are sent to the system (S1) at time zero and the simulation model is run 10 replications.

In order to detect the bottleneck stations, the utilization rates of the stations in the manufacturing process were analyzed and the obtained results are shown in Figure 4. According to the results given in Figure 4, station S8 which corresponds to the gear cutting operation performed by the subcontractor, has the highest utilization rate. The gear cutting is an operation that requires a long processing time and is involved in the production process of many components such as worm wheel, worm shaft, pinion, coupling etc. Therefore, alternative solutions should be developed to overcome the bottleneck problem related to this operation.

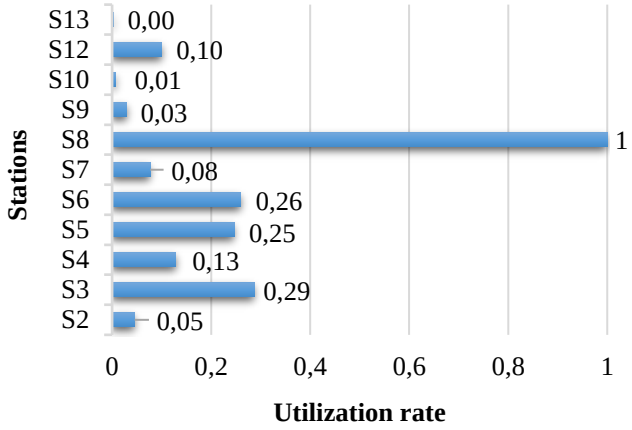


Figure 4. Utilization rates of resources.

In this regard, two alternative solutions are developed regarding to the bottleneck problem. These two solutions aim to solve the bottleneck problem through capacity expansion. One of the alternative solutions is working with an additional subcontractor for the gear cutting operation. In this solution, it is assumed that the additional subcontractor has the same characteristics as the existing one in terms of processing times. However, it is anticipated that working with a new subcontractor may lead to some uncertainties regarding quality. Therefore, we considered the different cases in terms of quality in the performance evaluation of this alternative solution. Another alternative solution is investing in a new machine for the gear cutting operation. In this solution, it is assumed that the processing speed of the new machine is 25% greater than the existing machine used by the subcontractor. On the other hand, it is thought that a machine used for the first time may create uncertainty about component quality.

3.2 Computational Analysis

Simulation models of the solution alternatives are developed and their effects on the existing system are analyzed. In the computational analyses, completion of 100 gearbox assemblies is considered and the performance evaluations are made based on makespan, produced units and profit. The quality rate for the current situation is defined as 95%. However, the quality problems that alternative solutions may create cannot be predicted exactly. For this reason, performance evaluations of alternative solutions are made based on three different quality rates such as 85%, 90% and 95% which correspond to the minimum acceptable quality level, moderate quality level and high quality level, respectively. As a result, six different scenarios regarding solution alternatives were created as it is presented in Table 6.

Table 6. Alternative scenarios.

Scenario	Description
CS	Current situation
SN1	Additional subcontractor, 85% quality
SN2	Additional subcontractor, 90% quality
SN3	Additional subcontractor, 95% quality
SN4	New machine investment, 85% quality
SN5	New machine investment, 90% quality
SN6	New machine investment, 95% quality

Simulation models of the current situation and the alternative scenarios are run for 10 replications and the results are obtained as presented in Table 7. When the results given in Table 7 are examined, it is seen that alternative solutions provide better results in terms of makespan and the best value occurs in SN5 which corresponds to the new machine investment with 90% quality rate. When we evaluate the results in terms of the number of gearboxes produced, we can conclude that the best result is obtained in SN6. In SN6, quality rate increases and the number of components scrapped decreases accordingly. Thus, the number of gearboxes produced increases.

Table 7. Results of computational experiments.

Scenario	Makespan	Number of gearboxes produced	Time saving	Number of additional gearboxes that can be produced
CS	117901.56	78	-	-
SN1	61261.59	74	56639.97	52
SN2	61819.55	76	56082.01	47
SN3	60614.84	77	57286.72	57
SN4	58434.00	75	59467.56	69
SN5	57300.30	76	60601.26	73
SN6	58578.45	79	59323.11	75

In addition, time savings are calculated based on the difference in makespan between alternative solutions and the current situation. Then, the simulation models are run again to calculate how many additional gearboxes can be produced with this time saving. Further, economic analysis is carried out considering the profit that can be obtained by producing additional gearboxes and the results are shown in Table 8.

Table 8. Economic analysis.

Scenario	Number of gearboxes produced	Number of additional gearboxes that can be produced	Total number of gearboxes produced	Additional unit cost	Unit profit	Total profit
CS	78	-	78	-	20000	1560000
SN1	74	52	126	12560	7440	937440
SN2	76	47	123	12560	7440	915120
SN3	77	57	134	12560	7440	996960
SN4	75	69	144	9000	11000	1584000
SN5	76	73	149	9000	11000	1639000
SN6	79	75	154	9000	11000	1694000

Currently, the profit obtained from one gearbox is 20000 TL. For the gear cutting operation, the unit cost of working with an additional subcontractor is 12560 TL, while the unit cost of investing in a new machine is 9000 TL. In this case, the unit profit obtained from a gearbox is 7440 TL for working with an additional subcontractor alternative and 11000 TL for the new machine investment alternative. As it is seen in Table 8, investing in a new machine (SN6) is more profitable than the current situation despite the additional costs, as it leads to increased production quantities.

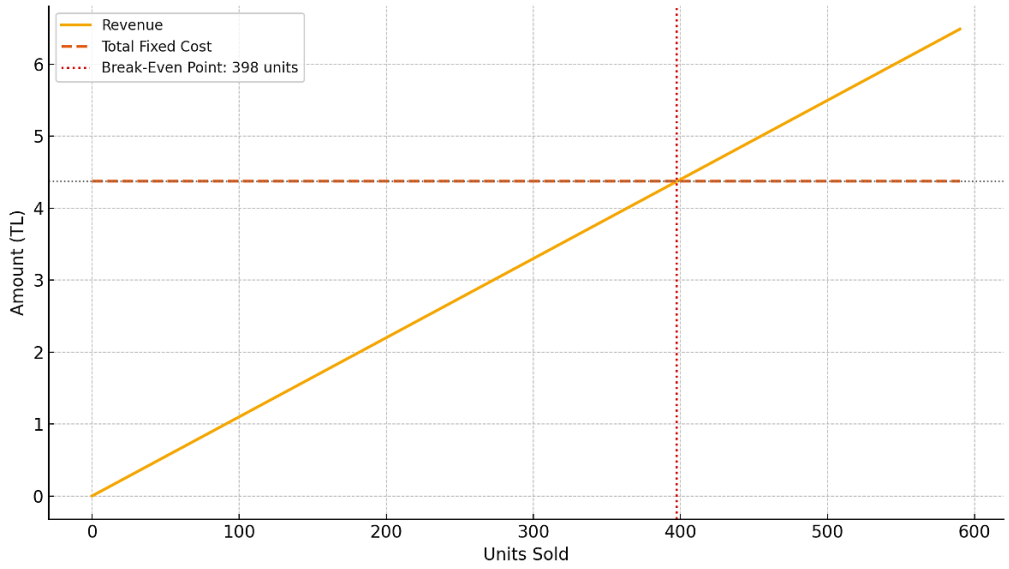


Figure 5. Break-even analysis of new machine investment.

Besides this, we also performed a break-even analysis of the new machine investment. Annual fixed cost of the machine is 3 573 504 TL and the initial investment cost is 800 000 TL. Therefore, total fixed cost is obtained as 4 373 504 TL. As it is stated before, contribution margin of a gearbox is 11 000 TL. When the total fixed cost is divided by the contribution margin, break-even point is obtained as 398 gearboxes as it is presented in Figure 5. This means that at least 398 gearboxes must be sold per year to cover investment and fixed costs.

3.3 Comparison of the Alternative Scenarios using Paired t-Test

Paired t-test is a statistical test used to determine whether there is a significant difference between the means of two variables. The hypothesis tested is as follows:

H_0: $\mu_1 - \mu_2 = 0$

H_1: $\mu_1 - \mu_2 \neq 0$

In this study, the current situation and alternative scenarios are compared using paired t-test in terms of makespan performance measure and the obtained results are given in Table 9. According to the test results, we can conclude that H_0 is rejected in each pairwise comparison made between the current situation and the alternative scenarios. This means, there is a statistically significant difference between the current situation and alternative scenarios in terms of makespan. In addition it is concluded that the model that gives the best result compared to the current situation in terms of makespan is SN5 which corresponds to the new machine investment with 90% quality rate.

Table 9. Results of paired t-test.

Scenario (*i*)	Scenario (*j*)	μ_i	μ_j	Difference ($\mu_i - \mu_j$)	Confidence interval	*p* value
CS	SN1	117901.56	61261.59	56639.97	(54974;58306)	0.000
CS	SN2	117901.56	61819.55	56082.01	(53982;58182)	0.000
CS	SN3	117901.56	60614.84	57286.72	(56475;58098)	0.000
CS	SN4	117901.56	58434.00	59467.56	(56113;62822)	0.000
CS	SN5	117901.56	57300.30	60601.26	(56784;64418)	0.000
CS	SN6	117901.56	58578.45	59323.11	(56530;62116)	0.000

4 CONCLUSION AND SUGGESTIONS

Industrial valves play a critical role in directing, stopping and adjusting pressures of fluids. Gearboxes in industrial valves provide the torque and power transmission needed to

operate a valve. The main purpose of this study is to analyze the gearbox manufacturing process of an industrial valve producer using simulation modelling and to plan process improvement efforts. For this purpose, the existing gearbox manufacturing process is simulated and the bottleneck station is detected. Then, solution alternatives are proposed to overcome the bottleneck and the performance evaluation of these alternatives is carried out using simulation.

Two solution alternatives such as working with an additional subcontractor and investing in a new machine are proposed for the gear cutting operation which is determined as a bottleneck. Computational analyses are performed for the proposed alternatives by considering the quality problems that may occur and the results are evaluated in terms of makespan, production quantities and profit. The results obtained revealed that investing in a new machine provides better results with respect to makespan performance measure, even if the quality rate decreases.

It is believed that this study will support the decision makers in bottleneck detection and process improvement studies and will also enable companies to use resources more efficiently. One of the biggest advantages of the proposed approach is that it considers the quality problems that bottleneck solution alternatives may create. In addition, with the help of simulation modelling, the effectiveness of bottleneck solution alternatives can be easily tested without disrupting the real system. From another point of view, success of the proposed approach highly depends on the accuracy of the simulation models and the effectiveness of the bottleneck solution alternatives will vary depending on production systems. On the other hand, including different bottleneck detection methods such as queue waiting time, inter-departure time, blocking rate etc. and due-date-based performance measurements will enrich the study. From another point of view, optimizing the number of machines at a bottleneck station using simulation optimization is a promising avenue for future research.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Bilal Coşkun: Data collection, input analysis, model development, model validation, experimental analysis, output analysis. **Hülya Güçdemir:** Conceptualization, model development, financial analysis, manuscript writing and editing.

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