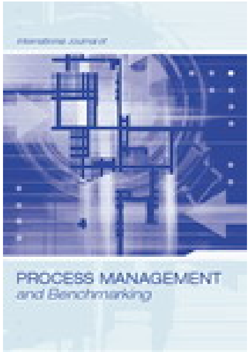

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A simulation-based multi-objective optimisation for critical parameters design of an automotive paint shop using design of experiments

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Abstract: Regarding the increasing demand for luxury cars throughout the world, the painting process in the automotive industry is one of the most important issues. Considering the need for improvement in production performance, quality and agile customer responsiveness, this paper aims to use simulation to present how we can eliminate bottlenecks, and measure the obtained quality enhancement and increase production quantity. Making modifications to an active production line for optimisation purposes is a challenging process if not impossible. Thus, a process simulation method can be suitable for studying the system. This research implements how to use simulation tools in a real paint shop in one of the largest automobile manufacturing companies in Iran. Also, optimisation is used to find the best responses to the changes in the controllable variables or critical parameters. The results show a 58% increase in production capacity and 60% decrease in waiting time of the product.

Keywords: design of experiments; DOE; parameter design; computer simulation; multi-objective optimisation.

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1 Introduction

The automotive industry, one of the most important industries in the world, influences not only the world economy but also world culture. It has provided millions of jobs, billions of incomes and is a base activity for many supportive industries and service companies. Optimisation of production lines can significantly increase production capacity and decrease production time in all manufacturing firms. Establishing a balanced production line is a way to increase productivity and decrease costs. In an unbalanced production system, more cost and resource waste are imposed on the system. In the balancing production line problem, capacity of a line is studied using different indicators to make an optimised decision (Boysen et al., 2007). Afolalu et al. (2021) investigated on production inventory control in automotive industry. They considered analytical and simulation models in this review as they are used in several papers by different authors. There are many tools to optimise planning processes and utilising sources and facilities such as linear programming, Integer programming, queue theory, dynamic programming, simulation, etc. Among them, computer simulation solutions as an analytical tool can dominate many methods in some ways (Shukla et al., 2010). Azab and AlGeddawy (2012) used several simulation methods for changeable manufacturing systems and analysed their cons and pros. Simulation can be described as the process of designing a model of real systems for understanding the system's behaviour or evaluating various strategies of the system's performance. In decision making or operational problems, especially in investment projects, simulation is a very powerful tool. In addition, most manufacturers in the automotive industry analyse simulation models for their operational affairs, new equipment's design or making changes in production systems as a preliminary process before a purchasing process. To follow this policy, purchasing or designing instruments or production lines, should be confirmed in terms of efficiency and effectiveness in a simulation model. Former research also confirms that simulation in design and manufacturing processes has been very effective in many industrial areas such as the automotive industry and helps managers and experts in decision making and lowering costs in many countries, vastly. Application of simulation in automobile industry can be divided to four sections:

1. design new automobile models or design and manufacture production systems' equipment
2. construct new assembly lines or extend existing lines
3. construct factories for main production parts (press parts, engines, power transmission systems, etc.) or assembly of small parts
4. design and boost the productivity of supply chain and applications related to logistics systems.

Among the mentioned applications of simulation, the improvement of production systems is one of the first applications and accounts for the major part. Hao and Shen (2008) studied transportation in a production section using simulation. They showed applying just in time rules in transportation processes can increase not only the production line, but the whole system. Considering strategical, tactical and operational levels, Pawlewski and Fertsch (2010) utilised simulation to describe a debottlenecking study of a production-logistics system. Sharda and Bury (2010) investigated the problem of identification and elimination of bottlenecks in the production process in a chemical manufacturing plant using computer simulation. Brito et al. (2010) used discrete-event simulation and multi-criteria decision making to develop a tool for strategic problems studies, planning and capacity determination of production and logistics facilities in a steel manufacturing plant. Wang et al. (2011) simulated complex processes in an automobile general assembly plant using Arena software. Supsomboon and Varodhomwathana (2017) presented a case study for automotive part production process design using robot and plant simulation. Steinemann et al. (2013) adapted discrete-event simulation tools to support tactical forecasting in the automotive industry. Fabri et al. (2022) proposed simulation models' concepts that evaluate assembling lines under the internal logistics point of view. Yúmina and Ramos (2022) used simulation for decision support in process reengineering in the automotive industry.

Among production processes, painting is one of the most influential processes in final product pricing, due to its effect on the beauty of the products, especially when it comes to automobiles. Nevertheless, paint shops are considered as bottlenecks in many automobile manufacturing plants (Monazzam et al., 2021). Today painting is a multistage, complicated and expensive operation which has a harmful effect on the environment (Bysko et al., 2020). Therefore, many researchers have been working on this step or production line with the purpose of increasing the quality and capacity of painting or decreasing the duration of the painting process. For this purpose, one of the most popular approaches is using simulation methods. Graehl (1992) described a simulation study in an automotive paint shop. They introduced a second body style and studied the effects of making modifications to some of the conveyors. Trakultongchai et al. (2013) used simulation tools to reduce the bottleneck problem in the paint shop process in an automotive company in Thailand. They found that the major bottlenecks are in the paint shops and hence, optimised the production line. Monazzam et al. (2021) proposed a case study in an automotive paint shop. They presented an online simulation optimisation using DEA and experimental design. Also, simulation-optimisation approach has been widely used in the areas of supply chain (Barbosa et al., 2021; Shahabi et al., 2022), production control (Gailan Qasem et al., 2021) and inventory management (Felberbauer et al., 2022). Taguchi method has been used frequently in the automotive industry researches, too. Karaoglan and Ozden (2021) used the Taguchi method to investigate the effects of process parameters on the response and reduce the number of parameters. Then, response surface method (RSM) was utilised for modelling a mathematical relationship between the process parameters and the response, namely dry film thickness (DFT). Finally, optimisation was performed to meet the minimum 75 micrometre DFT requirement. Kumar et al. (2021) applied the Taguchi experimental design approach to optimise the workstation of an assembly line in the automotive industry to diminish forces and ANOVA to find the significance of design factors. Gerger and Firuzan (2021) presented a Taguchi-based case study in the automotive industry using Six Sigma methodology. Verma et al. (2022) improved sigma level of galvanisation process by zinc over-coating reduction using an integrated Six Sigma and design of experiments (DOE) approach.

Most of the research in the area of production line optimisation, assumed some parameters such as production capacity and production capacity to be constant and used conventional operation research methods like mathematical modelling and stochastic processes modelling. Therefore, we aim to detect critical parameters in the paint shop of an automobile company in Iran and identify the optimised levels of them using simulation, experimental design and mathematical modelling. In order to do that, we first use computer simulation to provide results of applying proposed scenarios in the real world and then after proving the validation of the model, new scenarios are followed using Taguchi DOE. Finally, mathematical modelling is applied to the set of introduced parameters in simulated results of estimated response levels. The remainder of this paper is organised as follows. The research methodology and case study are provided in Section 2. The design of the simulation model is presented in Section 3. Finally, in Section 4 is conclusions and future research opportunities are discussed.

2 Research methodology and case study

When facing complex systems, in many cases, the objective functions cannot be obtained in the standard form of optimisation research. One way of efficiently analysing those kinds of systems is using the methodologies like simulation. So, the objective functions are estimated using a valid computer simulation model. The steps are briefly as follow:

1 a list of performance measures (PFMs) should be prepared presenting by Y_i, $i = 1, 2, \ldots, I$, where I is the number of PFMs

2 controllable variables should be found and can be presented by X_j, $j = 1, 2, \ldots, J$, where J is the number of controllable variables

3 a simulation model should be developed in this stage to show the flow of entities in the system

4 DOE can be used to obtain all scenarios

5 experimental data should be used for RSM to estimate I fitness functions

6 present a multi-objective programming model

7 solve the multi-objective model to obtain the best scenario or process settings.

In this paper, paint shop 2 of the biggest automobile manufacturing factory in Iran, has been simulated from start to the end of the sanding phase. In this hall, bodies coming from body shop are transferred to pretreatment (PT) and delivered via conveyor of paint shop's PT line. Four hooks are installed on forward and backward doors of both right and left sides and bodies are moved. Then, hooks are connected to the hood and trunk door and body are positioned on the determined place. Iron products are usually coated to have a better appearance and more protection against rusting. To improve the efficiency of coating, PT operation is done. This step is vital for achieving an appropriate quality and two main goals of it are adhesion increase and better protection against corrosion. PT process consists of five steps:

1 degreasing
2 rinsing
3 activation
4 phosphate (cover a chemical layer on top of the surface)
5 rinsing with DI water.

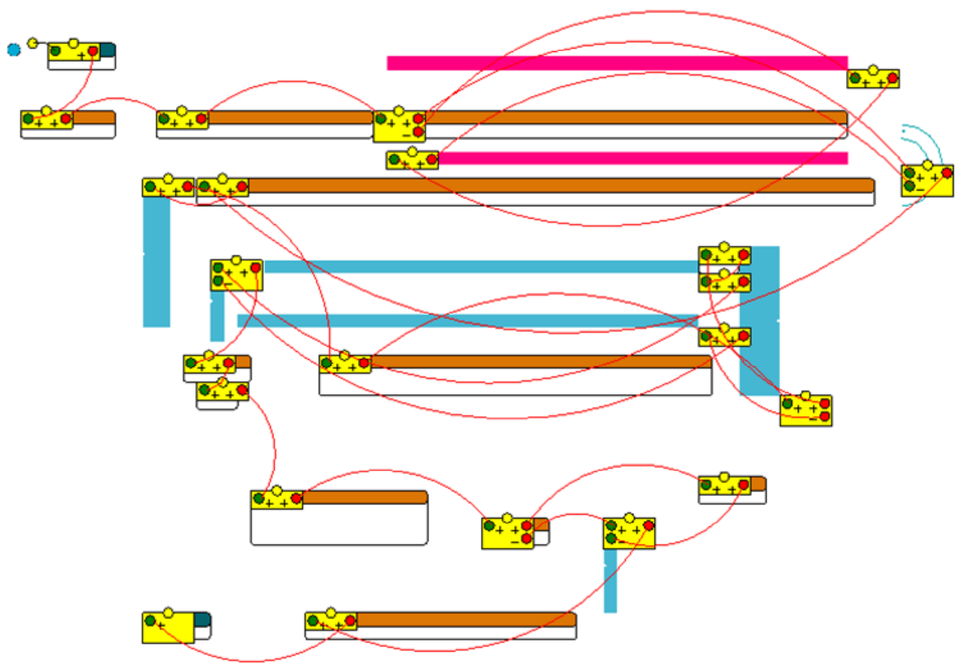
The enterprise dynamics (ED) software has been used to simulate the painting process consisting of PT and ElectroDeposition (ED) using large amounts of data. In addition to analysing the existing conditions, simulation process can help to investigate the proposed scenarios before executing them. To identify critical process points and perform optimisation setups, Taguchi experimental design is applied with the L16 orthogonal vector. Two response levels are used, and regression and variance analysis are employed to estimate them. To optimise managing paint shops policies, robust and optimised parameter values are obtained using three proposed objective functions. For this purpose, we use three performance indicators; average daily production, average monthly imperfect produced bodies and average hanger installation time as response variables or performance measures (PFMs). The most important PFMs of the production process are affected by the way process parameters are set which cannot be mathematically defined. Additionally, critical parameters identification and setting their optimised values is intended. Thus, the steps carried out for this research are as follows:

1 Design a computer simulation model in the ED environment due to the supply needed to investigate the case study.
2 Gather data and estimate rules and probability patterns of research problem using fitness tests.
3 Execute multiple times the simulation model under existing setups in the factory
4 Perform the validity test of the model.
5 Propose new scenarios to apply changes in process setup values.
6 Estimate mathematical patterns of the way process controllable variables effect on response variables using regression methods and obtain multi-objective optimisation model of performance indicators.
7 Solve the model and find optimised values.

3 Design of simulation model

First analysis of the current situation of the paint hall was done. Then, the related layout was designed in the ED simulation software environment (Figure 1). In order to do the simulation and system analysis of the production line, affecting parameters were identified after a meeting with the experts. Afterwards, we collected 100 samples for each parameter and did a fitness test in the Minitab software environment (with diagnosis level of 5%). In this paper, the schedule of receiving bodies is considered as the identity. We used the 'source' atom with a distribution function of time between arrivals, obtained from the real system's information, to show the entrance of products (bodies) to the intended production line. Atom 'server' has been used to simulate lines F1, F2, F4 and part of F5. Also for lines F3, F6, F16 and part of the F5, the 'conveyor' atom is utilised.

Figure 1 Simulation model of factory's paint shop (see online version for colours)



Identification of various scenarios should be done after studying and executing simulation which has a significant effect on the design and modification of the model. Considering those scenarios in the first stages can result in an expandable and efficient model. As we mentioned, objectives of this study are increasing reliability and monthly production capacity of the system. So, the developed model is based on changing production parameters due to decreasing production time, improving duration of fixing, decreasing time between failures with establishing efficient net system (automated net, designing information bank of net) and optimising the usage of all resources like human resource.

To validate the simulation model, we used the Mann-Whitney non-parametric test. Since ED software has acceptable two and three-dimensional graphics, we executed the model many times and it turned out that the model's behaviour is exactly the same as the real world behaviour. Thus, raw material moves in the specified routes as in reality. In addition, executing the current situation shows the same results of real production planning with an acceptable error.

After investigation of the simulation model and real world information, it was shown that the maximum possible changes are possible on lines F4, F6 and F16; so that DOE and optimisation on these lines were carried out. Table 1 shows the range of possible changes regarding the experts' viewpoints and real world constraints. To increase colour quality, some methods can be used such as increasing vacuum and hand wiping workers. Also, changing paint tank temperature between 30 and 32 degrees, increasing solid percent from 15% to maximum 18% and increasing voltage, can be done in order to decrease time duration.

Table 1 Controllable parameters with their levels

Parameter	*Description*	*Level*	
		Low	*Up*
X_1	F4 line's time (second)	65	76
X_2	F6 and F16 conveyors' speed (metre per second)	0.13	0.1
X_3	Fixing defectives station time (hour)	12	24
X_4	Imperfect percentage	0.3	0.5

Table 2 Simulation results in 16 designed scenarios

76	0.1	24	0.5	12,098.3	18.6	158.59
76	0.13	12	0.3	18,765.4	26.2	100.93
76	0.1	12	0.3	19,126.1	28.3	98.8
76	0.1	24	0.3	16,047.1	17.7	118.22
76	0.13	24	0.5	12,643	19.1	152.17
76	0.13	24	0.3	16,058.1	16.7	118.86
76	0.13	12	0.5	16,586.4	33	114.7
76	0.1	12	0.5	15,818.2	32.1	19.99
65	0.13	12	0.3	19,133.6	25.7	98.99
65	0.1	24	0.5	13,654.9	18.5	142.3
65	0.13	24	0.5	12,164.2	18.9	158.14
65	0.13	12	0.5	16,753.1	32.2	113.43
65	0.1	12	0.3	18,489.1	26.1	102.34
65	0.1	24	0.3	14,942	17	126.8
65	0.1	12	0.5	16,623.4	32.4	114.3
65	0.13	24	0.3	16,459.4	17.2	115.93

As it was mentioned, due to robust design of tests, we used the Taguchi test design method with an orthogonal L16 vector for four variables (in two levels each) (see Table 2). So in this step, the Taguchi test is used as DOE to identify the best parameters layout. In order to increase responsiveness, production speed and quality three PFMs are defined:

Y_1 monthly production capacity

Y_2 average imperfect bodies in a month

Y_3 average installation time of hanger.

Results from under current conditions of the simulation are as below:

$$Y_1 = 12098.30, Y_2 = 18.60, Y_3 = 158.59$$

To estimate the response levels, we used multivariate regression based on information that came from the system simulation under 16 scenarios. Orthogonal array L16 related to the result of each experiment with observed response values obtained from simulation runs can be seen in Table 2.

In this stage, parameters as controllable variables can be chosen considering decision makers' priority or using optimisation approach. In this case for the first method, we obtain decision makers priority and as a result the most important objective is maximising the monthly production capacity (Y_1). Decision maker determines a lower limit for this objective as 18,000. It means the preference is to maximise Y_1 as much as possible but it cannot be lower than 18,000. The second priority of the management is minimising objective Y_2 considering upper bound 27. So, we can choose Scenarios 2, 3, 9 and 13. Scenario 2 eliminates due to the upper bound of Y_2. Thus, the best scenario between 3, 9 and 13 is 9 for both Y_1 and Y_2. To use optimisation approach, after obtaining response levels in various experiments using ED, the Minitab software is used to estimate regression coefficients with minimum square method. Estimated model for the response levels are as below:

$$\text{Max } Y_1 = 26753 - 12.2X_1 + 7350X_2 - 284X_3 - 14175X_4 \quad (1)$$

$$\text{Min } Y_2 = 31.4 + 0.0420X_1 - 7.1X_2 - 0.961X_3 + 18.7X_4 \quad (2)$$

$$\text{Min } Y_3 = 59 - 1.02X_1 + 383X_2 + 3.41X_3 + 58.0X_4 \quad (3)$$

There are many ways to solve a multi-objective model like goal programming, metaheuristics, weighted sum method and compromise programming. We used normalised weighted sum method with following formulation, when all objective functions are considered to be minimisation:

$$\text{Min } Y = \sum_{i=1}^{I} \frac{w_i \left(Y_i - Y_i^l\right)}{Y_i^u - Y_i^l} \quad (4)$$

Due to the decision makers' opinions, weights are considered to be 0.5, 0.3 and 0.2 for Y_1, Y_2 and Y_3, respectively. Maximum and minimum values of objective functions are obtained from Table 2. Then, the obtained model has been solved by the MATLAB software and the results are as below:

$$Y_1 = 19126.1,\ Y_2 = 28.3,\ Y_3 = 98.80,\ X_1 = 76,\ X_2 = 0.1,\ X_3 = 12,\ X_4 = 0.3 \quad (5)$$

It means that Scenario 3 is chosen. Also giving all scenarios to the software, four scenarios 2, 3, 9 and 13 where very closed (Pareto front) in terms of the final objective function values. The answers are:

$$Y^{Scenario2} = -0.9754 \quad (6)$$

$$Y^{Scenario3} = -0.9945 \quad (7)$$

$$Y^{Scenario9} = -0.9596 \quad (8)$$

$$Y^{Scenario13} = -0.9781. \quad (9)$$

4 Conclusions

In today's competitive environment, high quality and agile responsiveness to customer's demand are crucial for a company to stay in a market. Thus, companies need to improve production power and customer satisfaction. In this paper, we considered optimising three performance measures of the production line's paint shop in one of the biggest automotive firms in Iran. Due to difficulty of describing PFMs mathematically, a computer simulation model is used to define relevant performance measures. We used DOE to generate 16 scenarios and simulation was executed many times to reach mean of each PFM. Then regression analysis was applied to define a function of four critical parameters for each. Thus, three distinct objective functions were presented for the multi-objective optimisation model using RSM. Finally, optimisation was done using three objectives simultaneously and the results showed 58% increase in production capacity and 60% decrease in waiting time of the product. For the future research, we suggest to use methods like NSGA II for multi-objective optimisation. Also considering other PFMs in addition to investigated PFMs in the proposed model, generating more scenarios and simulating paint shops in other industries can be good ideas for the future research.

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