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TOPSIS BASED TAGUCHI METHOD FOR MULTI-RESPONSE SIMULATION OPTIMIZATION OF FLEXIBLE MANUFACTURING SYSTEM

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ABSTRACT

This study presents a simulation design and analysis case study of a flexible manufacturing system (FMS) considering a multi-response simulation optimization using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) based Taguchi approach. While in order to reduce expensive simulation experiments with the Taguchi design, the TOPSIS procedure is used to combine the multiple FMS responses (performance measures) into a single response in the optimization processes. Thus, TOPSIS carries out an important role to build a surrogate objective function that represents multiple responses of the system. The integrated approach finds a new design considering discrete factors (physical and operational parameters) which affect the performance measures of FMS. Optimal design configuration is obtained for the considered system with improved performance.

1 INTRODUCTION

The Flexible manufacturing system (FMS) is a manufacturing system that has flexibility to allow the system to react in case of changes. This flexibility generally occurs in two classes; machine flexibility, meaning the ability to be changed to produce new products, and routing flexibility, meaning the system has the ability to use multiple machines to perform the same operation on a part, as well as to make changes in volume, capacity or capability of the machines.

FMS consists of a group of processing stations with highly automated cellular manufacturing technology. It controls both material and information flows online, by an integrated computer system (Groover 2007). While the FMS has advantages like reduction in number of workers, better planning, getting better quality or greater productivity with the same number of workers, some technological problems like sophisticated environments are among the known disadvantages. Because of the variety of advantages and disadvantages mentioned above, FMS has gained increasing attention among researchers during the last 20 years to obtain high utilization rates and high productivity volumes. Therefore, the design and operation of the FMS includes sophisticated and interconnected factors that influence the performance of the system. Gupta and Buzacott (1989) mentioned that the flexibility is the result of a combination of factors such as design (physical) characteristics and operating conditions. System utilization, work-in-process, set-up time, tool changes, production rate, due dates, job tardiness, flow time, and the balance of machine usage are the most commonly considered factors among those in the FMS design and performance evaluation in the literature. Thus, the problem of finding the optimal configuration (working conditions) of an FMS is a complex stochastic non-linear problem which includes both physical and operating system characteristics. This design problem is to choose the optimal parameter values to maximize the FMS performance.

Simulation is one of the most useful modeling tools to solve a variety of problems in complex manufacturing systems. One objective of the application of simulation is to search for a set of operational parameters so that system performance is optimized (Tsai 2002). Thus, simulation is widely used to analyze the behavior, system design, scheduling or production planning in the FMS (Park et al. 2001; Savsar 2005; Um et al. 2009) instead of using complex mathematical models because of its stochastic nature and complex structure.

The problem of evaluating the most preferred alternative systems through experimental design integrated by simulation is called simulation optimization. To date, some methodologies such as response surface methods, gradient search methods, and heuristic search methods have been used for single or multi response simulation optimization. On the other hand, Taguchi methods which are initially used in quality engineering (Phadke 1989) are suitable, simple simulation optimization strategies allowing a reduction in the number of experimentations by using the orthogonal array. However, the conventional Taguchi strategy does not provide a method for multi response simulation optimization by default. In the technological environment of an industrial area, many problems that can occur in real FMS often embody many operating and physical characteristics under more than one performance measure (multi response). In those cases, Taguchi strategy needs a multiple attribute decision making method such as TOPSIS, a technique used for order preference by similarity to ideal solution (Yang and Chou 2005). To solve the problems faced in the FMS, multi response simulation optimization has to be used first to easily understand and explain the response behavior, and secondly to show the effects of physical, operational, or both factors on the FMS performance.

Therefore TOPSIS based Taguchi optimization provides a useful approach to convert multi-response simulation-optimization problem into the single-response problem. The TOPSIS method presents the global performance scores (C_i^*) for all responses. Hence, according to the Taguchi's robust design principles, the optimal factor levels are easily obtained. S/N (Signal to Noise) ratios and Taguchi's basic orthogonal arrays are two main advantages of the Taguchi method: i) The optimization process becomes more reliable when the S/N ratio is used, especially when various conflicting responses can be treated as a dynamic system characteristic. ii)using an orthogonal array reduces the experiment time and the simulation costs. For example, in the Taguchi's L_{27} (3**5: 5 factors with 3 levels each) orthogonal array only 27 simulation experiment scenario are required. If the full factorial design were used, it would have at least 5^3= 125 simulation runs.

The optimization of stochastic simulation includes gradient-based search methods, stochastic optimization, Response Surface Methodology (RSM), meta-heuristic methods or statistical methods. RSM has attracted a growing interest among these methodologies in recent years(Dengiz and Belgin 2014).The TOPSIS-based Taguchi optimization is easy to perform compared to the RSM. The calculation steps of the TOPSIS-based Taguchi application can easily be done. The RSM could be an unusable tool as the number of the design factors and/or the responses increase (Şimşek et al. 2013). For example, if the RSM design were used for 5 factors with 3 levels each, it would have least 46 simulation runs.

All methods discussed above; Taguchi method, full factorial design and RSM can only consider a single response at a time. In order to improve the FMS performance a method integrated with Taguchi method for multi-response simulation optimization is needed.

In the literature, some simulation search heuristic procedures such as genetic algorithms (GA), simulated annealing (SA), tabu search (TS), and particle swarm optimization (PSO) were developed and compared both with respect to the best results achieved by each algorithm in a limited time span and their speed of convergence to the results for finding the optimum system performance (Alabaş et al. 2000). Simulation is used to model the manufacturing system while GA, SA, TS or PSO can be used to guide the overall factor combination search process to identify the best performing ones. The stopping criterion should be defined as a number of solutions visited based on preliminary experimentation. This number changes depending on the type of the problem and heuristic procedures. Generally, these procedures need more computational time than the proposed method in this study.

Kosturiak and Gregor (1998) describe the effective simulation application steps of the manufacturing system and how discrete event simulation can be used for the improvement of FMS with the Taguchi approach as a case study. They generalize their experience gained from many industrial applications of simulation projects that were worked on. They, finally, investigate the effect of some production control strategies on the manufacturing system parameters in FMS. Chan and Chan (2004) present a state of the art perspective and comprehensive discussion about studies focused on FMS scheduling and point out that most past research on the design and operation of the FMS considered only a single performance measure as their decision criteria. Chan et al. (2007) pointed out that the decision maker may require a focus on effective decision making in manufacturing systems by considering both physical and operating parameters of the system to identify the suitable type and level of flexibility with all other parameters of the system that can affect the system performance. They establish the need of modeling of the physical and operating parameters of FMS along with flexibility, and present a simulation study under Taguchi's method to analyze the considered parameters in their study. Although there is a significant body of literature for single and multi response optimization of manufacturing systems, recently, several researchers have applied multi-response optimization approaches particularly to solve the scheduling and design problem of hypothetic FMS (Park et al. 2001; Kumar and Sridharan 2009; Um et al. 2009; Pandian et al. 2011; Joseph and Sridharan 2011). However, none of these methods consider both multi responses simultaneously and the approach by the Taguchi quality loss function integrated with TOPSIS to reduce multiple responses to one objective function. A few studies involve Taguchi method in the optimization of a single response in the FMS (Kosturiak and Gregor 1998, Chan et al. 2007).

In this study, we aim to show the usability of the TOPSIS based Taguchi method to solve a real case design problem by multi response simulation optimization of the FMS problem.

2 PROPOSED METHODOLOGY

2.1 TOPSIS Based Taguchi Optimization

TOPSIS has been developed by Hwang and Yoon (1981) for solving the MADM problems. It is based on the idea that an alternative, which is chosen, should have the farthest distance from the negative ideal solution and on the other side, the shortest distance from the positive ideal solution. TOPSIS procedure is rational and understandable. The computation process of the TOPSIS method is depicted in a simple mathematical form and the importance weights can be obtained by direct assignation. For these reasons, the TOPSIS method is highly stable for decision making studies (Sen and Yang 1998).

TOPSIS based Taguchi optimization follows the Taguchi optimization (Yang and Chou 2005) and is used to combine the multiple FMS performance characteristics into a single value that can then be used as the single optimization function.

The first step is to make simulation runs which are executed by following the experimental structure of the selected orthogonal array. The signal-to-noise ratio (S/N ratio, η) is an effective way to find significant factors by evaluating minimum variance (Yang and Chou 2005; Kuo et al. 2008). The S/N ratios can then be defined as shown in Eq. (1-2). While Eq.(1) is used for "smaller-the-better" responses, Eq.(2) is applied for "larger-the-better" responses (Kuo et al. 2008).

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{k=1}^{n} y_{ijk}^{2}\right) \tag{1}$$

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^{2}}\right) \tag{2}$$

2.2 Multi Response Simulation Optimization

After computation of the S/N ratios for each response of the system for all scenarios, the TOPSIS method is applied. The modification of Yang and Chou's (2005) TOPSIS-based Taguchi approach for multi response simulation optimization of FMS is shown below:

Step 1: Determine the factors that affect specified performance measures for the FMS problem.

Step 2: Formulate the experimental design matrix using orthogonal array.

Step 3: Make simulation runs of FMS simulation model according to the orthogonal array.

Step 4: Compute the S/N ratios for all scenarios, $(\eta)_{m\times r}$ using Eq. (1-2).

Step 5: Enter characteristic values of S/N ratios at responses (η_{ij}; *i=1,2,…,m "number of scenarios," j=1,2,….,r "number of responses"*) as inputs in matrix as shown in Eq. (3).

$$D = \begin{bmatrix} \eta_{11} & \eta_{12} & \cdots & \eta_{1r} \\ \eta_{21} & \eta_{22} & \cdots & \eta_{2r} \\ \cdots & & & \\ \eta_{m1} & \eta_{m2} & & \eta_{mr} \end{bmatrix} \tag{3}$$

Step 6: Prepare normalized decision matrix using Eq. (4).

$$\eta_{ij}^{*} = \frac{\eta_{ij}}{\sqrt{\sum_{i=1}^{m}\eta_{ij}^{2}}} \qquad i=1,2,\ldots..,m j=1,2,\ldots.,r \tag{4}$$

Step 7: Construct the weighted normalized decision matrix using Eq. (5-7).

$$V = \left[X_{ij}\right]_{mxr} \quad i=1,2,\ldots..,m j=1,2,\ldots.,r \tag{5}$$

$$X_{ij} = \eta_{ij}^{*}\, w_j \tag{6}$$

$$W = \left[w_1, w_2, \ldots, w_r\right] \tag{7}$$

Step 8: Determine the ideal and negative-ideal solutions: The ideal solution (A*) and negative-ideal solution ($A-$), representing the maximum and minimum S/N ratios, respectively, are as follows:

$$A^* = \left(\overset{*}{X}_1, \overset{*}{X}_2, \ldots.., \overset{*}{X}_r \right) \tag{8}$$

$$\overset{*}{X}_j = \left\{ \left(\max_i \quad X_{ij} \middle| j \in J \right) i = 1, \ldots m \right\} \tag{9}$$

$$A- = \left(\overset{-}{X}_1, \overset{-}{X}_2, \ldots.., \overset{-}{X}_r \right) \tag{10}$$

$$\overset{-}{X}_j = \left\{ \left(\min_i \quad X_{ij} \middle| j \in J \right) i = 1, \ldots m \right\} \tag{11}$$

The ideal solution, (A^*), is made of all the best values (maximum S/N ratio) and the negative-ideal solution, (A^-), is made of all the worst values (minimum S/N ratio) at the responses in the weighted normalized decision matrix (Sen and Yang 1998) (Eq.5).

Step 9: Calculate the distance of scenario *i*to the ideal solution (d_i^*), and from the negative ideal solution (d_i^-) using Eq. (12-13).

$$d_i^* = \sqrt{\sum_{j=1}^{r} (X_{ij} - \overset{*}{X}_j)^2} \quad i=1,2,\ldots.m;\ j=1,2,\ldots r \tag{12}$$

$$d_i^- = \sqrt{\sum_{j=1}^{r} (X_{ij} - \overset{-}{X}_j)^2} \quad i=1,2,\ldots.m;\ j=1,2,\ldots r \tag{13}$$

Step 10: Calculate the ranking score (C_i^*) using Eq. (14).

$$C_i^* = d_i^- / (d_i^- + d_i^*), \quad i=1,2,\ldots.m;\ j=1,2,\ldots r \tag{14}$$

Step 11: Determine the optimal parametric combination to maximize S/N: The optimal combination of factor-levels is finally determined, in view of the fact that a larger TOPSIS value indicates better quality. Taguchi method is to be applied finally to evaluate this optimal setting (by maximizing the TOPSIS index).

3 PROBLEM DESCRIPTION: A CASE STUDY OF FMS

3.1 Company Overview

The increasing competition and rapid technological changes in the world have forced manufacturers to find new adaptation ways for their manufacturing systems. Therefore, manufacturing companies need new approaches to be able to respond to market changes rapidly and with high productivity.

In this study, a new design for an existing FMS is obtained with high productivity in a company using the simulation optimization method. 'X Manufacturing Co.' produces an extensive range of over 100 types of products such as cams, crankshafts, shafts, motor blocks, pistons and transmission elements. The company includes three major production lines and a FMS department.

3.2 The Production System & Performance Measures

The production system considered in this research is the FMS department, which is producing brake cylinder casing, gear box and flywheel housing. As known, there are two types of levels of flexibility: dedicated and random. The current FMS in this company is a dedicated type FMS in which parts are routed to the next operation in the machining center.

There are four CNC machining centers (MAZAK FH 6800) with one separate local buffer area that has a capacity of 20 pallets for incoming and outgoing parts in this department. Parts are moved by transporting robots on bidirectional paths, and processed at any one of the available CNC machining centers. The buffer sizes in the system are the same as advised in Groover (2007). A schematic layout of the system is given in Figure 1. When a transporting robot completes its service, it stays idle if there is no work waiting for the load-unload station.

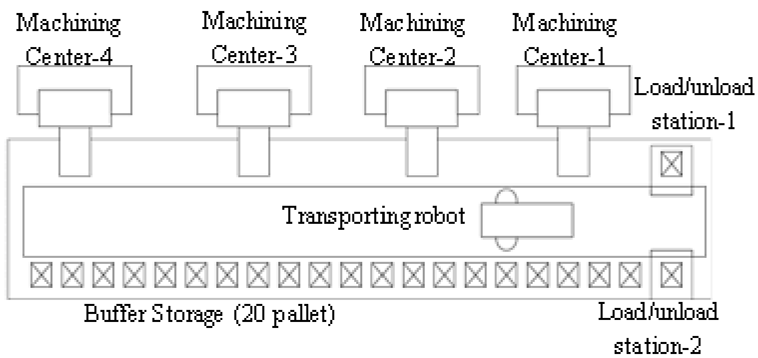

Figure 1: FMS Layout

One of the unique characteristics of dedicated FMS is to use no routing flexibility, so it is not allowed for a part to be processed on an alternative machine for each operation (Park et al. 2001). The challenge of coping with large fluctuations in product demand cannot be solved with dedicated FMS that are not scalable. It is commonly known that the FMS should be able to produce (1) any part within the machine capability, (2) any mix of parts, and (3) be able to use different sequences. This approach increases cost since it requires a parallel system structure for the FMS. On the other hand, CNC machines, that are the cornerstones of an FMS, are designed as general-purpose machines that use a single tool that can be manipulated in different directions to provide flexibility (Koren 2006).

The company has already implemented three policies such as line-balancing, shorten set-up time, training seminars for employees to improve the performance of the FMS in the current system. However, the FMS still had some problems due to the delay of final product delivery. Two main reasons behind this problem are determined (1) long cycle time (CT) and (2) the long waiting times in queue (WIQ), resulting in a throughput level that is less than desired. The company's aim is to increase the overall productivity.

3.3 Decision Variables

To obtain a highly productive and cost-effective system design, five factors, or decision variables, such as the number of cutting tools, the number of operators, the number of pallets and the velocity of transporter robots (m/min) and one operational parameter (pallet selection procedure such as dedicated or random) are selected based on our preliminary investigation.

The different flexibility principles are used to see whether the performance of the FMS is affected or not. In addition, three performance measures; CT (hour), Throughput (T) (units/month) and WIQ (hour) are considered for this design optimization problem. Table 1 represents five factors with three-levels. TOPSIS based the Taguchi approach is used to find the optimum working condition which reveals high productivity with the values of CT, T and WIQ.

Table 1: Factors and levels

		Level		
Symbol	**Factor**	**Lower (Current System)**	**Middle**	**Upper**
A	Number of operators	2	3	4
B	Velocity of transporter (m/min)	1	1.5	2
C	Number of cutting tools	120	160	200
D	Pallet selection strategy	Dedicated	Random	Dedicated to first non-busy pallet
E	Number of pallets	20	30	40

The simulation model was constructed using ARENA© software. Validated simulation outputs (three responses T, CT and WIQ) are collected via an L_{27} orthogonal array design. The simulations are run for ten replications at each design point. The normalized S/N ratios are computed using Eq. (1-2) and the rest of the methodology is applied following steps 4 through 11 as described in Section 2.1.

Table 2 shows the resulting factor effects that are obtained by the TOPSIS-based Taguchi approach explained in Section 2. New design parameters of the FMS is $A_2B_1C_3D_3E_3$.

Table 2: Average TOPSIS values by factor levels using vector normalization

Level	A	B	C	D	E
1	0.4063	**0.4926**	0.2983	0.3321	0.4422
2	**0.4772**	0.4602	0.5029	0.3312	0.3939
3	0.4471	0.3779	**0.5294**	**0.6673**	**0.4946**
Selected Factor Levels	**A2**	**B1**	**C3**	**D3**	**E3**

The performance comparison of current and the new FMS designs is given in terms of considered performance measures. Table 3 shows obtained performance improvements for the three responses, respectively.

The results show a significant positive change in overall performance measures. The benefits of changing the FMS design as suggested by the simulation optimization with the TOPSIS based Taguchi method is seen as multiples of current system's capacity. The overall performance improvement of the new proposed design is approximately 3 times better than the current system design.

Table 3: Comparison of the Performance of Results with the Current System

Performance Measures	Current System (I)	TOPSIS-based Taguchi (II)	Improvement
T(units/month)	348	1183	239.94 %
CT (hour)	1.815	0.636	64.95 %
WIQ(hour)	1.776	0.434	75.56 %

4 CONCLUSION

This study presents a TOPSIS based Taguchi method as multi response simulation optimization approach to solve the multi response optimization problem for a real case study of a FMS.

The performance of the current FMS design and the proposed FMS design obtained by the TOPSIS-based Taguchi method are compared in terms of throughput, cycle time and waiting time in queue. It is shown that the proposed system, designed by simulation optimization using the TOPSIS-based Taguchi method reveals better throughput rates, shorter cycle times and better WIQ.

The proposed system has an overall performance improvement of approximately 3.4 times higher throughput, 2.86 times shorter cycle time, and waiting times decreased to $1/5^{th}$ when compared with the current FMS in use.

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