Investigation of the Importance of Machine Sequence Flexibility on A Flexible Manufacturing System Performance

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Highlights
• The performance level of a flexible manufacturing cell is investigated in this study.
• Two main performance metrics (MLT and SR) are considered for the optimization of the FMC performance.
• The machine sequence flexibility is the most effective input factor among the four input factors.

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Abstract
Machine sequence flexibility is defined as the combination of operation and routing flexibilities in this study. Its importance in the performance level of a flexible manufacturing cell (FMC) is investigated in this study. Studies related to the effects of various flexibility types, such as routing flexibility, are available in the literature. For example, studies related to routing flexibility try to measure the effects of routing flexibility on the performance levels in the operation of manufacturing systems under their own manufacturing environments. Similarly, this study also aims to present a performance measurement model based on Taguchi methods to evaluate the effects of machine sequence flexibility factors on the FMC performance and obtain an optimum and robust performance level. Two crucial responses, such as manufacturing lead time (MLT) and surface roughness (SR) are analysed to optimize the FMC performance. Robot speed, cutting tool type, and work-part material type are taken as the three other input factors to show the importance of machine sequence flexibility with respect to the other inputs. The study presented in this paper points out that machine sequence flexibility is the most effective input factor among the four input factors in the performance of the FMC.

1. INTRODUCTION

The need to meet customer demands in a competitive market without compromising quality expectations is important for today’s manufacturing companies. If this issue cannot be achieved, a decrease in sales and a contraction in market share may occur. Flexible manufacturing systems offer significant advantages in recent years in order to produce the products with the desired quality in the expected time.

Computer-controlled and highly automated systems developed to produce on the basis of certain part families in order to reduce the times that do not create added value are called Flexible Manufacturing Systems (FMS) [1]. The initial level of FMS is called the flexible manufacturing cell and has a maximum of 3 computer numeric control (CNC) machining centres. Automatic material transport systems are used for the movement of parts between the CNCs. Work parts are moved within the cell and loaded and unloaded at machining centres by an automated material handling system. Other activities such as part capturing, clamping, and inspection are also performed automatically by operating sub-systems.

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There are different studies in the literature to analyse FMS. For example, Knopp et al. [2] analysed an FMS designed to expand routes between machines in a semiconductor production system. The main focus of the study is to reduce the cycle time of the system. Goncalves [3] presented a study demonstrating the benefits of robot-controlled manufacturing in an FMS. Cutkosky et al. [4] analysed the flexibility capability of FMS. Yadav and Jayswal [5] examined the effects of different layout designs on FMS performance by using Taguchi methods integrated with simulation. Chan [6] presented a study on route flexibility by combining Taguchi methods with simulation. In the study, “Routing Rules,” “Routing Flexibility,” “Sequencing Rules,” and “Number of Pallets” factors were considered, and the system was analysed using six different machine tools. Lozano et al. [7] and Chandra and Tombak [8] examined the effect of dynamic part routing issues in FMS. Also, Özkinan and Durmuşoğlu [9] presented a study examining the effect of product mix on the performance of cellular manufacturing systems. Wadhwa [10] proposed a study demonstrating the effects of flexible automation in SME foundries in Norway. Galbraith and Grene [11] presented a simulation-based study to improve system performance by analysing flexibility based on the level of variation of the density of the number of components per square centimetre of the printed circuit board.

Pérez-Pérez et al. [12] reviewed 284 academic articles published in peer-reviewed international journals up to 2017 in the flexible manufacturing field. The crucial information of Pérez-Pérez et al. [12]’s review paper is the necessity for the ‘development of generalizable, structured, homogeneous and simplified definitions for each manufacturing flexibility type or a combination of them.’ This paper provides a combination of operation flexibility (‘ability to produce a product by alternative ways’) and routing flexibility (‘system’s ability to have multiple alternative processing paths within the system, by which a part could be made’) using the finding of Perez-Perez et al. [12]. In this study, the combined flexibilities provide altering machine sequence while the allocated portion of workload stays identical at each machine. In such a case, the combined flexibility can be called ‘machine sequence flexibility.’ At the highest level of ‘machine sequence flexibility,’ any machine in the process plan can start, continue or finish processing on a part.

In this paper, three other input factors (robot speed, cutting tool type, and work part material type) are also included in the study, along with machine sequence flexibility as inputs. Although each input factor has its own individual effect on the system performance, their integrated effect can have a larger value than a total of their individual effects because of their interactions along with their individual effects.

In the second part of the literature review, there are some other review articles on FMC/FMS design. Yadav and Jayswal [13] reviewed different attempts at the modelling of the FMC/FMS. Some designing methodologies of FMC/FMS are highlighted in [14-36]. One can conclude that there are various methodologies that can be applied to solving the problem of FMC/FMS designing and modelling in different manufacturing environments. However, Experimental Design Approaches can handle interactions among input factors and their combined effects on system performance. Therefore, this paper presents a TOPSIS-based Taguchi method to handle both input factors’ individual and their interactions’ effects on system performance. In the literature, the TOPSIS-based Taguchi method is used to solve the multi-objective decision-making problems in major areas [37-53].

The proposed TOPSIS-based Taguchi method optimizes two separate performance metrics (responses), namely, a quality characteristic MLT (manufacturing lead time) and SR (Surface Roughness), simultaneously by using different input factor levels in an FMC.

The paper is organized as follows: In section 2, the TOPSIS-based Taguchi model is presented. In section 3, the experimental setup is described. The application and application results of the TOPSIS-based Taguchi model are presented in section 4.

2. DEVELOPMENT OF THE TOPSIS BASED TAGUCHI MODEL

Taguchi methods, which are integrated with multi-criteria decision-making (MCDM) methods, are recommended in the literature for multi-response design of experiment applications. Among the MCDM methods, the TOPSIS method is the most integrated method with the Taguchi methods. The TOPSIS-based
Taguchi Model developed in this study to link the multiple response performance of FMC with the levels of its factors is given in Figure 1.

TOPSIS approach is based on information entropy and measures Euclidean distances from a negative ideal solution and a positive ideal solution for alternatives. The ideal solutions are made of all the positive and negative ideal solution values at performance metrics in the weighted normalized decision matrix. A ranking score (Ck*) is assigned for each alternative (k) based on their distances from the negative and positive ideal solution.

In addition, the Taguchi method is a suitable method for determining the optimal values of the levels of the factors. There is no need to calculate all possible combinations of factors in the Taguchi method to find the optimum factor levels. Taguchi’s methodology uses the orthogonal array table to determine optimal factor levels with far less experimentation [54-59]. In Taguchi’s orthogonal array, each line corresponds to an experimental scenario, and experiments are performed in accordance with these scenarios to obtain experimental results [58]. These results are converted into the signal-to-noise (S/N) ratio. The signal value presents the actual response value, and the noise factor represents the variance.

There are three types of S/N ratio: larger is better, smaller is better, and nominal is best. Taguchi’s approach optimizes each S/N ratio with respect to its type. S/N ratios are obtained with the following equations [1-5]:

Smaller is better:
\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\] (1)

Larger is better:
\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)
\] (2)

Nominal is best:
\[
S/N = 10 \log \frac{\bar{y}^2}{S^2}
\] (3)
\[
\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i
\] (4)
\[
S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2
\] (5)

where, \(y_i\): response in \(i^{th}\) experiment, \(n\): number of experiments, and \(S^2\): variance.
3. DESCRIPTION OF THE EXPERIMENTAL SETUP

In this study, three different types of aluminium are used as work-piece material. Each work-part is painted with a different colour (White: ASTMSA: Al 7075, Blue: ASTM SAE Al 6082, Pink: ASTM SAE Al 6061) [60]. On the other hand, high speed steel (HSS) cutting tools differ in terms of their diameter (Figure 2.d). The selected cutting tools have diameters of 3, 4 and 5 mm [61].
The experiments are performed using the fully-automated FMC set-up (Figure 2) installed in Production Systems Laboratory at Baskent University, Turkey. The FMC set-up uses “Maher-Marsurf PS1” equipment (Figure 2.a) for the measurement of the SR of the machined parts and three pallets (Figure 2.b) move workparts among the machines. Loading and unloading the parts at machines are performed with robot arms (Figure 2.c). At each considered machine (Figure 2.d), a buffer is also installed to store parts.

4. THE APPLICATION OF THE TOPSIS BASED TAGUCHI MODEL AND ANALYSIS OF THE RESULTS

The input factors and their levels used in this study are provided in Table 1. In this study, the total work load is distributed among the three machines and an individual CNC G-code is written for each CNC machining centre. The codes are named as P1, P2 and P3 for machining centres 1-3 respectively. The effect of machine sequence flexibility on the performance of FMC is represented by changing the machine sequence as P1→P2→P3 (level 1), P2→P1→P3 (level 2) and P3→P1→P2 (level 3). L9 orthogonal array with two replications is considered for the four input factors and their three levels. The corresponding output values (responses) are presented in Table 2. Hence the system has the machining sequence flexibility by relating different part program processing opportunities at the same time with the three identical CNC milling machines in an FMC. In this paper, the identical and real CNC milling machine, industrial robot, and conveyor is considered for a deterministic and real-time simulation approach to obtain each scenario’s results. Figure 3 illustrates the system structure considered in this study. When the machine sequence is differentiated, the machining lead time differs according to the part program changes related to the machining requirements. This paper aims to answer an important question: which machine sequence plan (operation flexibility) provides a lower manufacturing lead time and reaches to expected quality requirements at the same time. Therefore, an optimal machine sequence connected with other design factors for the system can be obtained using the TOPSIS based Taguchi model.

In the application of the TOPSIS-Taguchi approach; weights of the performance responses are required to convert normalized decision matrix to weighted normalized decision matrix. Nine separate weight sets are developed to analyse the robust importance of machine sequence flexibility with respect to other input factors in the overall FMC performance. The application is illustrated for the weight set in which equal weights (0.5) are assigned for the two performance responses, MLT and SR.
**Table 1. Input Factors and their three levels**

| INPUT FACTORS                              | LEVEL 1              | LEVEL 2              | LEVEL 3              |
|--------------------------------------------|----------------------|----------------------|----------------------|
| MACHINE SEQUENCE FLEXIBILITY (A)           | P1/P2/P3             | P2/P1/P3             | P3/P1/P2             |
| ROBOT ARM SPEED (B)                        | 30% (630 mm/s)       | 50% (1050 mm/s)      | 70% (1470 mm/s)      |
| CUTTING TOOL TYPE (C)                      | HSS-3mm              | HSS-5mm              | HSS-4mm              |
| WORK PART MATERIAL TYPE (D)                | PINK-P ASTMSAE: Al 6061 | BLUE-BL ASTMSAE: Al 6082 | WHITE-W ASTMSAE: Al 7075 |

**Figure 3. Considered system for the study**

Table 3 presents the weighted normalized decision matrix and ranking scores of the eighteen experiments. Each S/N ratios in the decision matrix of the TOPSIS model are calculated using Equation (1). To calculate S/N ratios in Table 3, “smaller is better” is used for both MLT and surface roughness responses. The ranking scores and input factors’ levels of experiments (Table 4) are input to MINITAB-R14 for analysis of variance. At this stage, “larger is better case” (Equation (2)) is used. The analysis of variance results of the MINITAB are shown in Table 5. The contribution ratios of the four input factors can be determined based on the ANOVA table (Table 5). Machine sequence flexibility has the highest impact ratio with 46% and

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1 Imaginations are gathered from the https://www.festo-didactic.com/ov3/media/customers/1100/00987874001075223761.pdf
correspondingly is the most effective input factor for the FMC performance in ‘the equal weight for the performance responses’ case.

Table 2. L9 orthogonal array with two replications, specified by Taguchi’s design of experiment (with input factors’ levels and performance response values)

| MACHINE SEQUENCE FLEXIBILITY | ROBOT ARM SPEED (%) | WORKING TOOL TYPE | MACHINE SEQUENCE FLEXIBILITY | WORKING TOOL TYPE | MLT (second) | SURFACE ROUGHNESS (μm)* |
|------------------------------|---------------------|-------------------|------------------------------|-------------------|--------------|------------------------|
| 1                            | 1                   | 1                 | 1                            | P1/P2/P3          | 30           | 3                      | Rep.1  |
| 2                            | 1                   | 2                 | 2                            | P1/P2/P3          | 50           | 4                      | Rep.2  |
| 3                            | 1                   | 3                 | 3                            | P1/P2/P3          | 70           | 4                      | Rep.1  |
| 4                            | 2                   | 1                 | 2                            | P2/P1/P3          | 30           | 5                      | Rep.2  |
| 5                            | 2                   | 2                 | 3                            | P2/P1/P3          | 50           | 4                      | Rep.3  |
| 6                            | 2                   | 3                 | 1                            | P2/P1/P3          | 70           | 3                      | Rep.1  |
| 7                            | 3                   | 1                 | 3                            | P3/P1/P2          | 30           | 4                      | Rep.2  |
| 8                            | 3                   | 2                 | 1                            | P3/P1/P2          | 50           | 3                      | Rep.3  |
| 9                            | 3                   | 3                 | 2                            | P3/P1/P2          | 70           | 5                      | Rep.1  |

*3 measured value from machined work-piece surface

Table 3. Obtaining the weighted normalized decision matrix and ranking scores of the eighteen experiments (Equal weight set)

| EXP  | MLT    | SR    | Weight>0.5 | 0.5  | MLT | SR    | Weighted normalized decision matrix |
|------|--------|-------|------------|------|-----|-------|-------------------------------------|
| 1    | -68.589| 15.703| -0.236     | 0.46 | -0.118 | 0.203 | 0.00150*  |
| 2    | -68.921| 9.816 | -0.237     | 0.254| -0.119 | 0.127 | 0.0760313 | 0.9844  |
| 3    | -68.192| 10.257| -0.235     | 0.265| -0.117 | 0.133 | 0.0700318 | 0.8197   |
| 4    | -68.402| -0.490| -0.235     | 0.013| -0.118 | -0.006 | 0.2090180 | 0.4621   |
| 5    | -68.846| 4.4011237 | 0.088 | -0.118 | 0.044 | 0.159 | 0.2300591 | 0.5913   |
| 6    | -68.315| -1.046| -0.236     | -0.023| -0.118 | -0.014 | 0.2160172 | 0.4430   |
| 7    | -68.520| 8.778 | -0.236     | 0.227| -0.118 | 0.113 | 0.0890299 | 0.7700   |
| 8    | -68.527| -11.756| -0.236 | 0.304| -0.118 | -0.152 | 0.3550034 | 0.0870   |
| 9    | -68.640| 2.510 | -0.236     | 0.065| -0.118 | 0.032 | 0.1100218 | 0.5820   |
| 10   | -68.138| 13.993| -0.235     | 0.359| -0.117 | 0.180 | 0.0230365 | 0.9400   |
| 11   | -68.809| 8.947 | -0.237     | 0.231| -0.118 | 0.116 | 0.0870302 | 0.7750   |
| 12   | -68.212| 13.191| -0.235     | 0.341| -0.117 | 0.170 | 0.0320356 | 0.9170   |
| 13   | -68.042| -2.594| -0.234     | 0.067| -0.117 | -0.034 | 0.2360152 | 0.3920   |
| 14   | -68.777| 3.840 | -0.237     | 0.099| -0.118 | 0.050 | 0.1530236 | 0.6060   |
| 15   | -68.339| 1.618 | -0.235     | 0.042| -0.118 | 0.021 | 0.1820207 | 0.5320   |
| 16   | -68.488| 11.341| -0.236     | 0.293| -0.118 | 0.147 | 0.0560332 | 0.8550   |
| 17   | -68.449| -14.387| -0.236 | -0.372| -0.118 | -0.186 | 0.3890003 | 0.0020   |
| 18   | -68.236| 2.745 | -0.235     | 0.071| -0.117 | 0.035 | 0.1670221 | 0.5690   |

\[ \sum_{i=1}^{18} w_i^2 = 290.51 \]

\[ \sum_{i=1}^{18} v_i^2 = 38.7 \]

\[ \frac{290.51}{290.51 - 0.236} = 0.046 \]

\[ \frac{0.236 + 0.5}{0.118} = 0.203 \]

\[ v_i^2 = 0.211 0.041 \]

\[ v_i^2 = 0.214 0.037 \]

\[ \frac{0.236}{0.118} = 0.3890001 \]
Table 4. Input factors’ levels and corresponding TOPSIS ranking scores \((C_k^*)\) for the equal weight set

| Experiments | MACHINE SEQUENCE FLEXIBILITY (A) | ROBOT SPEED (B) | TOOL TYPE (C) | MATERIAL TYPE (D) | \(C_k^*\) |
|-------------|---------------------------------|----------------|--------------|-------------------|----------|
| 1           | 1                               | 1              | 1            | 1                 | 0.997714 |
| 2           | 1                               | 2              | 2            | 2                 | 0.804315 |
| 3           | 1                               | 3              | 3            | 3                 | 0.819012 |
| 4           | 2                               | 1              | 2            | 3                 | 0.461851 |
| 5           | 2                               | 2              | 3            | 1                 | 0.591145 |
| 6           | 2                               | 3              | 1            | 2                 | 0.443357 |
| 7           | 3                               | 1              | 3            | 2                 | 0.769843 |
| 8           | 3                               | 2              | 1            | 3                 | 0.087426 |
| 9           | 3                               | 3              | 2            | 1                 | 0.561549 |
| 10          | 1                               | 1              | 1            | 1                 | 0.939841 |
| 11          | 1                               | 2              | 2            | 2                 | 0.775436 |
| 12          | 1                               | 3              | 3            | 3                 | 0.916514 |
| 13          | 2                               | 1              | 2            | 3                 | 0.391934 |
| 14          | 2                               | 2              | 3            | 1                 | 0.606043 |
| 15          | 2                               | 3              | 1            | 2                 | 0.531913 |
| 16          | 3                               | 1              | 3            | 2                 | 0.855006 |
| 17          | 3                               | 2              | 1            | 3                 | 0.002089 |
| 18          | 3                               | 3              | 2            | 1                 | 0.569369 |

Table 5. Analysis of variance for the equal weight set

| Source | DF | Seq SS   | Adj SS   | Adj MS   | F      | P      | Contribution (%) |
|--------|----|----------|----------|----------|--------|--------|------------------|
| A      | 2  | 0.59926  | 0.59926  | 0.29963  | 130.78 | 0.0    | 46               |
| B      | 2  | 0.20460  | 0.20460  | 0.10230  | 44.65  | 0.0    | 15.7             |
| C      | 2  | 0.20672  | 0.20672  | 0.10336  | 45.11  | 0.0    | 18.8             |
| D      | 2  | 0.26547  | 0.26547  | 0.13274  | 57.94  | 0.0    | 20.1             |
| Error  | 9  | 0.02062  | 0.02062  | 0.00229  | 1.5    |        | 1.5              |
| Total  | 17 | 1.29668  |          |          |        |        | 100              |

On the other hand, Figure 4 presents the 3D plots offering the \(C_k^*\). The optimal recipe of the \(C_k^*\) parameters is as follows: machine sequence flexibility (A) is P1/P2/P3; robot arm speed (B) is 30% (630 mm/s); Cutting Tool Type (C) is HSS-4mm; and work part material type (D) is Al 6061 (A1B1C3D1).

Because we are interested in the relationship between the factors and the \(C_k^*\) values, an each Y \((C_k^*)\) versus each X (factors) matrix plot is most appropriate tool for analysing the results. To help visualize the relationships, we can create a matrix plot of each Y versus each X with smoother lines. As a result from the matrix (Figure 5) the strongest relationship seems to be between \(C_k^*\) and cutting tool type factor (C).

The model is also applied for the other eight weight sets and the application results for the whole nine weight sets are given in Table 6. The F values, contribution ratios and rankings of the four input factors for the nine weight sets according to the contribution ratios are provided in Table 7. For all weight sets machine sequence flexibility is the most effective input factor in determination of the FMC performance.
Table 6. The ranking scores of the eighteen experiments for the nine weight sets

| Exp. | Weight Sets | TOPSIS Scores |
|------|-------------|---------------|
|      | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} | W_{MLT} - W_{SR} |      |
| 1.000 | 0.999 | 0.999 | 0.998 | 0.998 | 0.997 | 0.997 | 0.995 | 0.991 | 0.980 |
| 2.000 | 0.804 | 0.804 | 0.804 | 0.804 | 0.804 | 0.804 | 0.804 | 0.804 | 0.802 |
| 3.000 | 0.819 | 0.819 | 0.819 | 0.819 | 0.819 | 0.819 | 0.819 | 0.819 | 0.819 |
| 4.000 | 0.462 | 0.462 | 0.462 | 0.462 | 0.462 | 0.462 | 0.462 | 0.462 | 0.462 |
| 5.000 | 0.591 | 0.591 | 0.591 | 0.591 | 0.591 | 0.591 | 0.591 | 0.591 | 0.590 |
| 6.000 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 |
| 7.000 | 0.770 | 0.770 | 0.770 | 0.770 | 0.770 | 0.770 | 0.770 | 0.770 | 0.769 |
| 8.000 | 0.087 | 0.087 | 0.087 | 0.087 | 0.087 | 0.087 | 0.087 | 0.087 | 0.089 |
| 9.000 | 0.562 | 0.562 | 0.562 | 0.562 | 0.562 | 0.562 | 0.562 | 0.562 | 0.561 |
| 10.000 | 0.940 | 0.940 | 0.940 | 0.940 | 0.940 | 0.940 | 0.940 | 0.940 | 0.940 |
| 11.000 | 0.775 | 0.775 | 0.775 | 0.775 | 0.775 | 0.775 | 0.775 | 0.775 | 0.774 |
| 12.000 | 0.917 | 0.917 | 0.917 | 0.917 | 0.917 | 0.917 | 0.917 | 0.916 | 0.916 |
| 13.000 | 0.392 | 0.392 | 0.392 | 0.392 | 0.392 | 0.392 | 0.392 | 0.392 | 0.393 |
| 14.000 | 0.606 | 0.606 | 0.606 | 0.606 | 0.606 | 0.606 | 0.606 | 0.606 | 0.605 |
| 15.000 | 0.532 | 0.532 | 0.532 | 0.532 | 0.532 | 0.532 | 0.532 | 0.532 | 0.532 |
5. CONCLUSIONS

The presented study in this paper clearly shows that the machine sequence flexibility is the most effective input factor in all nine different weight sets. This may be the reason why different types of flexibility are studied so much in the literature. It should not be forgotten that the experiments are performed in a manufacturing cell defined as ‘flexible’. Although there are many different types of flexibility, studies that define new flexibility types and show their importance are still needed. This study satisfies such a need by defining a new flexibility type and showing its importance in determination of the performance of a FMC. The CNC machine programmers can use the new flexibility type in allocating the machining requirements into different machining centres and writing the NC part programs for machining centres.

| Weight Set | Input Factors | F | Contribution Ratio (%) | Ranking |
|------------|---------------|---|------------------------|---------|
| 0.1 – 0.9  | MACHINE SEQUENCE FLEXIBILITY (A) | 129.38 | 46.15 | 1 |
|            | ROBOT SPEED (B) | 44.27 | 15.3 | 4 |
|            | CUTTING TOOL TYPE (C) | 44.50 | 15.8 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 57.39 | 20 | 2 |
| 0.2 – 0.8  | MACHINE SEQUENCE FLEXIBILITY (A) | 129.60 | 46.51 | 1 |
|            | ROBOT SPEED (B) | 44.33 | 15.5 | 4 |
|            | CUTTING TOOL TYPE (C) | 44.60 | 15.9 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 57.47 | 20.1 | 2 |
| 0.3 – 0.7  | MACHINE SEQUENCE FLEXIBILITY (A) | 129.88 | 46.51 | 1 |
|            | ROBOT SPEED (B) | 44.41 | 15.9 | 4 |
|            | CUTTING TOOL TYPE (C) | 44.72 | 16 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 57.58 | 20.6 | 2 |
| 0.4 – 0.6  | MACHINE SEQUENCE FLEXIBILITY (A) | 130.26 | 45.45 | 1 |
|            | ROBOT SPEED (B) | 44.51 | 15.7 | 4 |
|            | CUTTING TOOL TYPE (C) | 44.89 | 15.8 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 57.73 | 20.4 | 2 |
| 0.5 – 0.5  | MACHINE SEQUENCE FLEXIBILITY (A) | 130.78 | 46.2 | 1 |
|            | ROBOT SPEED (B) | 44.65 | 15.7 | 4 |
|            | CUTTING TOOL TYPE (C) | 45.11 | 15.9 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 57.94 | 20.4 | 2 |
| 0.6 – 0.4  | MACHINE SEQUENCE FLEXIBILITY (A) | 131.56 | 46.21 | 1 |
|            | ROBOT SPEED (B) | 44.87 | 15.7 | 4 |
|            | CUTTING TOOL TYPE (C) | 45.46 | 15.9 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 58.24 | 20.5 | 2 |
| 0.7 – 0.3  | MACHINE SEQUENCE FLEXIBILITY (A) | 132.85 | 46.2 | 1 |
|            | ROBOT SPEED (B) | 45.23 | 15.7 | 4 |
|            | CUTTING TOOL TYPE (C) | 46.02 | 15.9 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 58.74 | 20.4 | 2 |
| 0.8 – 0.2  | MACHINE SEQUENCE FLEXIBILITY (A) | 135.35 | 46.2 | 1 |
|            | ROBOT SPEED (B) | 45.94 | 15.6 | 4 |
|            | CUTTING TOOL TYPE (C) | 47.12 | 15 | 3 |
|            | WORK PART MATERIAL TYPE (D) | 59.69 | 20.3 | 2 |
| 0.9 – 0.1  | MACHINE SEQUENCE FLEXIBILITY (A) | 142.30 | 46.3 | 1 |
|            | ROBOT SPEED (B) | 48.04 | 15.6 | 4 |
|            | CUTTING TOOL TYPE (C) | 50.26 | 16.4 | 3 |

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Eguti, C.C.A, Trabasso, E.L.G., “The virtual commissioning technology applied in the design process of a flexible automation system”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40: 396-408, (2018).

[2] Knopp, S., Dauzère-Pérès, S., and Yugma, C., “Flexible job-shop scheduling with extended route flexibility for semiconductor manufacturing”, In Proceedings of the Winter Simulation Conference, 2478-2489, (2014).

[3] Gonçalves, J.P.M., “Robot interface in a flexible manufacturing cell”, Master's Thesis, Lehigh University, Lehigh (1992).

[4] Cutkosky, M. R., Fussell, P. S., and Milligan Jr, R., “Precision flexible machining cells within a manufacturing system (No. CMU-RI-TR-84-12)”, Carnegie-Mellon Univ. Pittsburgh Pa Robotics Inst., (1984).

[5] Yadav, A., Jayswal, S. C., “Evaluation of batching and layout on the performance of flexible manufacturing system”, The International Journal of Advanced Manufacturing Technology, 101: 1435–1449, (2019).

[6] Chan, F.T., “The effects of routing flexibility on a flexible manufacturing system”, International Journal of Computer Integrated Manufacturing, 14(5): 431-445, (2001).

[7] Lozano, S., Teba, J., Larrañeta, J., Onieva, L., and de Toledo, P. A., “Dynamic part—routing in a flexible manufacturing system”, Belgian Journal of Operations Research, 34(4): 16-28, (1994).

[8] Chandra, P., Tombak, M.M., “Models for the evaluation of routing and machine flexibility”, European Journal of Operational Research, 60(2): 156-165, (1992).

[9] Özkirim, M., Durmuşoğlu, M.B., “Dışsal rota esnekliğine sahip hücresel üretim sistemlerinin benzetim analizi”, İTÜ Journal (D), 6(2): 41-52, (2010).

[10] Wadhwa, R.S., “Flexibility in manufacturing automation: A living lab case study of Norwegian metal casting SMEs”, Journal of Manufacturing Systems, 31: 444–454, (2012).

[11] Galbraith, L., Greene, T.J., “Manufacturing system performance sensitivity to selection of product design metrics”, Journal of Manufacturing Systems, 14(2): 71-79, (1995).

[12] Pérez-Pérez, M., Bedía, A-M., S., López-Fernández, M-C., and García-Piqueres, G., “Research opportunities on manufacturing flexibility domain: A review and theory-based research agenda”, Journal of Manufacturing Systems, 48: 9–20, (2018).

[13] Yadav, A., Jayswal, S.C., “Modelling of flexible manufacturing system: a review”, International Journal of Production Research, 56(7): 2464-2487, (2018).

[14] Bazargan-Lari, M., “Layout designs in cellular manufacturing”, European Journal of Operational Research, 112:258-272, (1999).

[15] Stecke, K.E., “Formulation and solution of nonlinear integer production planning problems for flexible manufacturing systems”, Management Science, 29 (3): 273–288, (1983).
[16] Stecke, K.E., “A hierarchical approach to solve machine grouping and loading problem of fms”, European Journal of Operation Research, 24: 369–378, (1986).

[17] He, Y., Stecke, K.E., and Smith, M. L., “Robot and machine scheduling with state-dependent part input sequencing in flexible manufacturing systems”, International Journal of Production Research, 54(22): 6736–6746, (2016).

[18] Kia, A., Baboli., N., Javadian, R., Tavakkoli-Moghaddam, M., and Khorrami, J., “Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible configuration by simulated annealing”, Computers & Operations Research, 39: 2642–2658, (2012).

[19] Khannan, M.S.A., Maruf, A., “Development of robust and redesigning cellular manufacturing system model considering routing flexibility, setup cost, and demand changes”, Proceedings of the Asia Pacific Industrial Engineering Management Systems Conference, Puket, (2012).

[20] Ahkioon, S., Bulgak, A.A., Bektas T., “Cellular manufacturing systems design with routing flexibility, machine procurement, production planning and dynamic system reconfiguration”, International Journal of Production Research, 47(6):1573–1600, (2009).

[21] Singholi, A., Ali, M., Sharma C., “Evaluating the effect of machine and routing flexibility on flexible manufacturing system performance”, International Journal of Services and Operations Management, 16(2): 240–261, (2013).

[22] Jain, V., Raj, T., “Modeling and analysis of FMS performance variables by ISM, SEM and GTMA approach”, International Journal of Production Economics, 171: 84–96, (2016).

[23] Mahmood, K., Karaulova, T., Otto, T., and Shevtshenko, E., “Performance analysis of a flexible manufacturing system performance.” Proceedings of the 50th CIRP Conference on Manufacturing Systems, Taichung City, (2017).

[24] Rauch, E., Spena, P.R., Matt, D.T., “Axiomatic design guidelines for the design of flexible and agile manufacturing and assembly systems for SMEs”, International Journal of Interactive Design and Manufacturing, 13: 1–22 (2019).

[25] Ojistersek, R., Buchmeister, B., “The impact of manufacturing flexibility and multi-criteria optimization on the sustainability of manufacturing systems”, Symmetry, 12: 157-179, (2020).

[26] Tsai, T.-N., Chen, L.-H., Guh, R.S., “Measuring machine-group flexibility: a case study for surface mount assembly line with different configurations”, Journal of Industrial and Production Engineering, 34(4):261-273, (2017).

[27] Suresh, N.C., “Toward an integrated evaluation of flexible automation investment”, International Journal of Production Research, 28: 1657–1672, (1990).

[28] Reddy, B.S.P., Rao, C.S.P., “A Hybrid multi objective GA for simultaneous scheduling of machines and AGV in FMS”, International Journal of Advance Manufacturing Technology, 31: 602–613, (2006).

[29] Shin, K.S., Park, J.O., and Kim. Y.K., “Multi-objective FMS process planning with various flexibilities using a symbiotic evolutionary algorithm”, Computers and Operations Research, 38: 702–712, (2011).
[30] Chan, F.T.S., Jiang, B., Tang, N.K.H., “The development of intelligent decision support tools to aid the design of flexible manufacturing systems”, International Journal of Production Economics, 65: 73–84, (2000).
[31] Borenstein, D., “A visual interactive multi criteria decision analysis model for FMS design”, International Journal of Advance Manufacturing Technology, 14: 848–857, (1998).
[32] Borenstein, D., “Intelligent decision support system for flexible manufacturing system design”, Annals of Operation Research, 77: 129–156, (1998).
[33] Bramhane, R., Arora, A., Chandra, H., “Simulation of flexible manufacturing system using adaptive neuro fuzzy hybrid structure for efficient job sequencing and routing”, International Journal of Mechanical Engineering and Robotics Research, 3(4): 33–48, (2014).
[34] Dosdogru, A. T., Gocken, M., Geyik, F., “Integration of genetic algorithm and monte carlo to analyze the effect of routing flexibility”, International Journal of Advanced Manufacturing Technology, 81: 1379–1389, (2015).
[35] Liu, Y.-H., Huang, H.P., Lin, Y.S., “Attribute selection for the scheduling of flexible manufacturing systems based on fuzzy set-theoretic approach and genetic algorithm”, Journal of the Chinese Institute of Industrial Engineers, 22(1): 46-55, (2005).
[36] Gholipour-Kanani, Y., Tavakkoli-Moghaddam, R., Khorrami, A., “Solving a multi-criteria group scheduling problem for a cellular manufacturing system by scatter search”, Journal of the Chinese Institute of Industrial Engineers, 28(3): 192-205, (2011).
[37] Su, T.-L., Chen, H.-W., Lu, C.-F., “Systematic Optimization for the evaluation of the microinjection molding parameters of light guide plate with TOPSIS-based Taguchi Method”, Advanced Polymer Technology, 29(1): 54–63, (2010).
[38] Hong, G.B., Su, T.L., “Statistical analysis of experimental parameters in characterization of ultraviolet-resistant polyester fiber using a TOPSIS-Taguchi method”, Iranian Polymer Journal, 21(12): 877-885, (2012).
[39] Lan, T.-S., “Taguchi optimization of multi objective CNC machining using TOPSIS”, Information Technology Journal, 8(6): 917-922, (2009).
[40] Liao, H.C., “Using PCR-TOPSIS to optimize Taguchi’s multi response problem”, International Journal of Advanced Manufacturing Technology, 22: 649-655, (2003).
[41] Lu, J.-C., Yang, T., Su, C.-T., “Analysing optimum push/pull junction point location using multiple criteria decision-making for multistage stochastic production system”, International Journal of Production Research, 50(19): 5523-5537, (2012).
[42] Yang, T., Chou, P., “Solving a multi-response simulation-optimization problem with discrete variables using a multiple-attribute decision-making method”, Mathematics and Computers in Simulation, 68 (1): 9–21, (2005).
[43] İç, Y.T., Yıldırım, S., “MOORA-Based Taguchi Optimization for Improving Product or Process Quality”, International Journal of Production Research, 51(11): 3321–3341, (2013).
[44] Şimşek, B., İç, Y.T., and Şimşek, E.H., “A TOPSIS-based Taguchi optimization to determine optimal mixture proportions of the high strength self-compacting concrete”, Chemometrics and Intelligent Laboratory Systems, 125: 18–32, (2013).
[45] Şimşek, B., İç, Y.T., “Multi-response simulation optimization approach for the performance optimization of an alarm monitoring center”, Safety Science, 66: 61–74, (2014).

[46] Şimşek, B., İç, Y.T., and Şimşek, E.H., “Hybridizing a fuzzy multi-response Taguchi optimization algorithm with artificial neural networks to solve standard ready-mixed concrete optimization problems”, International Journal of Computational Intelligence Systems, 9(3): 525-543, (2016).

[47] İç, Y.T., Elaldı, F., and Keçeci, B., “Topsis based taguchi optimization of machining characteristics in end milling operation of kevlar-epoxy composites”, Journal of The Chinese Society of Mechanical Engineers, 37(6): 653-662, (2016).

[48] İç, Y.T., Saraloğlu Güler, E., and Erbil Çakır Z., “Reducing uncertainty in a type j thermocouple calibration process”, International Journal of Thermophysics, 40(53): 1-22, (2019).

[49] Chavan P., Patil A., “Taguchi-based optimization of machining parameter in drilling spheroidal graphite using combined TOPSIS and AHP method”, Advances in Intelligent Systems and Computing, 949: 787-797, (2020).

[50] Gopal, P.M., Prakash, K.S., “Minimization of cutting force, temperature and surface roughness through GRA, TOPSIS and Taguchi techniques in end milling of Mg hybrid MMC”, Measurement, 116:178–192, (2018).

[51] Nguyen, H.-P., Pham, V.-D., and Ngo, N.-V., “Application of TOPSIS to Taguchi method for multi-characteristic optimization of electrical discharge machining with titanium powder mixed into dielectric fluid”, The International Journal of Advanced Manufacturing Technology, 98: 1179–1198, (2018).

[52] Rajamanickam S., Prasanna J, and Sastry C.C., “Analysis of high aspect ratio small holes in rapid electrical discharge machining of super alloys using Taguchi and TOPSIS”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42: 99-105, (2020).

[53] Pradeep, N., Sundaram, K.S., and Kumar, M.P., “Multi-response optimization of electrochemical micromachining parameters for SS304 using polymer graphite electrode with NaNO3 electrolyte based on TOPSIS technique”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41: 323-333, (2019).

[54] Jain, A., Jain, P., Chan, F.T., and Singh, S., “A review on manufacturing flexibility”, International Journal of Production Research, 51(19): 5946–5970, (2013).

[55] Malhotra, M., Sharma, S., “Measurement equivalence using generalizability theory: an examination of manufacturing flexibility dimensions”, Decision Sciences, 39(4): 643–669, (2008).

[56] Wahab, M., Wu, D., and Lee, C., “A generic approach to measuring the machine flexibility of manufacturing systems”, European Journal of Operations Research, 186(1): 137–149, (2008).

[57] Ranjit, K.R., “A Primer on the Taguchi Method”. USA: Van Nostrand Reinhold Press, (1990).

[58] Phadke, M.S. “Quality Engineering Using Robust Design”. USA: Prentice Hall, (1989).

[59] Unal, R., Dean, E.B., “Taguchi Approach to Design Optimization for Quality and Cost: An Overview”. USA: NASA Press, (1990).

[60] http://seykoc.com.tr/. Access date: 14.12.2015
[61] http://www.cadcamsektoru.com/makaleler/Talasli-Imalatta-Kullanilan-Kesici-TOOLLar-9949.htm. Access date: 09.15.2015