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

Yusuf Tansel IC[1,*], Mustafa YURDAKUL[2], Berna DENGIZ[1], Turgut SASMAZ[3]

[1] Baskent Unversity, Department of Industrial Engineering, 06790, Ankara, Turkey
[2] Gazi Unversity, Department of Mechanical Engineering, 06570, Ankara, Turkey
[3] NUROL Machinery Co., Organize Sanayi Bölgesi, Avrupa Hun Cad. No: 6, 06935, Sincan, Ankara, Turkey

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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Keywords

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Machine sequence flexibility,
Performance measurement model,
TOPSIS
Taguchi method

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.

*Corresponding author, e-mail: yustanic@baskent.edu.tr

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, Özkırım 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 (C_k^*) 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:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right) \tag{1}$$

Larger is better:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^{2}}\right) \tag{2}$$

Nominal is best:

$$S/N = 10\log\frac{\bar{y}^2}{S^2} \tag{3}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{4}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{5}$$

where, y_i: response in i^{th} experiment, n: number of experiments, and S^2: variance.

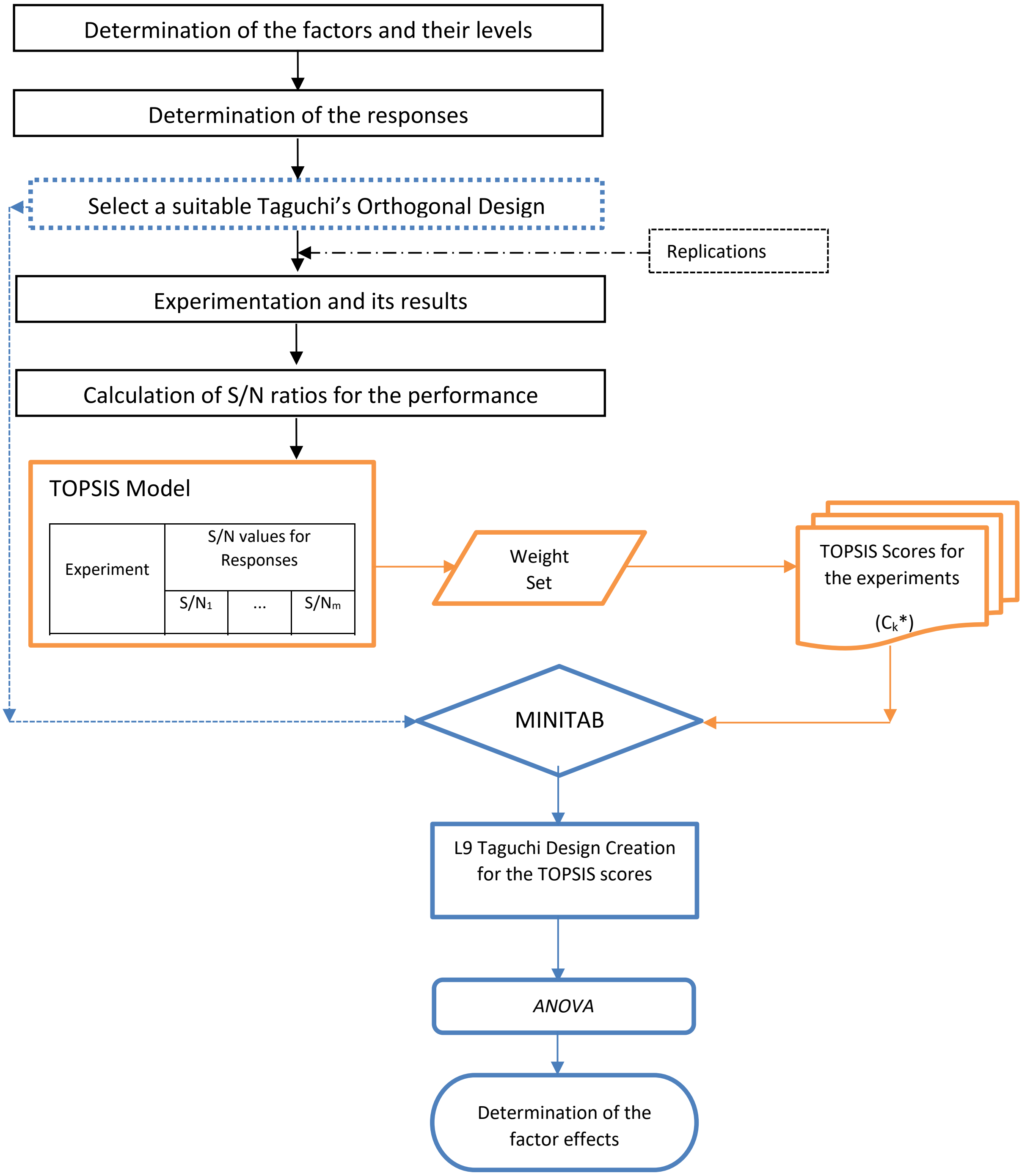


Figure 1. *The TOPSIS based Taguchi model to link input factors' levels and multi-response performance of a FMC*

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].

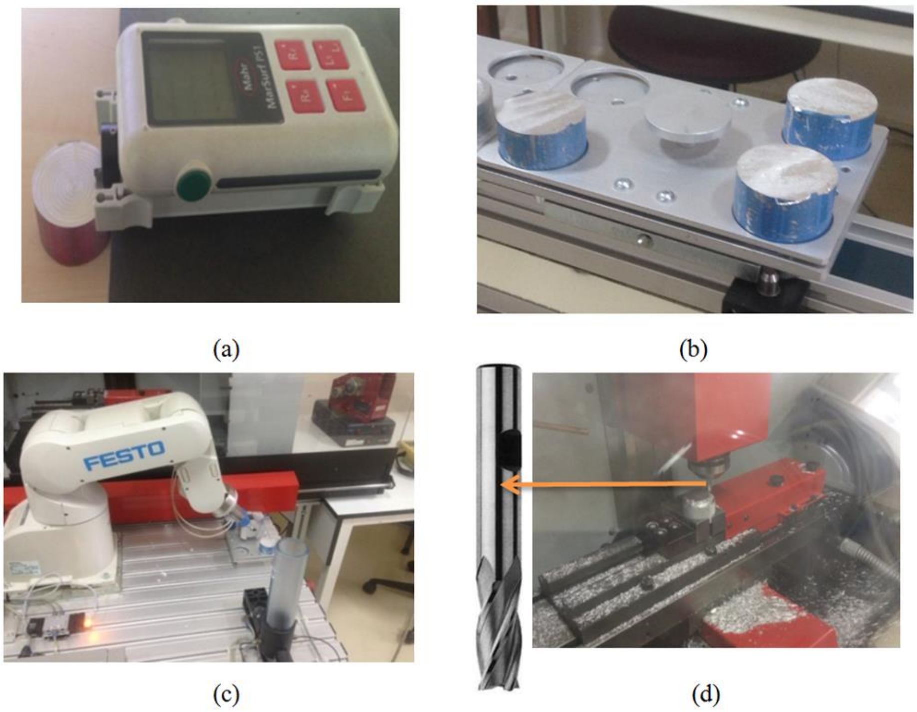


Figure 2. *Experimental set-up*

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 work-parts 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% (1470mm/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

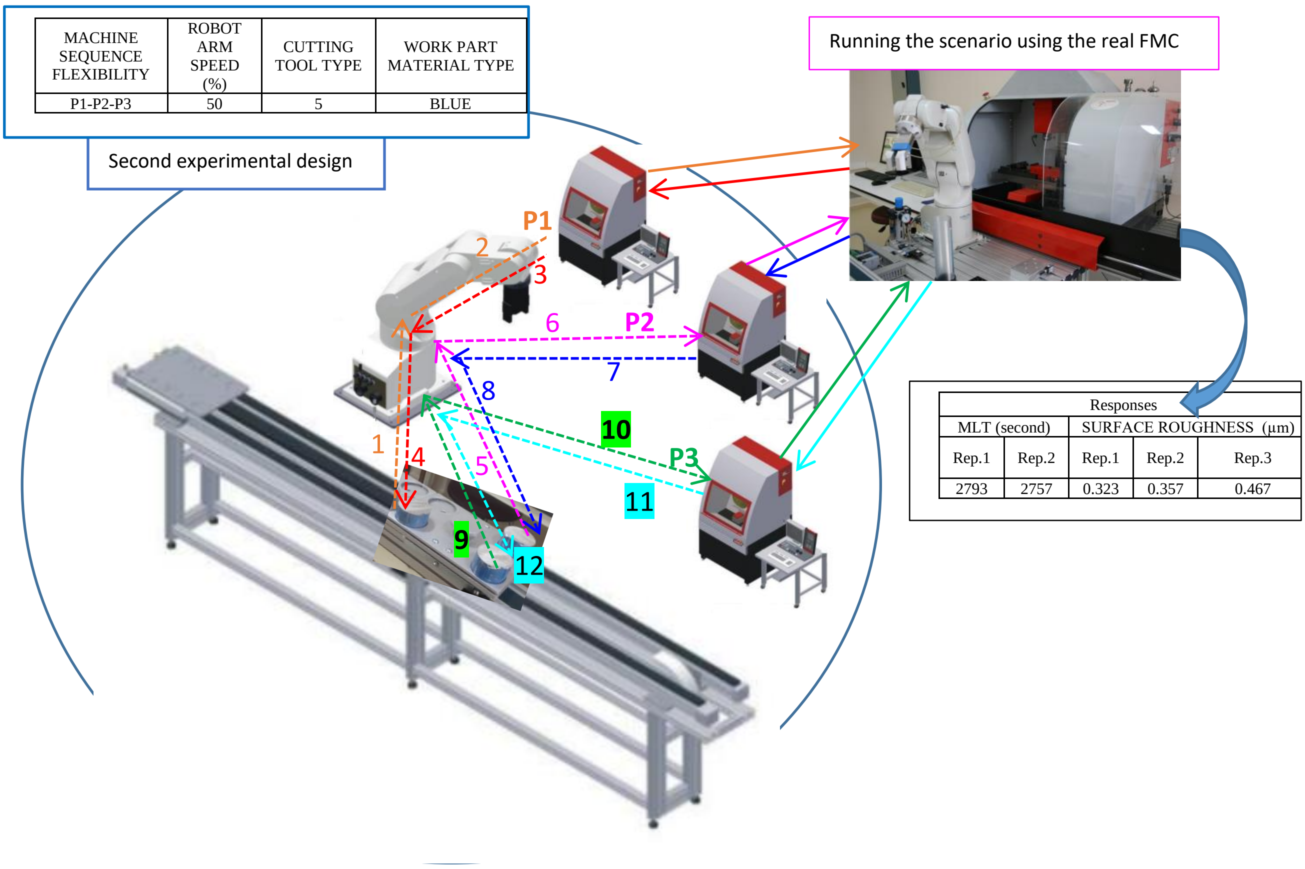


Figure 3. *Considered system for the study*[1]

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

[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)*

	L9 Design-Coded				L9 Design-Uncoded				Responses				
									MLT (second)		SURFACE ROUGHNESS (μm)[a]		
	MACHINE SEQUENCE FLEXIBILITY	ROBOT ARM SPEED (%)	CUTTING TOOL TYPE	WORK PART MATERIAL TYPE	MACHINE SEQUENCE FLEXIBILITY	ROBOT ARM SPEED (%)	CUTTING TOOL TYPE	WORK PART MATERIAL TYPE	Rep.1	Rep.2	Rep.1	Rep.2	Rep.3
1	1	1	1	1	P1/P2/P3	30	3	P	2,679	2,552	0.164	0.202	0.198
2	1	2	2	2	P1/P2/P3	50	5	BL	2,793	2,757	0.323	0.357	0.467
3	1	3	3	3	P1/P2/P3	70	4	W	2,568	2,574	0.307	0.219	0.452
4	2	1	2	3	P2/P1/P3	30	5	W	2,631	2,524	1.058	1.348	1.258
5	2	2	3	1	P2/P1/P3	50	4	P	2,769	2,747	0.676	0.642	0.631
6	2	3	1	2	P2/P1/P3	70	3	BL	2,640	2,612	1.128	0.83	0.948
7	3	1	3	2	P3/P1/P2	30	4	BL	2,667	2,657	0.364	0.271	0.24
8	3	2	1	3	P3/P1/P2	50	3	W	2,669	2,645	3.871	5.24	4.319
9	3	3	2	1	P3/P1/P2	70	5	P	2,704	2,581	0.749	0.729	0.762

[a]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.	Decision Matrix		Normalized Decision Matrix		Weighted normalized decision Matrix				
	$R = \left\| r_{ij} \right\|$ (*i=1,…,18; j=1,2*) of the *i*-th experiment for the *j*-th response		A= $\left\| a_{ij} \right\|$; $a_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}$		$V = \begin{pmatrix} w_1 r_{11} & \cdots & w_5 r_{15} \\ \vdots & \ddots & \vdots \\ w_1 r_{321} & \cdots & w_5 r_{325} \end{pmatrix} = \begin{pmatrix} v_{11} & \cdots & v_{15} \\ \vdots & \ddots & \vdots \\ v_{321} & \cdots & v_{325} \end{pmatrix}$		$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}$	$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}$	$C_k^* = \frac{S_i^-}{S_i^- + S_i^*}$,
	MLT	SR	Weight=0.5	0.5	MLT	SR			
			MLT	SR					
1	-68.559	15.703	-0.236	0.406	-0.118	0.203	**0.001[a)]**	**0.389[b)]**	**0.998[c)]**
2	-68.921	9.816	-0.237	0.254	-0.119	0.127	0.076	0.313	0.804
3	-68.192	10.257	-0.235	0.265	-0.117	0.133	0.070	0.318	0.819
4	-68.402	-0.490	-0.235	-0.013	-0.118	-0.006	0.209	0.180	0.462
5	-68.846	3.401	-0.237	0.088	-0.118	0.044	0.159	0.230	0.591
6	-68.432	-1.046	-0.236	-0.027	-0.118	-0.014	0.216	0.172	0.443
7	-68.520	8.778	-0.236	0.227	-0.118	0.113	0.089	0.299	0.770
8	-68.527	-11.756	-0.236	-0.304	-0.118	-0.152	0.355	0.034	0.087
9	-68.640	2.510	-0.236	0.065	-0.118	0.032	0.170	0.218	0.562
10	-68.138	13.893	-0.235	0.359	-0.117	0.180	0.023	0.365	0.940
11	-68.809	8.947	-0.237	0.231	-0.118	0.116	0.087	0.302	0.775
12	-68.212	13.191	-0.235	0.341	-0.117	0.170	0.032	0.356	0.917
13	-68.042	-2.594	-0.234	-0.067	-0.117	-0.034	0.236	0.152	0.392
14	-68.777	3.849	-0.237	0.099	-0.118	0.050	0.153	0.236	0.606
15	-68.339	1.618	-0.235	0.042	-0.118	0.021	0.182	0.207	0.532
16	-68.488	11.341	-0.236	0.293	-0.118	0.147	0.056	0.332	0.855
17	-68.449	-14.387	-0.236	-0.372	-0.118	-0.186	0.389	0.001	0.002
18	-68.236	2.745	-0.235	0.071	-0.117	0.035	0.167	0.221	0.569
$\sqrt{\sum_{i=1}^{m} r_{ij}^2}$	290.51	38. 7	**-68.559/ 290.51 =-0.236**	**15.703/38.7 =0.406**	**- 0.236*0.5 =-0.118**	**0.406*0.5= 0.203**			
v_j^*					-0.211	0.041			
v_j^-					-0.214	-0.037			

a) √(-0.118-(-0.211))^2+(0.203- 0.041)^2=0.001
b) √(-0.118-(-0.214))^2+(0.203- (-0.037))^2=0.389
c) 0.389/(0.389+0.001)=0.998

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

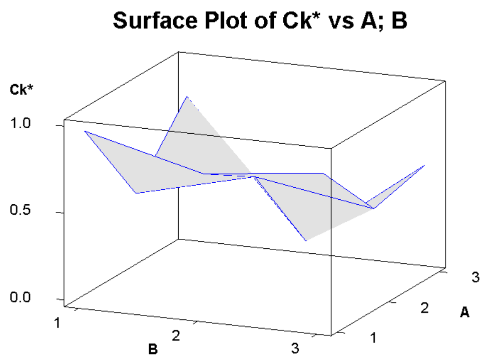
Table 5. *Analysis of variance for the equal weight set*

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
Total	17	1.29668					100
S = 0.0478648 R-Sq = 98.41% R-Sq(adj) = 97.00%							

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.


Surface Plot of Ck* vs A; B
Ck*
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B
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A
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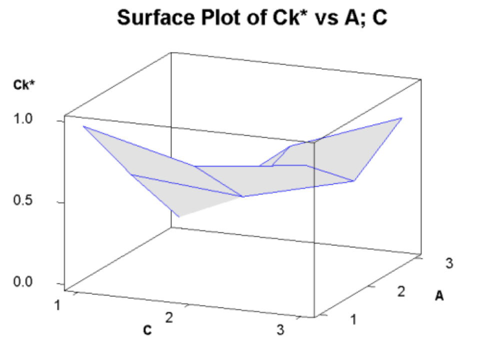
Surface Plot of Ck* vs A; C
Ck*
1.0
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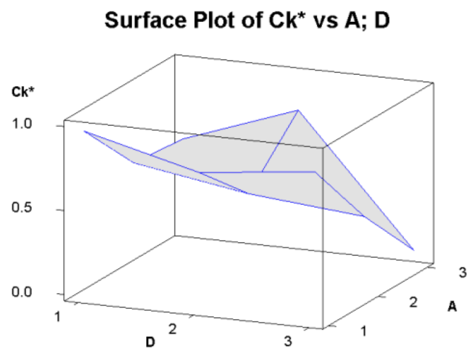
Surface Plot of Ck* vs A; D
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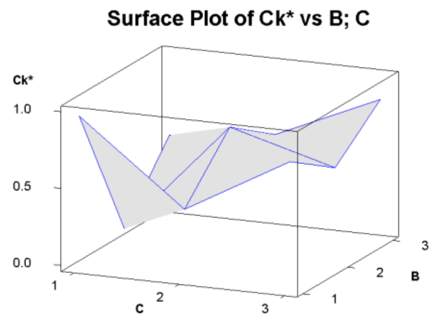
Surface Plot of Ck* vs B; C
Ck*
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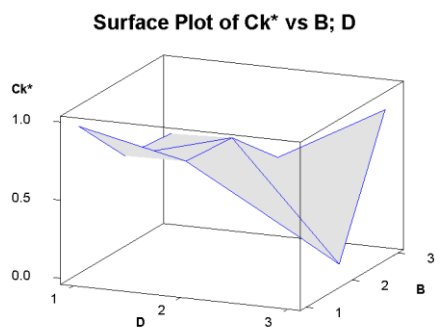
Surface Plot of Ck* vs B; D
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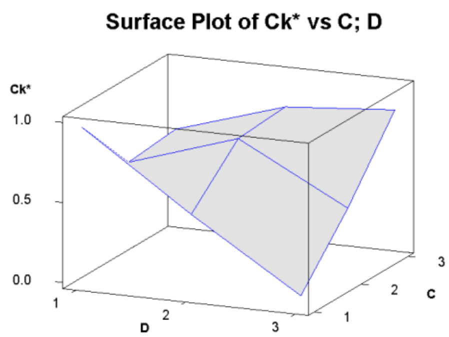
Surface Plot of Ck* vs C; D
Ck*
1.0
0.5
0.0
D
1
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C
1
2
3

Level	A	B	C	D
1	**0.8755**	**0.7360**	0.5004	**0.7109**
2	0.5044	0.4777	0.5941	0.6966
3	0.4742	0.6403	**0.7596**	0.4465

Figure 4. *Taguchi optimization result for the equal weight set*

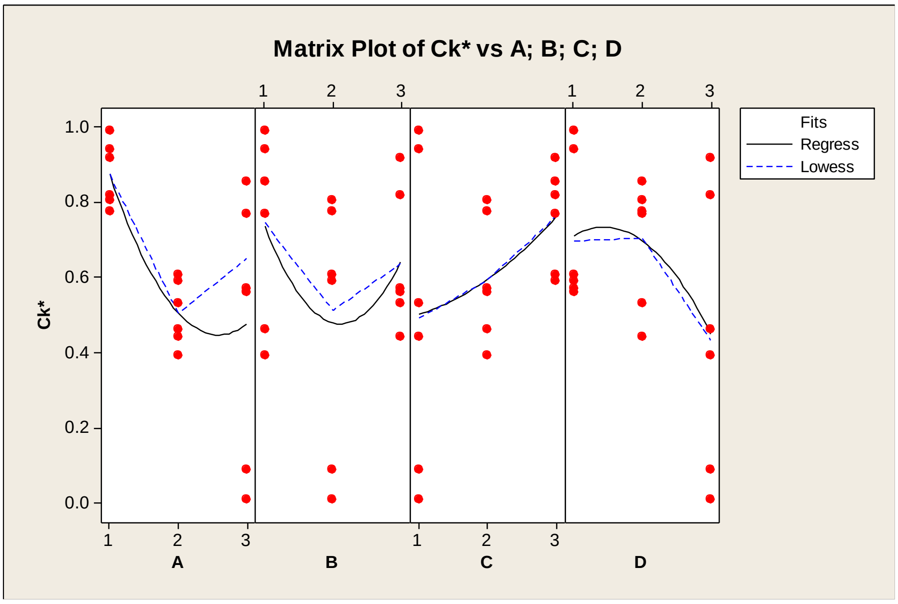

Figure 5. *Matrix plot of* C_k^*

Table 6. *The ranking scores of the eighteen experiments for the nine weight sets*

Exp.	Weight Sets								
	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}	w_{MLT} – w_{SR}
	0.1- 0.9	0.2 - 0.8	0.3 - 0.7	0.4 - 0.6	0.5 - 0.5	0.6 - 0.4	0.7 - 0.3	0.8 - 0.2	0.9 - 0.1
	TOPSIS Scores								
1.000	1.000	0.999	0.999	0.998	0.998	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	0.088	0.089
9.000	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.561	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

16.000	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.854
17.000	0.000	0.001	0.001	0.001	0.002	0.003	0.005	0.008	0.018
18.000	0.569	0.569	0.569	0.569	0.569	0.569	0.569	0.569	0.570
Optimal Levels	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1	A1B1C3D1

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.

Table 7. *Ranking results of the four input factors for the nine weight sets*

Weight Set $w_{MLT} - w_{SR}$	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 – 08	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
	CUTTINGTOOL 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
	WORK PART MATERIAL TYPE (D)	62.16	20.2	2

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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