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Abstract: This research focused primarily on self-fastening characteristics, standardisation of parts and minimal use of fasteners. The work investigated the significance of synergistic design for manufacturing techniques (DFMTs), with their inherent machine element systems (MES) and machining parameters (MPs) to evaluate which DFMT has the most influence on cost reduction and increasing throughput and under which circumstances. In sum, this research applies DFMT to product design. For each DFMT and associated MES and MP, process planning was used effectively with computer aided process planning (CAPP) tools to enhance the evaluation impact of the dialogue between the design and manufacturing functions. A systematic algorithm was inherently developed and incorporated into the software tools used herein. Generative process planning software is used to measure and analyse sensitivity in plan effectiveness. The final results showed a significant improvement in cost reduction and production rates. DFMTs 1 and 2 have the main influence on the systematic algorithm.

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Keywords: design for manufacturing; computer-aided process planning; machining parameters; machine element systems; MES; process planning; machining.

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1 Introduction

The main objective of analysing and improving the manufacturing processes is to increase the productivity and reducing the cost of manufacturing. Currently, design for manufacturing technique (DFMT) plays an important role in improving productivity as compared to the simpler systems without DFMT used in the early 19th century. This literature review is based on achievements enhancing manufacturing productivity in metal cutting, including the impacts of the DFM factors to reduce the product cost. With regard to manufacturing productivity, Gunasekaran (1998) implemented a new productivity improvement strategy in a small French company, Valeo, located in the UK, for their wiper production system. After three weeks of work, results showed that the cycle time was reduced from 18 seconds to 14 seconds per item. Huang et al. (2003) presented a systematic methodology for productivity measurement and an analysis at the factory level. Kabir et al. (2013) performed research use a fan manufacturing company, they proposed a way to improve productivity and quality by improving the existing Six Sigma level of the process. Al-Shebeeb and Gopalakrishnan (2016) studied the effectiveness of computer aided process planning (CAPP) on manufacturing outputs (production rate and production cost). Several process plans have been evaluated and process plan one had the highest influence on productivity. Tyagi et al. (2020) developed a methodology of manufacturing planning to evaluate and analyse several significant factors (capacity planning, loading, scheduling and process plans) inside manufacturing facility. They tried to match the production schedules with the production plans. The evaluation of this work performed by eight case studies and the results showed the proposed methodology has positive impact by comparing it to the conventional hierarchical one on manufacturing planning. Al-Shebeeb and Gopalakrishnan (2017) studied the influence of material properties on generative process planning by using generative process planning software tools.

In the area of machining productivity in metal cutting, Nishiguchi et al. (1991) developed spherical machining technology. Using the stylus method, technology, with in-situ metrology, researcher improved the machining accuracy and reduced the machining time. Pasko et al. (2002) studied the effects of high-speed machining (HSM) on productivity as well as accuracy in terms of tools and tool holders. The authors then proceeded to discuss examples of productivity within milling process. Agarwal (2016) conducted experiments to evaluate several parameters such as the depth of cut, table feed rate, size and density of grit, surface roughness, and surface and subsurface damages.

In field of design for manufacturing, Boothroyd(1996) discussed the importance of design for manufacture and assembly (DFMA) in the early stage of product design. The author used a case study to express the philosophy of DFMA methodology and its application. Kerbrat et al. (2011) presented a new approach concerning the DFM focusing on designing a hybrid modular product instead of focusing on one use manufacturing process to obtain the same product competitiveness. Ramos and Lorini (2013) focused on and analysed DFM demands/requirements and their influence on the framework of this domain. Al-Shebeeb (2018) investigated a way to simplify and improve the efficiency of desktop (hole) punch produced by ACCO's model A7074030. Author deployed the assembly analysis method in this context and suggests an enhanced design for the desktop punch, which reduces assembly time, increases production efficiency, and reduces necessary components and parts. Prasad et al. (2008) presented the DFM approach in terms of productivity improvement. This approach is referring to medical devices, being able to make the product easy to build, and reducing the production cost and time. Qehaja et al. (2015) developed a model for surface roughness to evaluate the machining parameters (MPs) of a dry turning machine, which included the feed rate, tool geometry, nose radius and machining time. Lata et al. (2018) investigated MPs, and tool material such as tungsten carbide and polycrystalline diamond (PCD) by determining the average chip-tool interface temperature. This work has been applied on turning process for machining IS 733 Gr. 63400 aluminium and IS 2062 steel. Chandra et al. (2018) analysed the effect of MPs (cutting speed, feed/revolution and depth of cut) for turning alloy steels following ISO3685 standards on surface toughness and cutting force. Baptista et al. (2019) presented a methodology to help mechanical designers of connecting design parameters (DPs) to mechanical processes. This methodology depends on a design constrain which is directly related to the number of spatial dimensions and its influence on product life-cycle. Cheng et al. (2020) investigated the complexity and difficulty of milling process for machining blisk. Finite element method was used to analyse the geometrical structure of blisk. By using the titanium alloy as a raw material, predesigned tool and fuzzy method, authors could optimise the cutting parameters. The conclusion obtained from reading and summarising the literature is that DFMTs and MPs can have a significant impact on cost savings and improving productivity. After reviewing these papers regarding manufacturing, machining, and DFMT, one can say that minimal work has been done considering the influence of DFMT and MP. Synergistic integration of DFMT with CAPP and MP to produce desirable results in terms of production cost, production rate, satisfaction of design and system parameters, and most importantly the functionality of the product. The main goal for this research is to analyse and investigate the DFMT, machine element systems (MES), and MP with respect to a specific product and associated product DPs. Then, determine the effectiveness of each DFMT, MES, and MP with respect to cost and productivity attributes and under which circumstances. That can be more fruitful by developing a systematic algorithm to organise and perform the work.

2 Methodology and research tools

The research approach and systematic algorithm adopted in this work. This study is investigated several DFMT and their relationships with MES and MPs, which have not been considered till date adequately within the scientific body of knowledge.

2.1 Systematic algorithm structure

This systematic algorithm has basic elements that are used as a foundation for critical evaluation. In sum, the algorithm provides guidance for analysing the DFMT, and presents several outputs that are useful for cost, material and design comparison. The structure and function of these critical elements of the algorithm was explained in detail in the following sections and subsections of this paper. The structure of these elements was integrated in one chart which was represented as the scheme of systematic algorithm later in Figure 2.

2.1.1 Design for manufacturing techniques

There are several DFMTs including modifying raw materials, modifying the quality (surface finish and tolerance), modifying geometry, and modifying the selection of process/es (Groover, 2007). The DFMT in this research are as follows:

1. *Modifying raw material (DFMT1):* This DFMT includes choosing alternative raw material instead of the one that was used originally in the preliminary process plan (PPP). Modifying the selection of raw material is not an arbitrary process and should be done under specific constraints. This modification can be performed by considering a specific constrained range of material properties on the preliminary design of the part. The values of these allowed ranges should be specified by the designer, thereby the functionality of the part can be maintained. Further, the material should be selected according to the performance criteria and functionality, in which the material should be compatible with design and process. Seven raw materials (alloys) have been selected in this work, including stainless steel 316L, to study the effectiveness of modifying the raw materials. The seven alloys selected are shown in Table 1.

   After considering the alloys as alternative raw materials, the values of material properties for each alloy has been gathered and arranged (Ashby, 2005; Ashby et al., 2013).

2. *Modifying quality (modifying tolerance and surface finish) (DFMT2):* Modifying the quality is considered one of the DFMTs. Altering the surface finish and tolerance can establish this modification of quality.

3. *Modifying geometry (DFMT3):* This DFMT can be performed by modifying the shape or the features of the part, for the workpiece and/or the final part. In this study, specific geometric guidelines were selected for modification.

4. *Modifying manufacturing process/es (DFMT4):* Modifying one or more machining processes inside this DFMT has an impact on cost reduction.

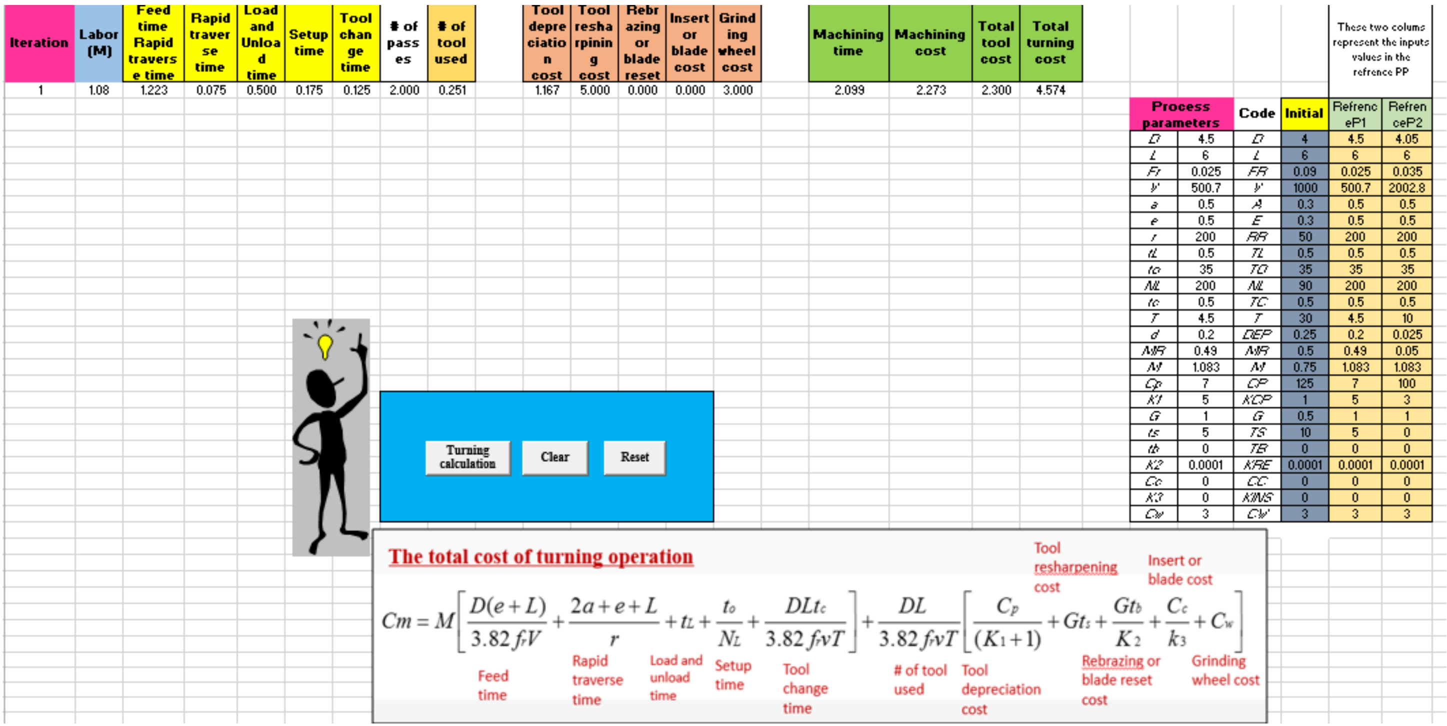
Table 1 The list of suggested raw materials

Index	*Engineering alloys*
1	Aluminium alloys
2	Stainless steel alloys
3	Copper alloys
4	Zinc alloys
5	Nickel alloys
6	Titanium alloys
7	Cast iron

2.1.2 Machine elements system and machining parameters

Two main MES have been modified while applying every DFMT. These two MES are machine tool and cutting tool. Several MPs are considered in this systematic algorithm.

Figure 1 The interface structure of the PPAC software (see online version for colours)



Iteration	Labor (M)	Feed time Rapid traverse time	Rapid traverse time	Load and Unload time	Setup time	Tool change time	# of passes	# of tool used	Tool depreciation cost	Tool resharping cost	Rebrazing or blade reset	Insert or blade cost	Grinding wheel cost	Machining time	Machining cost	Total tool cost	Total turning cost
1	1.08	1.223	0.075	0.500	0.175	0.125	2.000	0.251	1.167	5.000	0.000	0.000	3.000	2.099	2.273	2.300	4.574

These two colums represent the inputs values in the refrence PP

Process parameters		Code	Initial	RefrenceP1	RefrenceP2
D	4.5	D	4	4.5	4.05
L	6	L	6	6	6
Fr	0.025	FR	0.09	0.025	0.035
V	500.7	V	1000	500.7	2002.8
a	0.5	A	0.3	0.5	0.5
e	0.5	E	0.3	0.5	0.5
r	200	RR	50	200	200
tL	0.5	TL	0.5	0.5	0.5
to	35	TO	35	35	35
NL	200	NL	90	200	200
tc	0.5	TC	0.5	0.5	0.5
T	4.5	T	30	4.5	10
d	0.2	DEP	0.25	0.2	0.025
MR	0.49	MR	0.5	0.49	0.05
M	1.083	M	0.75	1.083	1.083
Cp	7	CP	125	7	100
K1	5	KCP	1	5	3
G	1	G	0.5	1	1
ts	5	TS	10	5	0
tb	0	TB	0	0	0
K2	0.0001	KRE	0.0001	0.0001	0.0001
Cc	0	CC	0	0	0
K3	0	KINS	0	0	0
Cw	3	CW	3	3	3

The total cost of turning operation

$$Cm = M\left[\underbrace{\frac{D(e+L)}{3.82 f_r V}}_{\text{Feed time}} + \underbrace{\frac{2a+e+L}{r}}_{\text{Rapid traverse time}} + \underbrace{t_L}_{\text{Load and unload time}} + \underbrace{\frac{t_o}{N_L}}_{\text{Setup time}} + \underbrace{\frac{DLt_c}{3.82 f_r vT}}_{\text{Tool change time}}\right] + \underbrace{\frac{DL}{3.82 f_r vT}}_{\text{\# of tool used}}\left[\underbrace{\frac{C_p}{(K_1+1)}}_{\text{Tool depreciation cost}} + \overbrace{Gt_s}^{\text{Tool resharpening cost}} + \underbrace{\frac{Gt_b}{K_2}}_{\text{Rebrazing or blade reset cost}} + \overbrace{\frac{C_c}{k_3}}^{\text{Insert or blade cost}} + \underbrace{C_w}_{\text{Grinding wheel cost}}\right]$$

2.1.3 Design parameters

One aspect of the suggested systematic algorithm is the DPs. The DP represents the qualitative and quantitative characteristics of a part's physical and functional construction:

a The qualitative characteristics in the systematic algorithm are represented by:
  1 Surface finish and tolerance of every surface or feature of the part.
  2 The raw material information, such as material type and environmental considerations (pressure, temperature, corrosion resistance, stiffness and strength).

b The quantitative characteristics in the DP are represented by:
  1 Raw material properties (density, hardness, heaviness, melting point and heat treatment).
  2 Raw material and final product measurable characteristics (dimensions, diameter, thickness, length and width).
  3 The shape of the raw material and final part.
  4 The features of the final product (holes, fasteners, chamfer, fillet, closed pocket, open pocket, slot with open end, slot, groove, keyway and snap fit).

2.1.4 Manufacturing system parameters

Before creating any process plan, work should be completed in the manufacturing system parameters (MSP) section. This involves selecting appropriate MES, including the machine tool, cutting tool, and cutting fluid for each machining process. These parameters can be selected according to their suitability for the machining process, by using the MPSEL expert software.

2.1.5 MPSEL

MPSEL is a software for machining system parameter selection. It is an expert system for MP selection in job shop environments. MPSEL was developed to select different MPs including machines, cutting tools, cutting fluids and to indicate the different cutting conditions (Gopalakrishnan, 1990). The expert system considers the following machine shop environment in which engine lathe, NC lathe, turret lathe, single spindle automat, cylindrical grinding machine, surface grinding machine, horizontal milling machine, vertical milling machine, NC mill, Turret drilling machine, vertical drilling machine and radial drilling machine are available. The processes that can be performed in this system are, turning, facing, milling, grinding, drilling, reaming, boring, tapping and threading

2.1.6 Process plan attributes calculator

The software interface created by the researcher is constructed through coded spreadsheets, using Visual Basic for Applications Software (VBA®). The input to the process plan attributes calculator (PPAC) depends on suitable MES information and material properties. Machining cost, machining time, and tool cost are calculated for each cutting pass, and are added to get the total machining cost and machining time for each machining process individually. Specific equation for every machining in this research process were developed and coded inside the PPAC.

2.2 *Systematic algorithm steps*

Concurrently, the part's quantitative and qualitative design characteristics (such as the part's shape and physical features) of the PPP are specified in the DP section, to determine which machining processes are most suitable. Each MP then, needs to be checked in the MSP section of the algorithm to decide which MES&MP were selected with this process. The same work is repeated on all the candidate machining processes to generate the PPP in the following section, then the DFMA of the PPP is calculated to determine whether the PPP should be executed, or not. If the PPP is not accepted (according to its DFMA), it is time to perform the first DFMT. After that, the modified information is transferred to the relevant sections [DP, MSP, MES&MP database (DB)] to create the alternative PP and its DFMA. This step is then repeated using all the DFMT until user satisfaction is obtained. A flowchart depicting the algorithm is provided in Figure 2.

Figure 2 Systematic algorithm structure (see online version for colours)

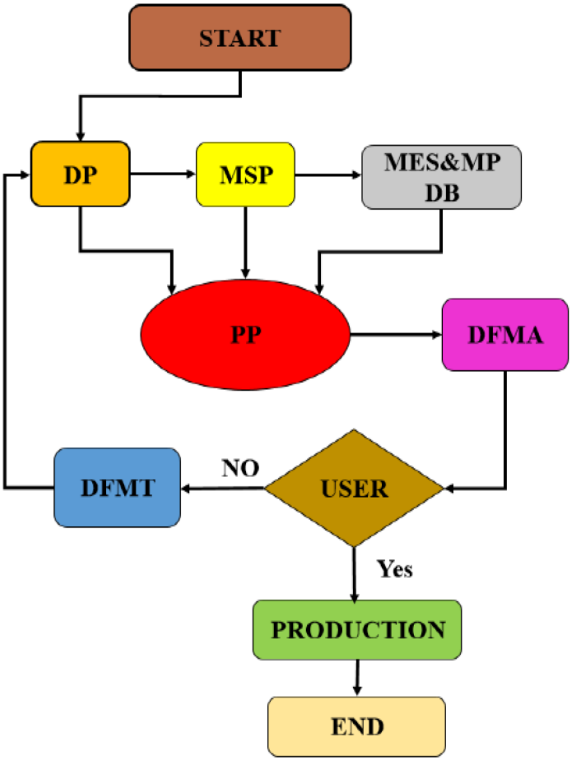
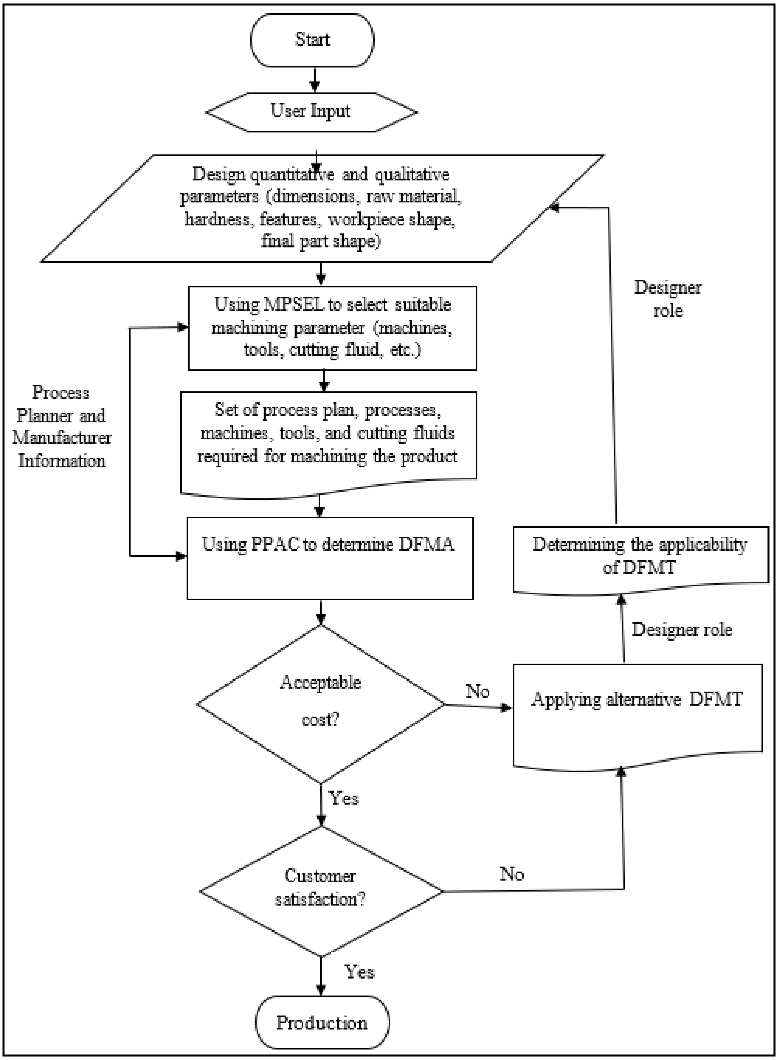


Figure 3 Methodology diagram



The scheme of the suggested systematic algorithm is shown in Figure 2. The algorithm works using the following steps:

1 The algorithm should start in the three sections (DP, MSP and MES&MP DB) to create a PPP. In the DP section, the quantitative and qualitative DPs (dimensions, density, hardness, shape of raw material and final part, physical features) of the part are assigned, and the machining process was specified.

2 A check has been done on the suitability of every process, and then the MES (machine tool and cutting tool) is assigned inside the MSP section.

3 The information was transferred simultaneously for each machining process to the MES&MP DB section for determining the values of MP.

4 This information was collected and entered into the PP section to create the PPP.

5 The attributes of the process plan are calculated inside the DFMA section to obtain the cost of manufacturing and the production rate of a PPP, by using the PPAC interface.

6 The decision is made for accepting the PPP (or not) by the user or by facility management.

7 If the decision is to accept the PPP, notification was sent to the production section to start the manufacturing; otherwise, the sequence of the algorithm has been moved to the DFMT section.

8 The first DFMT was applied (changing raw material) when the user is not satisfied with the results of PPP. The procedure of selecting alternative process plan (APP) is discussed in this research.

9 The new DP, MSP, and MES&MP DB are calculated to create the APP and calculate DFMA, by following the same steps from 1 to 5, listed above.

10 The same actions should be applied for Steps 7 to 9 for the rest the DFMT (modifying geometry, modifying quality and changing machining process/es) in order, according to its significance.

11 In this way, all the DFMT can be applied in sequence and the DP, MSP, and MES&MP DB can be changed with every DFMT, until the user is satisfied with one of the PP and its DFMA.

Note, if applying the DFMT does not produce convincing results, a combination of DFMT can be applied to acquire better results.

2.3 Applying methodology and results

In order to clarify the steps of the systematic algorithm, Figure 3 represents how the proposed methodology works in more detail. This flowchart illustrates how to perform the systematic algorithm.

1 In the first step, the user inputs data (such as workpiece and part dimensions, raw material properties, physical features, and workpiece and final part shapes), which are represented by DP.

2 Then, the PPP can develop by transferring the DP information to the MPSEL software, represented by MSP. Each machining process is reviewed in this section to determine related MES&MP suitability.

3 In the next block, the PPAC software calculates process plan attributes, which are represented by cost of machining and production rate.

4 The above work is then related to the process planner and manufacturer. If the DFMA remains unsatisfactory, the first DFMT is applied – thereby modifying the DP.

5 The designer executes this work, and APPs can be generated through the collaboration of the process planner and manufacturer, to determine the DFMA of APP.

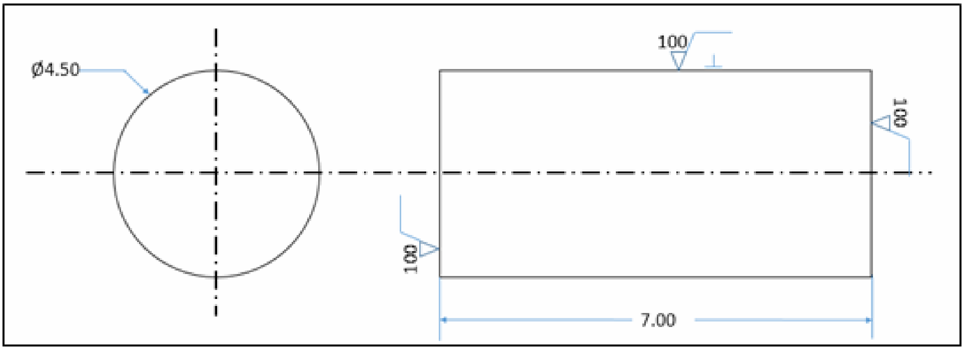
6 The same steps are then, repeated on all identified DFMT. Data extracted from modified DFMT is aggregated and reviewed to evaluate which PP is most acceptable.

7 These results are then, listed and presented to the customers in to obtain their approval, which allows manufacturing of the preferred process plan to proceed.

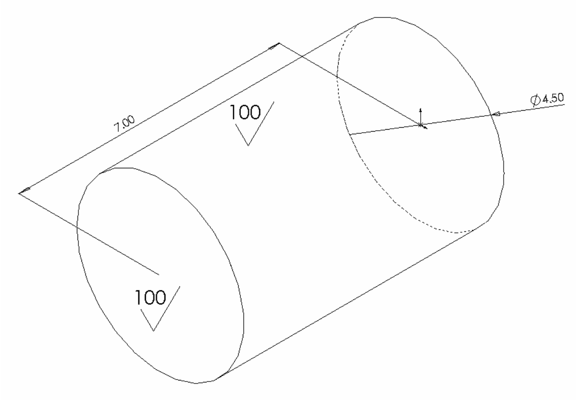
3 Case study

A case study was made to analyse the DFMT effectiveness on cost reduction and productivity within the algorithm. The base design of the part to be considered in this research is shown in Figures 4(a) and 4(b).

Figure 4 (a) Dimensions in inches of the workpiece (b) 3D drawing of the workpiece (see online version for colours)



(a)



(b)

3.1 Design parameters

One aspect of the suggested systematic algorithm is the design parameters (DP). The DP represents the qualitative and quantitative characteristics of a part's physical and functional construction.

3.1.1 Quantitative characteristics of DP

The quantitative characteristics of DP, as represented by the workpiece dimensions and shape, as well as the final part dimension, shape, and physical features are explained below.

3.1.1.1 Workpiece shape and dimensions

The bar stock dimensions of the workpiece are explained in Figure 4.

3.1.1.2 Final part shape, dimensions and features

The final product has the following required features and dimensions that are shown in Figures 5(a) and 5(b), the following part characteristic was used to specify the DPs of the part and select suitable machining processes:

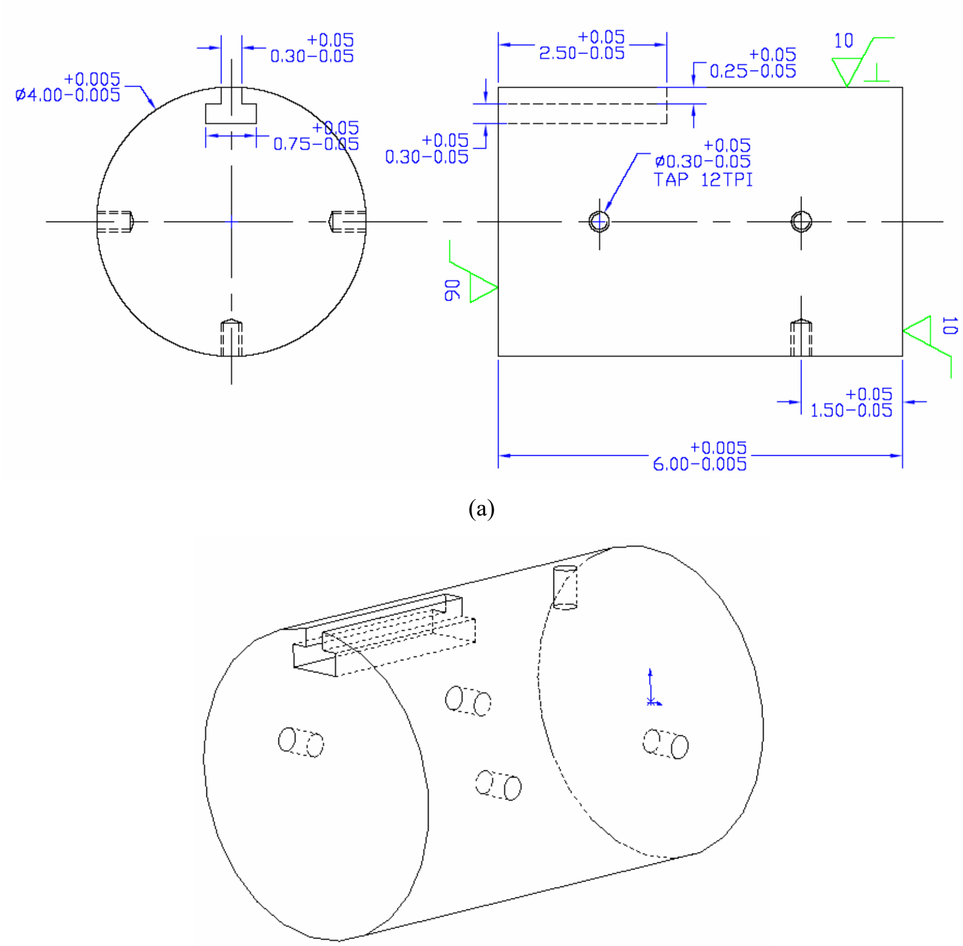
1. Five holes on the cylindrical surfaces as shown in the drawing. A hole diameter was 0.30 inch and the length was 0.5 inch. All holes have the same dimensions. The holes are threaded (12 TPI), and the inside surface finish of the holes should be 90 μin. Tolerances can be held to 0.05 inch.

2. A T-slot on the cylindrical surface of the cylinder. The slot width was 0.75 inch and depth was 0.3 inch. The slot neck has a depth of 0.25 inch and width of 0.3 inch. The slot length is 2.5 inch as shown in the drawing. The surface finish on the slot surfaces can be 90 μin and tolerances can be maintained at 0.05 inch.

3. The cylindrical surface must have a final diameter of 4 inches and a length of 6 inches. The surface finish on the cylindrical surface and one of the flat surfaces, as shown in the drawing, must be maintained at 10 micro inches. The tolerances on the length and diameter are 0.005 inch.

4. The two sides of the cylinder have a different surface finish and tolerance. Side 1 has a surface finish of 90 μin and a tolerance of 0.05; side 2 has a surface finish of 10 μin and a tolerance of 0.005.

Figure 5 (a) Dimensions of the final part (b) 3D drawing of the final part (see online version for colours)



(a)

(b)

3.1.2 *Qualitative characteristics of DP*

The first suggested material, which was used primarily to produce the above part, was austenitic stainless steel 316L with the following details. The following information is a sample from the DP used in the systematic algorithm in Table 2.

Table 2 DP of stainless steel 316L workpiece used in the case study

Workpiece material type	= Ferrous	Initial length	= 7”
Heat treatment condition	= Hot rolled/annealed	Initial diameter	= 4.5”
Melting Temperature	= 2,510 F°–2,550 F°	Density	= 0.29 lbs/in^3
Hardness (BHN)	= 149	Bar stock volume	= 111.33 in^3
Mass	= 31.62 lbs	Lot size	= 200

Table 3 Machining processes and outputs of the MPSEL for machining the 316L in PPP

Process index	*Process name*	*Type of cut*	*Surface finish (µin)*	*Machine*	*Tool*	*Required tolerance*
1	Face milling side 1	Rough	90	nc_mill_mc	hi_sp_steel (M 42)	±0.05
2	Face milling side 2	Finish	90	nc_mill_mc	hi_sp_steel (M 42)	±0.05
3	Turning	Rough	90	nc_lathe_mc	hi_sp_steel (M 42)	±0.05
4	Grinding of cylindrical surface	Finish	10	cyl_gr_mc	Grinding wheel	±0.005
5	Surface Grinding of flat side	Finish	10	sur_gr_mc	Grinding wheel	±0.005
6, 7, 8	Drilling 5 holes on cylindrical surface	Rough	90	ver_dr_pr	hi_sp_steel (TiN coated)	±0.05
9, 10, 11	Tapping 5 holes on cylindrical surface	Rough	90	ver_dr_pr	hi_sp_steel (TiN coated)	±0.05
12	End milling	rough	90	nc_mill_mc	mp_hss_t15_m42 grade (hss_m2_m3_m7)	±0.05
13	T-slot	finish	90	nc_mill_mc	hi_sp_steel (M grade) Slot mill	±0.05

Table 4 Inputs and outputs of PPAC for machining stainless steel 316L by using the HSS tool in PPP

Process index	*Depth of cut (in)*	*Diameter of cutter or WP diameter*	*Cutting speed (sfpm)*	*Feed rate (ipr/ipt)*	*Max. material that can be removed (in)*	*Number of passes*	*Depth of cut for the final pass (in)*	*Final D or L (in)*	*Total machining time (min)*	*Total machining cost ($)*	*Total tool cost ($)*	*Total cost for one process ($)*
1	0.2	4.5	3,298.67	0.008	0.9	5	0.1	L = 6.1	2.43	2.64	0.82	3.46
2	0.09	4.5	3,298.67	0.008	0.09	1	0.09	L = 6.01	1.13	2.30	0.16	2.46
3	0.2	0	500.69	0.025	0.49	2	0.045	4.01	2.05	2.22	2.22	4.44
4	0.005	8	2,099.63	0.02	0.01	1	0.005	D = 4	2.60	2.38	0.35	2.73
5	0.01	8	3,500.00	2.5	0.01	1	0.01	L = 6	6.63	5.08	1.02	6.1
6, 7, 8		0.29	102.88	0.004	0.5	5 holes	0	0.29	2.88	1.42	4.02	5.19
9, 10, 11		0.3	50	0.004	0.5	5 holes	0	0.3	1.6	1.53	5.26	6.11
12	0.2	0.3	219.91	0.008	0.55	3	0.1	L of cut = 2.5	2.41	2.61	1.13	3.74
13	0.2	0.75	549.78	0.008	0.3	2	0.1	L of cut = 2.5	2.29	2.48	0.76	3.23

3.2 Creating PPP in the PP section

All the above information and the output, data has been arranged in Table 3. Table 3 represents some of the inputs and the output of the MPSEL program. Multiple outputs have been obtained from the MPSEL program about the selected machines and tools. After obtaining all this information from MPSEL, the speed and feed have been calculated from Speed_Feed_Selection spreadsheet. PPAC was used to calculate the total cost of one of the parts in the lot that has size of 200 workpieces.

HSS tools were used for most of the machining processes (1, 2, 3, 6, 7, 8, 9, 10, 11, 12 and 13), as shown in Table 3. The speed, feed, and depth of cut have been selected from the Feed_Speed_Selection spreadsheet which was created in this work. Table 4 represents the inputs and outputs of PPAC for machining in PPP.

According to the output of the MPSEL, the surface finish of 10 µin on one face from the flat surfaces of the part, can be obtained only by using the surface grinding process. The values for each of the last four columns in Table 4 have been added and these added values were used to create the summarised Table 5.

Table 5 The summarised results of machining stainless steel in PPP

Total machining time (min)	24.02
Total machining cost ($)	22.07
Total tool cost ($)	15.74
Production rate per hour	2.49
Total cost of machining one part ($)	37.82
Material cost ($)	144.21
Total cost for producing one part ($)	182.03

These summarised results are represented by cost of production ($182.03) and hourly production rate (2.5) for producing one part from 316L stainless steel. The next step was to apply the systematic algorithm on the modified DFMT.

3.3 Applying the systematic algorithm on the DFMT section

This algorithm is performed in four levels, according to the type of DFMT. DFMT have been applied in the following sequence:

1. modifying the selection of raw material
2. modifying quality
3. modifying geometry
4. modifying the selection of process/es.

This sequence has been arranged according to the DFMT significance (DFMA outputs) and applicability, which has been assigned by the author according to the heuristic work performed by the author.

3.3.1 Modifying the selection of raw material

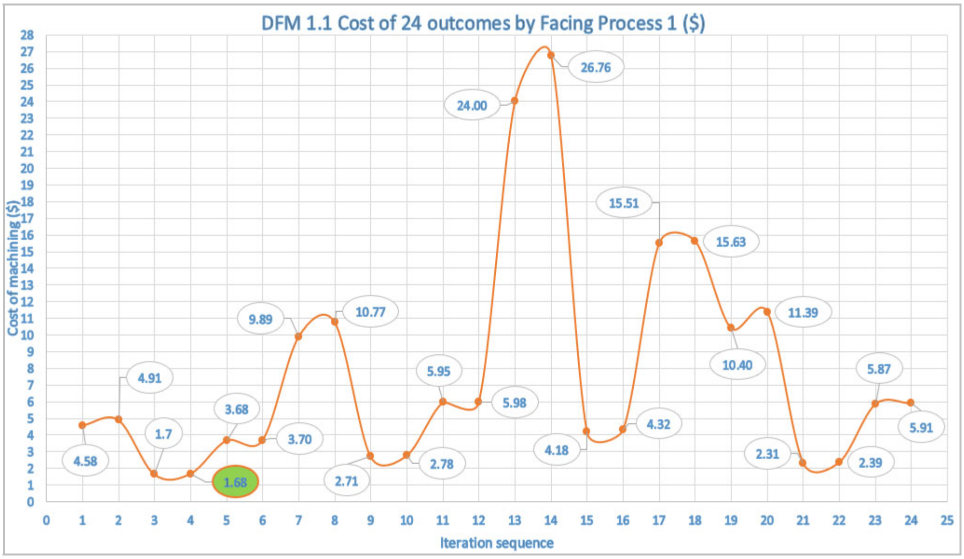
The selected DFMT was implemented by modifying the raw material of the workpiece. Keeping the functionality of the part in mind. This is dependent on whether the following material part properties remain in the ranges shown below:

- Young modulus (E) between 80 Gpa to 250 Gpa
- strength/elastic limit (σf) between 500 (Mpa) to 950 (Mpa)
- Production energy per cubic metre between 500,000 (MJ/m^3) to 700,000 (MJ/m^3).

The selection of the alternative raw materials (instead of the stainless steel 316L) must be within the range of the above three material properties. To select an alternative material, a procedure was developed. This procedure was performed by generating data tables identifying the values of material properties for several types of ferrous and non-ferrous alloys. The quantitative and qualitative characteristics of DP were entered into the DP section of the systematic algorithm. Then, this work was transferred to the MSP, MES&MP DB sections to generate the APP in the PP section. DFMA of APP was created to make the decision of accepting the APP (or not) by the user; these steps were repeated on all DFMT until the final decision is obtained.

Figure 6 shows the results of combinations between the MES elements (machine tools and cutting tools) for facing process 1 in DFMT1.1. All 24 combinations between the machine tools and cutting tools represented by different lathe machines are shown in Figure 6. From all of these combinations, the one with lowest cost ($1.68) was selected; the combination of the selected process was between the NC lathe and PCD cutting tools. The same process of combinations was followed for all machining processes in PP of DFMT1.1 to calculate the DFMA of DFMT1.1. This process was applied on all the DFMT selected in the systematic algorithm.

Figure 6 The possible outcomes for facing process 1 after applying DFMT1.1 (see online version for colours)



The summarised Table 6 was created to understand the change in the cost and production rate after performing DFMT1.1.

Table 6 The summarised results of PP for DFMT1.1

Total machining time (min)	12.13
Total machining cost ($)	11.49
Total tool cost ($)	10.72
Production rate per hour	4.95
Total cost of manufacturing one part ($)	22.24
Material cost ($)	19.71
Total cost for producing one part ($)	41.95

From the results in Table 6, the cost of machining processes to machine one part is $22.24, the material cost is $19.71, the total cost to produce one part is $41.95, and the hourly production rate is 4.95. These cost values appear much lower than machining stainless steel 316L in the PPP and higher than the production rate of the PPP. The DFMT1.2 was applied by using nickel alloy as raw material. The preferred properties of nickel alloy were inside the ranges of the alloy properties, which kept the functionality of the part without changing its design.

The summarised Table 7 has been created to understand the change in the cost and production rate after performing DFMT1.2.

Table 7 The summarised results of PP for DFMT1.2

Total machining time (min)	11.3
Total machining cost ($)	10.58
Total tool cost ($)	10.38
Total manufacturing cost ($)	20.96
Production rate per hour	5.31

From the information of Table 7, it was found that the cost of machining one part decreased by 5.76%, and the production rate increased by 7.27% between the results of the two alternative raw materials using DFMT1.1 and DFMT1.2.

3.3.2 DFMT2 modifying quality

The second DFMT was applied by using the original raw material: stainless steel 316L. DFMT2 is considered as modifying the quality. This modification can be performed by changing the surface finish and tolerance. Modifying the surface finish and tolerance are not arbitrary, but these modifications should be in specific permissible ranges. The maximum and minimum permissible ranges of surface finish were specified to maintain the functionality of the part. The functionality of the part was maintained inside the following ranges:

- surface finish range must be between 10 to 70 μin
- the tolerance must be between ±0.02 to ±0.005.

First, combinations were made between the surface finish and tolerance on the flat and cylindrical surfaces of the part. The new surface finish and tolerance values were assigned to machine these two surfaces by using facing and turning processes for machining the stainless steel 316L. The values of surface finish and tolerance that were assigned on both surfaces are 17 μin and ±0.01, respectively and they are inside the desired ranges mentioned above.

Second, other values of surface finish and tolerance have been selected to machine the two flat surfaces of the cylinder. The values were 65 μin for the surface finish and ±0.008 for the tolerance. These values were assigned in the drawing on the two flat surfaces of the cylinder. Modifying the surface finish and tolerance value were the reasons to change the machining process by checking the suitability in MPSEL from the facing process to the face milling process.

By comparing the obtained results between the DFMT2.1 and DFMT2.2 in Table 8, the production rate after applying DFMT2.1 was 4.94 and from DFMT2.2 was 4.83, which means the production rate was reduced by 2.23% and the cost increased by 4.64%. It could be concluded that modifying the surface finish and tolerance on the side surfaces of the part made this change in cost of manufacturing and throughput. The systematic algorithm was finished with DFMT2 and now moved to DFMT3 (changing geometry).

Table 8 The summarised results of PP for DFMT2.1 and DFMT2.2

	DFMT2.1	*DFMT2.2*
Total machining time (min)	12.14	12.41
Total machining cost ($)	11.20	11.79
Total tool cost ($)	10.78	11.23
Total manufacturing cost ($)	22.00	23.02
Production rate per hour	4.942	4.835

3.3.3 DFMT3 modifying geometry

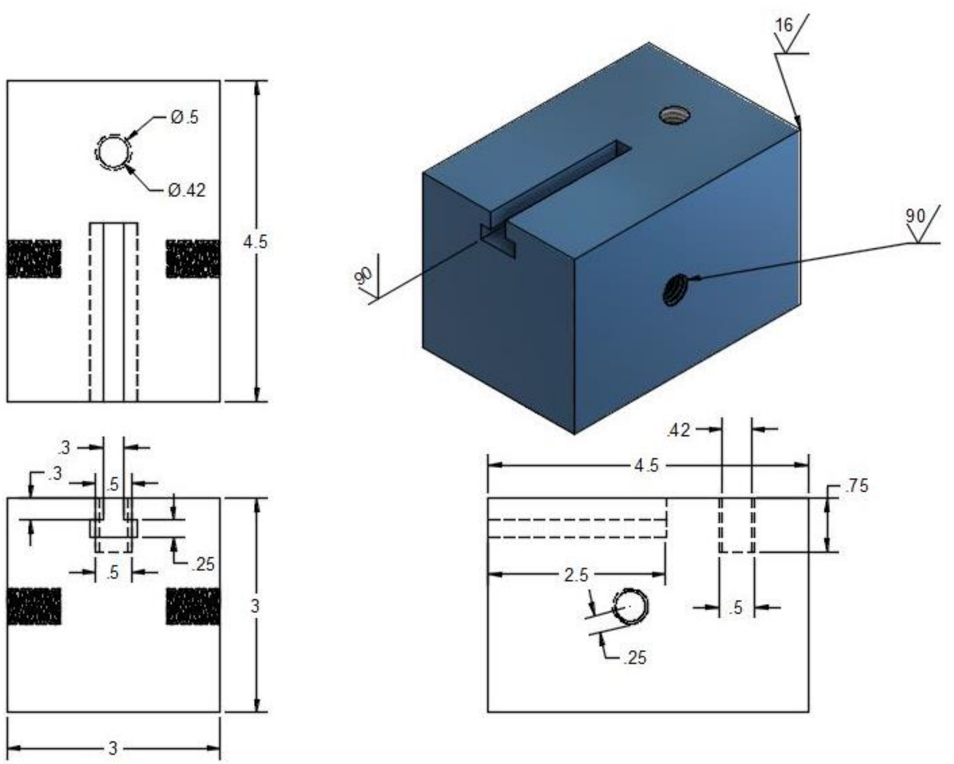
The third DFMT was represented by modifying the geometry of the part. The original shape of the raw material and the final part has been analysed, considering the functionality of the part. A new design has been suggested by the designer after doing analysis. This new design was created by modifying the shape of the raw material, the shape of the final part, the number of holes on the part, the L/D ratio of the tapped holes, and changing the key and keyway to a threaded hole.

The first modified geometry of the workpiece and manufactured part are depicted in Figure 7. The raw material used for the modified geometry was the same material used for the PPP (stainless steel 316L). The final product has the following required features and dimensions that are shown in Figure 7.

The information and characteristics of the modified part is shown in Figure 7. This information was transferred from the DFMT section to the DP section (the new geometric features, new dimensions, new surface finish and tolerance). Simultaneously, the information was utilised from the sections MSP and MES&MP DB to generate the alternative PP after performing DFMT3.1.

The outcomes of performing DFMT3.1 show that the total manufacturing cost was $25.86, and the total machining time was 16.76 minutes, thus the production rate of DFMT3.1 was 3.58 piece/hour. The cost was higher, and the production rate was lower than the cost and production rate of DFMT1 and DFMT2. It is worth mentioning that one workpiece from stainless steel 316L in the lot of 200 pieces is approximately $78.14 for the new design. The cost of the workpiece material in the PPP was $144.21. By comparing these two costs of raw material, the cost was reduced by 45.82%. For the total manufacturing cost and manufacturing time between the PPP and the DFMT3.1 PP, the cost was reduced by 31.62% and the production rate was increased by 43.2%.

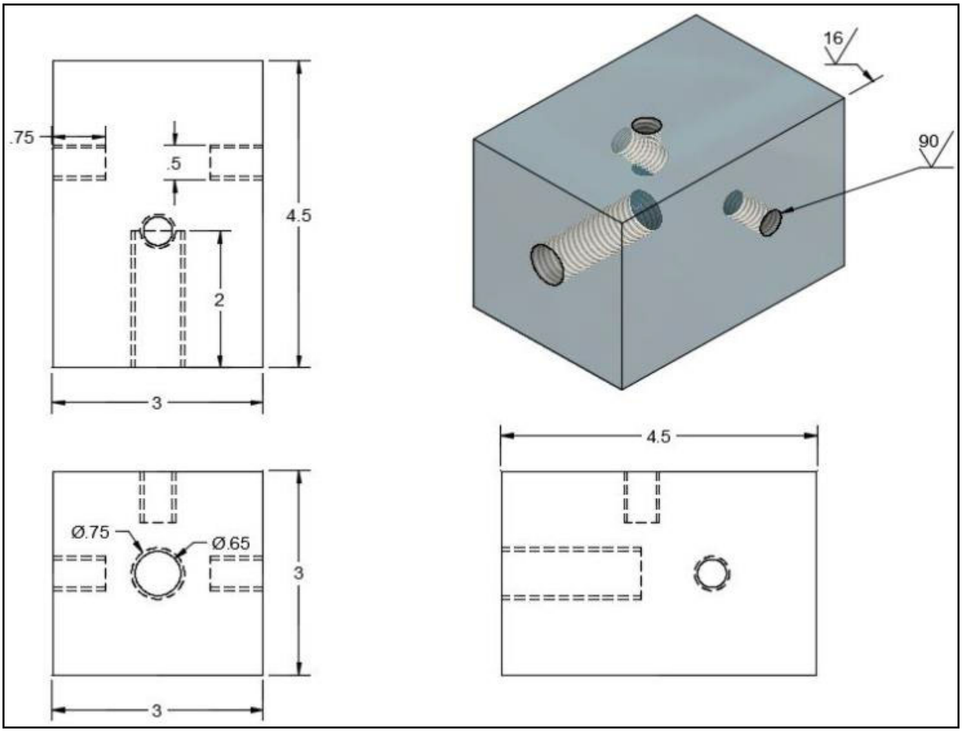
Figure 7 Orthographic views and 3D model of the final part modified by DFMT3.1 (see online version for colours)



In the alternative design of DFMT3.2, the same raw material (stainless steel 316L) was used, the shape and dimensions of the raw material used in DFMT3.1 remained the same. One modification has been made on the final part, the key and keyway feature were replaced by a threaded hole as depicted in Figure 8.

The difference between the final part in DFMT3.1 and DFMT3.2 was that, instead of using the T-slot on front face of the block, the threaded hole (12 TPI) was used with dimensions: diameter 0.75 inches and length 2 inches. The cost of manufacturing the part after applying DFMT3.2 was $29.33, the manufacturing time was 15.12 minutes, and production rate was 3.97 piece/hour. This cost was higher than DFMT3.1. In other words, the cost between DFMT3.1 and DFMT3.2 increased by 13.42% and the production rate reduced by 10.9%. Modifying the design in DFMT3.1 and DFMT3.2 affected the type of machining process used. Specifically, the facing and turning processes were replaced with face milling and side milling. The systematic algorithm was performed on DFMT3, and subsequently on DFMT4 (modifying the selection of machining process/es).

Figure 8 Orthographic views and 3D model of the final part modified by DFMT3.2 (see online version for colours)



3.3.4 DFMT4 modifying the selection of machining process/es

The last DFMT applied in the systematic algorithm was modifying the selection of process/es. For example, the facing process on the flat surface of the part can be alternately machined by using a face milling process. The number of processes is also matters in this DFMT, instead of machining the cylindrical surface by two turning processes to obtain the desired surface finish, one turning process may be used instead. Modifications in the machining processes are concurrent to checking the suitability of each process in MSP section. The first alternative PP after applying DFMT4 was considered in DFMT4.1. In DFMT4.1 after reanalysing the PPP, it was possible to machine the two flat surfaces of the part by using the face milling process instead of the facing process. Also, in one turning process, the cylindrical surface could be machined to 17 µin surface finish. The manufacturing cost of the part from DFMT4.1 is $21.87, and the production rate is 5.16 parts per hour. These results are in line with the results of DFMT1 and DFMT2. Another DFMT4 has been applied, named DFMT4.2. As an alternative DFMT4, the facing process was used to machine the two flat surfaces of the cylinder with an equal amount of material to be removed from both sides. Moreover, one turning process was used to machine the cylindrical surface with 17 µin, the modified process plan for DFMT4.2.

Table 9 The summarised results of better nine process plans (see online version for colours)

	PPP	*DFMT1*		*DFMT2*		*DFMT3*		*DFMT4*	
	Ref PP	*DFMT1.1*	*DFMT1.2*	*DFM 2.1*	*DFM 2.2*	*DFMT3.1*	*DFMT3.2*	*DFMT4.1*	*DFMT4.2*
Machining time (min)	24.02	12.13	11.3	12.14	12.41	16.76	15.21	11.62	11.34
Total tool cost ($)	15.74	10.72	10.38	10.78	11.23	9.14	15.52	10.94	10.43
Machining cost ($)	22.07	11.49	10.58	11.18	11.79	16.72	13.81	10.94	10.63
Total manufacturing cost ($)	37.82	22.24	20.96	22	23.02	25.86	29.33	21.87	21.1
Production rate (hr)	2.5	4.95	5.31	4.94	4.83	3.58	3.94	5.16	5.29
Reduced/increased cost %	0.00%	–41.2%	–44.6%	–41.8%	–39.1%	–31.6%	–22.4%	–42.2%	–44.20%
Reduced/increased production rate %	0.00%	98.00%	112.6%	97.90%	93.50%	43.30%	57.90%	106.70%	111.80%

3.4 Summarising the results and discussion

The systematic algorithm was tested for all the DFMT; every DFMTs was applied in two alternative modifications, and for each modification, there is a specific APP. That means nine process plans were obtained from this algorithm: the first one is the PPP, followed by eight alternative PPs. To understand the outcomes of all nine PPs, the important results of each PP was represented by machining time, total tool cost, machining cost, total manufacturing cost, production rate, percentage of production cost reduced/increased, and percentage of production rate reduced/increased. All the important outcomes of the nine process plans are depicted in Table 9.

The results of the nine process plans in Table 8 are more understandable and a user (facility manager) can decide which PP should be selected according to its preference outcomes, cost of manufacture and production rate. According to the results, the PP for DFMT1.2 involves using nickel alloy as a raw material. This PP has a minimum machining cost and maximum production rate among all PPs. It is not that the PP for DFMT1.2 should be selected, ignoring the other eight PPs, but the suitable process plan should be selected by considering different factors in addition to the cost and throughput. For example, even though the PP with DFMT1.2, the cost of nickel alloy workpiece is very expensive as compared to aluminium alloy workpiece.

4 Conclusions

This study included investigation for several DFMT in the machining domain. The results of analysing the DFMT showed significant influence on cost reduction and production rates. Little of existing literature has analysed the significance of DFMT with their inherent MES&MP to investigate which DFMT has the main influence on cost reduction and increasing throughput, and under which circumstances. The systematic algorithm was suggested in this work, from which all findings were drawn. The order of performing the DFMT is critical, and it is recommended that the appropriate DFMT sequence be followed:

1 modifying the selection of raw material

2 modifying quality

3 modifying geometry

4 modifying the selection of the process/es.

This sequence has been set according to systematic heuristic work and sensitivity analysis performed in this research. Working on the first two DFMTs in advance increased the influence of the systematic algorithm. These two DFMTs could be applied without any minor or major modifications in the workpiece or final design.

DFMT4 is considered as a floating DFMT between the other three DFMTs. This DFMT can be performed automatically within the other DFMTs (DFMT1, DFMT2 and DFMT3) because changing of the process should exist while the material, quality, or the geometry of the parts is changed.

The systematic algorithm guides and instructs the user to gradually apply the DFMT. The results showed that the algorithm has an influence on cost reduction and increase in production rate. When the manufacturing facility aims to reduce manufacturing costs by modifying PP. Significant time was saved when the algorithm was developed and performed, especially by giving guidance towards the suitable alternative solutions. The decision to accept or reject a specific process plan was depending on four factors. The following four factors should be evaluated by manufacturing facilities when selecting the optimum process plan:

- availability of material
- manufacturing cost
- material properties
- material manufacturability.

Possibilities for future work based on the research presented in this paper include: considering more DFMT factors, more MPs, the combinations between them, expanding the work to general manufacturing processes and more complicated parts and considering more metallic and non-metallic materials in the manufacturing field.

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