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MATHEMATICAL PROGRAMMING ANALYSIS OF ADDITIVE MANUFACTURING PROCESS PLANNING TOTAL COST EVALUATION MODEL FOR MULTIPLE PARTS

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ABSTRACT

It has been established that an effective and efficient cost evaluation of advanced manufacturing techniques, to a large extent, enhances process planning. In other to achieve an optimal advanced manufacturing process planning, a good estimation and evaluation of the process cost is required. In fact, an optimal total processing cost will help to achieve an optimal process planning. This study analyzed an adapted advanced manufacturing process planning cost evaluation models, using mathematical programming technique. The results of the analyses were discussed and represented with graphs, from where conclusions were drawn. The significant status of the different costs components in all the eight cases considered, concerning achievement of optimal total cost at the level of planning of the advanced manufacturing process, were revealed by the graphs. Specifically, it was observed that both the processing modules cost and the material handling cost are very significant in minimizing the additive manufacturing process planning total cost of multiple parts.

Keywords: additive manufacturing, mathematical programming, modeling and analysis, process planning, cost evaluation.

1. INTRODUCTION

It has been observed that for an efficient advanced manufacturing process planning and control, the processing cost involved should be optimal [1]. In this study, some existing cost models were adapted in modelling the cost estimation and evaluation of the advanced manufacturing process planning. Advanced manufacturing optimal total cost was modeled and analyzed in order to achieve an optimal total cost necessary for an efficient process planning.

Process planning (PP) is about the sequence of activity concern with the decision of the manufacturing processes and the machines that should be used to perform the various operations necessary to produce a part, which is basically converting raw materials into a final product to satisfying the constraints, the design requirements and the intent [2, 3, 4]. Manufacturing Process Planning (MPP), therefore, is the systematic determination of the detailed methods by which parts can be manufactured completely and economically [5]. It can broadly be divided into two parts: Machining Process Planning and Assembly Process Planning. However, most of the time, the former is just for short referred to as process planning, which is a preparatory step that determines the sequence of operations (processes) needed to produce a part, before manufacturing starts at all [6].

Additive manufacturing is an excellent advanced manufacturing technique, that involve a layer-by-layer method of production of parts. It is also referred to as 3D printing [7].

Process planning in additive manufacturing always improves output and minimized cost. Also, on the other hand an optimal process planning can only be achieved with an optimal cost. Recently, several cost models were developed for different advanced manufacturing processes [7, 8, 9, 10]. In this study, some existing process planning models were adapted in building, analytically, an additive manufacturing process planning cost evaluation model. The models are presented with brief discussion for the sake of an overview of cost estimation of manufacturing processes, including AM processes.

2. ADDITIVE MANUFACTURING PROCESS PLANNING COST EVALUATION MODEL

Additive manufacturing (AM) Technologies have been proven to be a process cost effective way to produce parts, including metal and multiple parts. Additive Manufacturing does not require tools. Tooling is a term of cost only for traditional technologies [11, 12, 13]. Consequently, in order to exploit the capability of additive technologies, existing components can be redesigned for additive manufacturing, with the cost of such activity being included in the analysis of the total cost. The total cost, therefore, is formulated as a function of many other costs, excluding the tooling cost [14, 15].

Presently, there are different technologies, including additive manufacturing technologies, for various types of materials, quality and energy sources; however, all of these have the following actions in common [16,17]:

- Creating a design CAD model (Design and planning)
- Converting the CAD model into STL format (Machine Preparation)
- Slicing the STL file into thin cross-sectional layers (Material Processing)
- Constructing the model layer by layer (Manufacturing)

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- Cleaning and finishing the model (Post - Processing)

Typically, Additive Manufacturing process steps include the following:

- Design and Planning
- Material Processing
- Machine Preparation
- Manufacturing
- Post- Processing
- Administration
- Sales and Quality

In order to evaluate and minimize the total processing cost of a manufacturing process planning for a multiple part, for instance, the modified cost items involved in the processing Cost of such Parts [18,19,20] are identified as follows:

$PMC =$ the processing module usage cost array

$PCC =$ the processing change cost

$SCC =$ the set-up change cost

$RC =$ the reconfiguration cost

$TC =$ the tool cost

$TCC =$ the tool change cost

$HC =$ the material handling cost

The sum of these cost items, excluding the tool cost (TC) and the total tool change cost (TCC,), which relates to the typical additive manufacturing process steps mentioned above, form the total processing cost of the multiple parts. In order to exploit the capabilities of additive manufacturing technology, the above modified cost components are redesigned as follows to constitute the total processing cost:

The cost of Design and planning $\equiv$ SCC
The cost of Machine Preparation $\equiv$ RC
The cost of Material Processing $\equiv$ PMC
The cost of Manufacturing $\equiv$ PCC
The cost of Post – Processing $\equiv$ HC

The above cost components can be expanded as follows [21,22]:

$$PMC = \sum_{I=1}^{K} PMCI \quad (1)$$

$$PCC = \sum_{I=1}^{K} PCCI \left[\sum_{I=1}^{K-1} \Omega(PM_{i+1} - PM_i) \right] \quad (2)$$

$$SCC = SCCI \left[\sum_{i=1}^{K-1} \{(1-\Omega(PM_{i+1} - PM_i))\} * \{\Omega(TAD_{i+1} - TAD_i)\} \right] \quad (3)$$

$$RC = RCI \left[\sum_{i=1}^{K-1} \{(1-\Omega(PM_{i+1} - PM_i))\} * \{\Omega(XS_{i+1} - XS_i)\} \right] \quad (4)$$

$$HC = HCI \left[\sum_{i=1}^{K-1} d_{i,j} \right] \quad (5)$$

With the following assumptions:

$$\Omega(PM_{i+1} - PM_i) = \begin{cases} 1 \text{ if } \mathrm{PM}_{i+1} \neq \mathrm{PM}_i \\ 0 \text{ if } \mathrm{PM}_{i+1} = \mathrm{PM}_i \end{cases}$$

$$\Omega(TAD_{i+1} - TAD_i) = \begin{cases} 1 \text{ if } \mathrm{TAD}_{i+1} \neq \mathrm{TAD}_i \\ 0 \text{ if } \mathrm{TAD}_{i+1} = \mathrm{TAD}_i \end{cases}$$

$$\Omega(XS_{i+1} - XS_i) = \begin{cases} 1 \text{ if } \mathrm{XS}_{i+1} \neq \mathrm{XS}_i \\ 0 \text{ if } \mathrm{XS}_{i+1} = \mathrm{XS}_i \end{cases}$$

Where,

$PMCI =$ the processing module cost index
$PCCI =$ the process change cost index
$SCCI =$ the set-up change cost index
$RCI =$ the reconfiguration cost index
$HCI =$ the material handling cost index
$PM_i =$ the processing module i
$TAD =$ the required PM key characteristic in processing consecutive points
$XS =$ are configuration scenerio, representing the required key part features for the manufacture of consecutive different part types
$d_{i,j} =$ the distance between processing module i and j in the manufacturing grid

The optimal total processing cost of multiple parts using additive manufacturing technology, therefore, can be represented as a mathematical programming model as follows:

$$Min\ C_{total} = PMC + PCC + SCC + RC + HC \quad (6)$$

$$= \sum_{I=1}^{K} PMCI + PCCI \left[\sum_{I=1}^{K-1} \Omega(OM_{i+1} - PM_i) \right] + SCCI \left[\sum_{i=1}^{K-1} \{(1-\Omega(PM_{i+1} - PM_i))\} * \{\Omega(TAD_{i+1} - TAD_i)\} \right] + RCI \left[\sum_{i=1}^{K-1} \{(1-\Omega(PM_{i+1} - PM_i))\} * \{\Omega(XS_{i+1} - XS_i)\} \right] + HCI \left[\sum_{i=1}^{K-1} d_{i,j} \right] \quad (7)$$

Subject to:

$$PMC + PCC + SCC + RC + HC > 0$$
$$PMC \geq 0, PCC \geq 0, SCC \geq 0, RCI \geq 0, HC \geq 0$$

3. MODEL ANALYSIS

All the cost components in additive manufacturing process are very significant in manufacturing of a multiple part from the designing stage to the finished product. As a result, the sum of all these costs must be greater than zero, because rarely can any of them be zero. Then the non- negativity constraint suggests that none of the cost components can take a negative value.

Let

$$\Omega(PM_{i+1} - PM_i) = X$$
$$\Omega(TAD_{i+1} - TAD_i) = Y$$
$$\Omega(XS_{i+1} - XS_i) = Z$$

The following eight possible cases were analyzed in this study:

$$X = 1, Y = 0, Z = 0$$
$$X = 1, Y = 1, Z = 0$$
$$X = 1, Y = 1, Z = 1$$
$$X = 1, Y = 0.Z = 1$$
$$X = 1, Y = 0, Z = 0$$
$$X = 0, Y = 1, Z = 0$$
$$X = 0, Y = 1, Z = 1$$
$$X = 0, Y = 0, Z = 1$$

Case 1: $X = 1, Y = 0, Z = 0$

This is when

$$\Omega(PM_{i+1} - PM_i) = 1$$
$$\Omega(TAD_{i+1} - TAD_i) = 0$$
$$\Omega(XS_{i+1} - XS_i) = 0$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Minimize } C_{total} = \sum_{I=1}^{K} PMCI + PCCI[1] + SCCI\left[\sum_{i=1}^{K-1}\{(1-1))\}*\{0\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-1))\}*\{0\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \tag{8}$$

The mathematics programming becomes;

$$\text{Minimize } C_{total} = \sum_{I=1}^{K} PMCI + PCCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \tag{9}$$

Subject to:

$$PMCI + PCCI + HCI > 0$$
$$PMCI \geq 0, PCCI \geq 0, HCI \geq 0$$

Case 2: $X = 1, Y = 1, Z = 0$

This is when

$$\Omega(PM_{i+1} - PM_i) = 1$$
$$\Omega(TAD_{i+1} - TAD_i) = 1$$
$$\Omega(XS_{i+1} - XS_i) = 0$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Minimize } C_{total} = \sum_{I=1}^{K} PMCI + PCCI[1] + SCCI\left[\sum_{i=1}^{K-1}\{(1-1))\}*\{1\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-1))\}*\{0\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \tag{10}$$

The mathematics programming becomes;

$$\text{Minimize } C_{total} = \sum_{I=1}^{K} PMCI + PCCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \tag{11}$$

Subject to:

$$PMCI + PCCI + HCI > 0$$
$$PMCI \geq 0, PCCI \geq 0, HCI \geq 0$$

Case 3: $X = 1, Y = 1, Z = 1$

This is when

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$$\Omega(PM_{i+1} - PM_i) = 1$$
$$\Omega(TAD_{i+1} - TAD_i) = 1$$
$$\Omega(XS_{i+1} - XS_i) = 1$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Min C}_{total} = \sum_{I=1}^{K} PMCI + PCCI[1] + SCCI\left[\sum_{i=1}^{K-1}\{(1-1)\}*\{1\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-1)\}*\{1\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (12)$$

The mathematics programming becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + PCCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (13)$$

Subject to:

$$PMCI + PCCI + HCI > 0$$

$$PMCI \geq 0, PCCI \geq 0, HCI \geq 0$$

Case 4: $X = 1, Y = 0, Z = 1$

This is when

$$\Omega(PM_{i+1} - PM_i) = 1$$
$$\Omega(TAD_{i+1} - TAD_i) = 0$$
$$\Omega(XS_{i+1} - XS_i) = 1$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Min C}_{total} = \sum_{I=1}^{K} PMCI + PCCI[1] + SCCI\left[\sum_{i=1}^{K-1}\{(1-1)\}*\{0\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-1)\}*\{1\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (14)$$

The mathematics programming becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + PCCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (15)$$

Subject to:

$$PMCI + PCCI + HCI > 0$$

$$PMCI \geq 0, PCCI \geq 0, HCI \geq 0$$

Case 5: $X = 0, Y = 0, Z = 0$

This is when

$$\Omega(PM_{i+1} - PM_i) = 0$$
$$\Omega(TAD_{i+1} - TAD_i) = 0$$
$$\Omega(XS_{i+1} - XS_i) = 0$$

Substituting these into the objective function of the above mathematical programming model, gives

$$\text{Min C}_{total} = \sum_{I=1}^{K} PMCI + PCCI[0] + SCCI\left[\sum_{i=1}^{K-1}\{(1-0)\}*\{0\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-0)\}*\{0\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (16)$$

The mathematics programming model becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (17)$$

Subject to:

$$PMCI + HCI > 0$$

$$PMCI \geq 0, HCI \geq 0$$

Case 6: $X = 0, Y = 1, Z = 0$

This is when

$$\Omega(PM_{i+1} - PM_i) = 0$$
$$\Omega(TAD_{i+1} - TAD_i) = 1$$
$$\Omega(XS_{i+1} - XS_i) = 0$$

Substituting these into the objective function of the above mathematical programming model, gives

$$\text{Min } C_{total} = \sum_{I=1}^{K} PMCI + PCCI[0] + SCCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{1\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{0\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (18)$$

The mathematics programming becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + SCCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (19)$$

Subject to:

$$PMCI + SCCI + HCI > 0$$

$$PMCI \geq 0, SCCI \geq 0, HCI \geq 0$$

Case 7: $X = 0, Y = 1, Z = 1$

This is when

$$\Omega(PM_{i+1} - PM_i) = 0$$
$$\Omega(TAD_{i+1} - TAD_i) = 1$$
$$\Omega(XS_{i+1} - XS_i) = 1$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Min } C_{total} = \sum_{I=1}^{K} PMCI + PCCI[0] + SCCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{1\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{1\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (20)$$

The mathematics programming becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + SCCI + RCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (21)$$

Subject to:

$$PMCI + SCCI + RCI + HCI > 0$$

$$PMCI \geq 0, SCCI \geq 0, RCI \geq 0, HCI \geq 0$$

Case 8: $X = 0, Y = 0, Z = 1$

This is when

$$\Omega(PM_{i+1} - PM_i) = 0$$
$$\Omega(TAD_{i+1} - TAD_i) = 0$$
$$\Omega(XS_{i+1} - XS_i) = 1$$

Substituting these into the objective function of the above mathematical programming model, gives:

$$\text{Min } C_{total} = \sum_{I=1}^{K} PMCI + PCCI[0] + SCCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{0\}\right] + RCI\left[\sum_{i=1}^{K-1}\{(1-0))\} * \{1\}\right] + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (22)$$

The mathematics programming becomes;

$$MinC_{total} = \sum_{I=1}^{K} PMCI + RCI + HCI\left[\sum_{i=1}^{K-1} d_{i,j}\right] \quad (23)$$

Subject to:

$$PMCI + RCI + HCI > 0$$

$$PMCI \geq 0, RCI \geq 0, HCI \geq 0$$

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4. DISCUSSIONS

From the above analysis, it is observed that some cost parameters are significant while some are not in minimizing the additive manufacturing process planning costs for the different cases considered, under some assumptions, in this study. Table-1 represents the significant parameters for different cases. The parameters marked 1 indicate significant, while the ones marked 0 indicates not-significant.

Table-1. Significant parameters for cost minimization of AM PP for different Cases.

CASES	PMCI	PCCI	SCCI	RCI	HCI
Case 1	1	1	0	0	1
Case 2	1	1	0	0	1
Case 3	1	1	0	0	1
Case 4	1	1	0	0	1
Case 5	1	0	0	0	1
Case 6	1	0	1	0	1
Case 7	1	0	1	1	1
Case 8	1	0	0	1	1

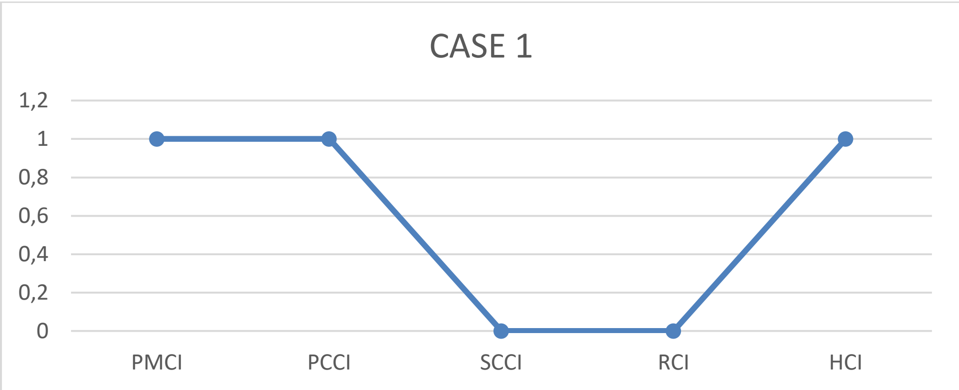

Figure-1. The significance status of the cost components in case 1.

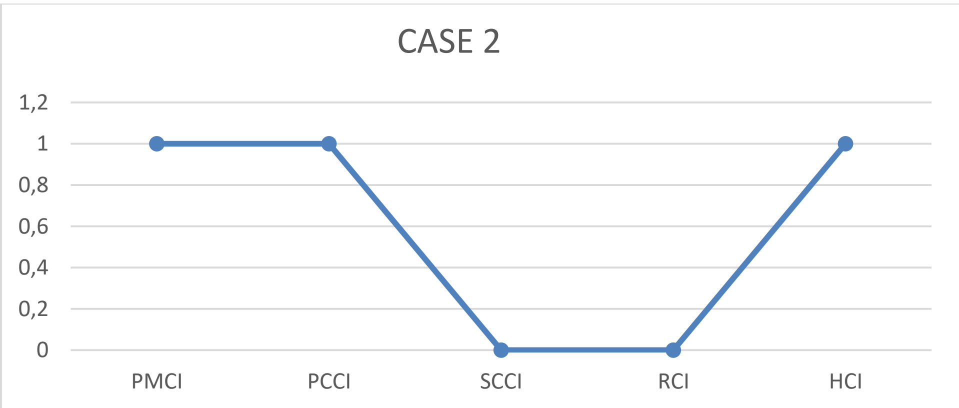

Figure-2. The significance status of the cost components in case 2.

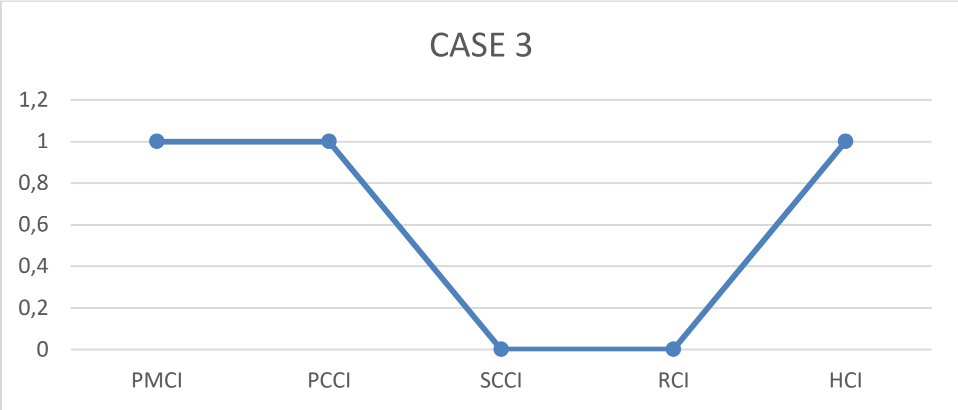

Figure-3. The significance status of the cost components in case 3.

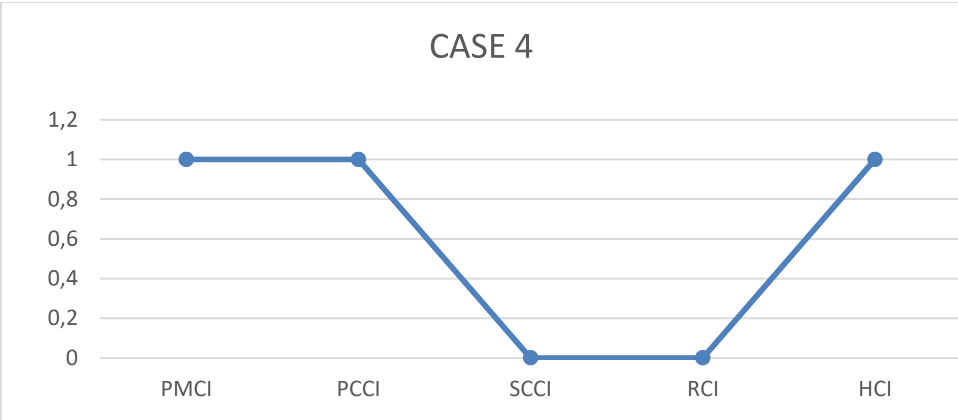

Figure-4. The significance status of the cost components in case 4.

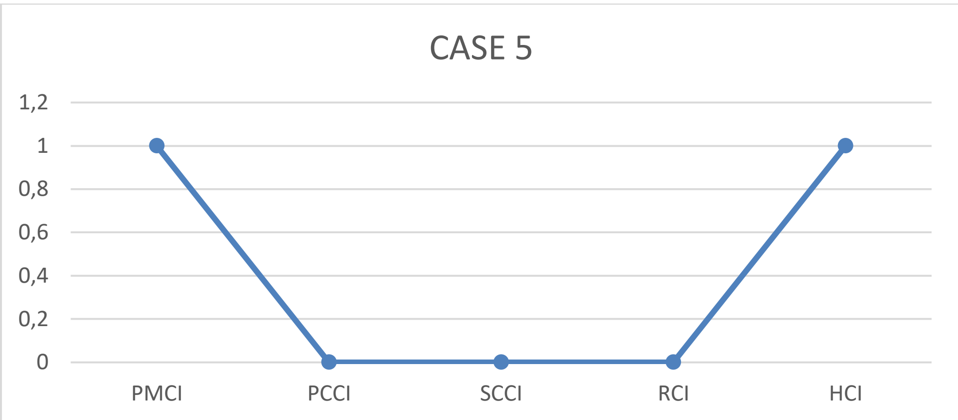

Figure-5. The significance status of the cost components in case 5.

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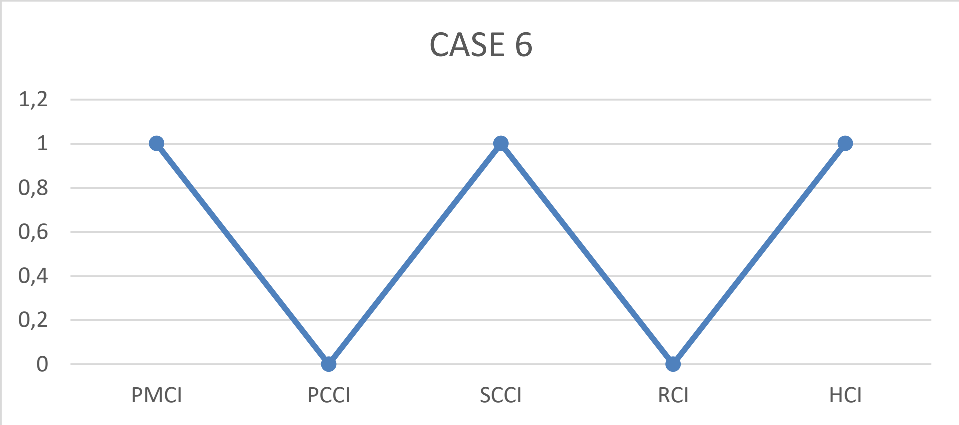

Figure-6. The significance status of the cost components in case 6.

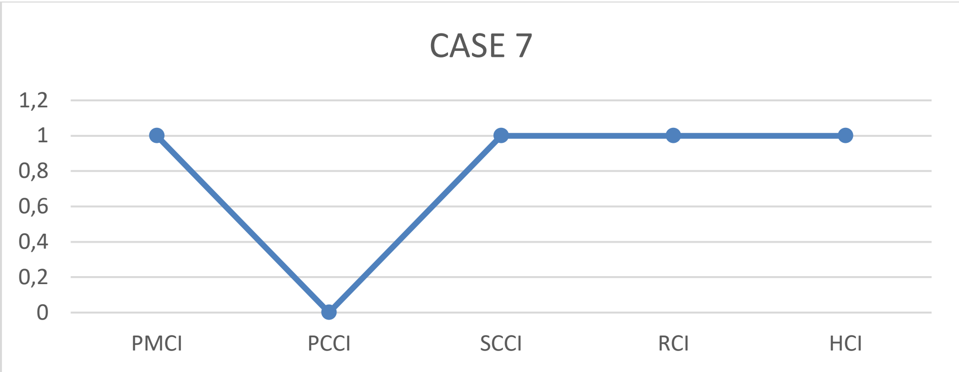

Figure-7. The significance status of the cost components in case 7.

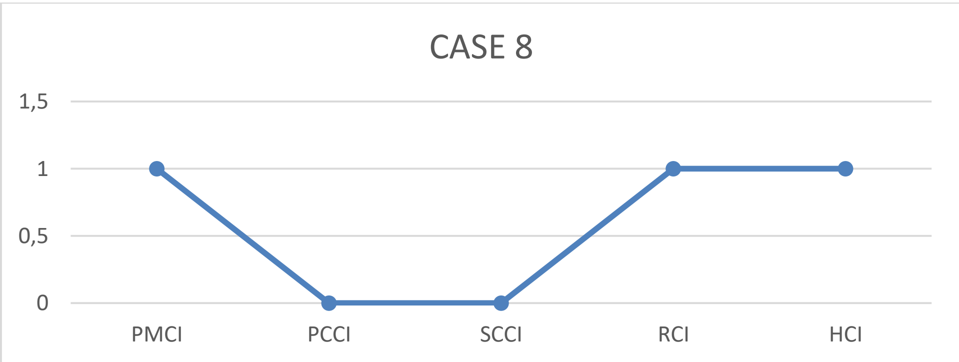

Figure-8. The significance status of the cost components in case 8.

Under the assumptions in this study, it turns out that in cases 1, 2, 3 and 4, the mathematical programming models for cost minimization of the additive manufacturing process planning, are the same. The SCCI and RCI are not significant in the above-mentioned cases. This implies that they are not needed if the cost minimization of the additive manufacturing process planning is to be minimized. However, PMCI, PCCI and HCI are very significant if the cost is to be minimized.

In case 5, the mathematical programming model changed, with only PMCI and HCI significant in the optimization of the AM process planning cost. In case 6, PMCI, SCCI and HCI are significant in the optimization. In case 7, PMCI, SCCI, RCI and HCI are all significant in the optimization. Finally, in case 8, PMCI, RCI and HCI are significant in the optimization of the AMPP cost.

In all the eight cases considered in this study it is observed that both PMCI and HCI are very significant in minimizing the additive manufacturing process planning cost.

Figures 1-8 graphically displayed the significance of all the cost components to the optimization of the AM total cost.

5. CONCLUSIONS

For any of the advanced manufacturing technologies to be sustainable, the costs involved must be optimal. In additive manufacturing process planning, some costs are involved. These costs were modeled using a mathematical programming technique. Some assumptions were taken and the significance of some cost parameters were obtained. Specifically, it was observed that both the processing module cost and the handling cost are very significant in the all the cases considered in this study. On the other hand, however, the set-up change cost and the reconfiguration cost are not significant the cost minimization of additive manufacturing process planning (AMPP) except in case 7, where $X=0, Y=1, Z=1$ was assumed. Only the process change cost was observed to be insignificant in this case. This study has modeled and analyzed the Additive Manufacturing Process Planning Cost Evaluation of Multiple Parts in order to optimize it for sustainability. The significant and not significant cost parameters in the optimization were obtained under some assumptions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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REFERENCES

[1] Planning and Controlling. http://www.pathways.cu.edu.eg/subpages/training_courses/planning_controlling/chapter1.htm

[2] Venkatesh, Relationship between Planning and Controllinghttps://www.yourarticlelibrary.com/management/planning-management/relationship-between-planning-and-controlling/53187.

[3] Venkatesh, Relationship between Planning and Controllinghttps://www.yourarticlelibrary.com/management/planning-management/relationship-between-planning-and-controlling/53187

[4] Kunlei Lian, Chaoyong Zhang, Xinyu Shao, Liang Gao. 2012. Optimization of process planning with various flexibilities using an imperialist competitive algorithm. Int. J. Adv. Manuf. Technol. 59: 815-828.

[5] N. Ismail, F. Musharavati, A.S.M. Hamouda, A.R. Ramli. 2008. Manufacturing process planning optimization in reconfigurable multiple parts flow lines. Journal of Achievements in materials and Manufacturing Engineering. 31(2): 671-677.

[6] Nada Manavizadeh, Taha Vafaeenezhad, Hamed Farrokhi-Asi.2016. Using Meta-heuristic Algorithms to Solve an Integrated Production Planning and Preventive Maintenance Model. Applied mathematics in engineering, management and technology. 4(2): 63-75.

[7] Lucas Carolo. 2020. The Seven Main Types of Additive Manufacturing. https://all3dp.com/2/main-types-additive-manufacturing/

[8] Sova A., Grigoriev S., Okunkova A., Smurov I. 2013. Potential of cold gas dynamic spray as additive manufacturing technology. International Journal of Advanced Manufacturing Technology. 69(9-12): 2269-2278.

[9] Mellor S., Hao L., Zhang D. 2014. Additive manufacturing: a framework for implementation. Int. J Prod Econ. 149:194-201.

[10] Qiang Li a, c, Ibrahim Kucukkoc a, b, David Z. Zhang a, c. 2017 Production planning in additive manufacturing and 3D printing. Computers and Operations Research. 83: 157-172.

[11] E.Atzeni, L. Iuliano, G. Marchiandi, P. Minetola, A. Salmi, E. Bassoli, L. Denti, A. Gatto. 2014. Additive Manufacturing as a cost-effective way to produce metal parts, In: High Value Manufacturing by Bartolo et al. pp. 3-8, CRC Press - Taylor and Francis Group, London, ISBN: 978-1-315-81741-5, 978-1-138-00137-4

[12] Douglas S. Thomas, Stanley W. Gilbet. 2014. Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion. NIST Specialo Publication. Applied Economic Office. http://dx.doi.org/10.6028/NIST.SP.1176

[13] Malte Schroder, Bjorn Falk, Robert Schmitt. 2015. Evaluation of Cost Structures of Additive Manufacturing Processes using a New Business Model. 7th Industrial Product-Service Systems Conference - PSS, industry transformation for sustainability and business. Procedia CIRP 30, 311-316

[14] 2012. Berman B. 3-D printing: The new industrial revolution, Business Horizons. 55: 155-162.

[15] Malte Schroder, Bjorn Falk, Robert Schmitt. 2015. Evaluation of cost structures of additive manufacturing processes using a new business model. 7th Industrial product-service system conference -

PSS, industry transformation for sustainability and business, procedia CIRP 30, 311-316.

[16] ASTM. F2792-102 standard terminology for additive manufacturing technologies, 2015, Online. accessed 29.04.15 http://www.astm.org/Standards/F2792. htm.

[17] Koff W., Gustafson P. 2015. 3D printing and the future of manufacturing. Leading Edge Forum; 2015 http://assets1.csc.com/innovation/downloads/LEF _ 20123DPrinting.pdf accessed 20.04.15

[18] Rickenbacher L.,Spierings A., Wegener K. 2013. An integrated cost-model for selective laser melting (SLM). Rapid Prototyp J. 19:208-14.

[19] Christoph Klahn, MirkoMeboldt.2018. Cost Factors and Cost Optimization. https://www.spotlightmetal.com/additive-manufacturing-cost-factors-and-cost-optimization-a-734518/

[20] Wings Yin Hailiana,b, Yu Xiongqingb. 2010. Integration of Manufacturing Cost into Structural Optimization of Composite. Chinese Journal of Aeronautics. 23; 670-676.

[21] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase, D. Pham. 2017. Cost models of additive manufacturing: A literature review. International Journal of Industrial Engineering Computations. 8: 263-282.

[22] M. Baumers, C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, R. Hague. 2012. Combined Built-Time, Energy Consumption and Cost Estimation for Direct Metal Laser Sintering.