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Cost based, integrated design optimization using a parametric CAD model

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ABSTRACT
This paper present a novel approach for developing a decision support tool for designers based on manufacturing cost. The approach focuses on exploiting the advantages offered by integrating parametric CAD, manufacturing processing time based cost estimation and optimization technique within an integrated framework. The methodology is then applied in optimizing the geometry for minimum manufacturing cost of rotor blade.

KEYWORDS
CAD; Design for Manufacturing (DFM); Integrated Design; Optimization

1. Introduction

Early helicopter blades were fabricated from wood and fabric. Today advanced composite rotor blades are widely used in modern helicopters. Blade construction is changed with the aerodynamic section that is fabricated from metal to composites. The design of composite rotor blades can be one of the most challenging tasks [4] [13] because of the sophisticated geometry changes in chord, twist, airfoils, length of the blade and tip shapes [7]. Better designs may also be produced if designers could evaluate the cost implications of their design parameters/factors in the early design process. Design for Manufacturing (DFM) is a strategy frequently used by manufacturers to reach a manufacturing cost reduction through design optimization. Previous studies showed that over 70% of the production cost of a product is determined during the conceptual design stage [12]. Cost reduction before the production process can be achieved by evaluation of the numerous trade-off scenarios related to product design, material choice, process performance and investment requirements. Design optimization is an important engineering design activity. Research on design optimization has considered better solution methods as well as novel formulations [6]. Design optimization methods have traditionally focused on lowering weight and improving structural performance. Although cost is an important factor in every emerging design, existing tools lack key features and capabilities in optimizing designs for minimum product cost at acceptable performance levels. It may be concluded that cost itself is a design element and should be controlled as part of the design process [3]. Computer-aided design tools such as CATIA, UGS NX and Pro-Engineer can be used by engineers to experiment with part definitions leading to optimal design. However, they could not access the impact of design on manufacturing cost. Many tasks the designer has to do, can be automatized. But the current CAD systems does not offer all needed functionalities [11]. The concurrent engineering and integrated product process development (IPPD) approaches open a new field for manufacturing cost and lead time estimation including manufacturing system performance to take into account as early as possible in the design stage. The integrated model is very robust, flexible and expandable. Many design alternatives could be evaluated within a short time interval. The integrated models and frameworks in [8] [9] [14] [15] were developed by author by integrating with the developed geometric parameters module, time estimation module, activity based cost estimation module and production system performance evaluation module.

This paper describes the construction of a system which overcomes the above issues by presenting a novel approach for seeking trade-offs between performance measures and production costs, using activity based cost estimation, a parametric CAD model and an optimizer concurrently to evaluate various designs. The remainder of the paper is organized as follows. First, an overview of the integrated design optimization process is presented. Following to the overview of the process, the role of geometry parameterization, manufacturing time estimation, manufacturing cost estimation, manufacturing system performance evaluation and optimization elements are explained. This section also briefly describes the various software tools used for the function listed above.

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Finally, in the last two sections, results and discussion is discussed and finally a conclusion.

2. Overview of the integrated design optimization process sequence

The idea of manufacturing cost reduction through design optimization is to make money and reduce the overhead. Cost reduction before the production process can be achieved by evaluation of the numerous trade-off scenarios related to product design, material choice, process performance and investment requirements. Keeping the manufacturing process simple, reducing the costs of materials and increasing the efficiency of the manufacturing process are the best ways to do this. Fig. 1 shows the overview of the proposed cost based design optimization methodology. The integrated framework (Fig. 1) is implemented using the five essential elements under the ModelCenter® data integrating environment. The five essential elements to the process used here are: (i) geometric parameters generation module (ii) manufacturing processing time estimation module (iii) manufacturing cost estimation module (iv) manufacturing system performance evaluation module and (v) a robust optimizer to provide the inputs to the parametric CAD model while simultaneously validating the cost values against the formulated problem. The developments of modules are explained details by authors in [8] [9] [14] [15]. The flow data (input-output) implemented modules are shown in the Fig. 2(a) (b).

The optimizer drives the entire process by feeding a set of input parameters to the parametric CAD model. The output data of modified geometry is then passed on the manufacturing processing time estimation module. The output data of manufacturing processing time module is then passed on to the manufacturing cost estimation module and manufacturing system performance evaluation module. The optimizer receives and optimize with the output data of manufacturing cost and system performance evaluation module. The calculated costs are then passed back to the optimizer. The optimizer uses a specified algorithm to calculate the input parameters for the subsequent iteration by comparing the cost output against the objective and constraint functions. This process is continued iteratively evaluating numerous candidate geometries until the optimum design solution is found.

2.1. Geometric parameters generation module

2.1.1. A parametric CAD model for rotor blade in CATIA®

Blade 3D surface and solid geometries are defined parametrically and modeled in CATIA V5. The input parameters of blade surface: airfoil coefficients (AU0, AU4, AL0, AL4), and planform parameters: span-wise distances (L1,

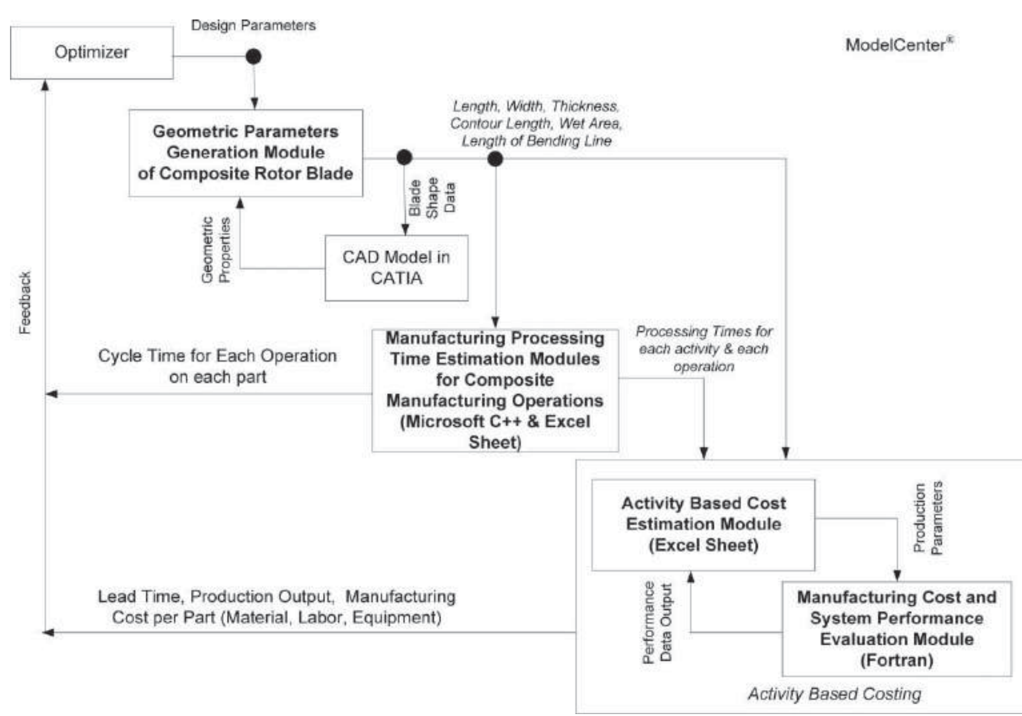

Figure 1. An overview of the cost based integrated design optimization process.

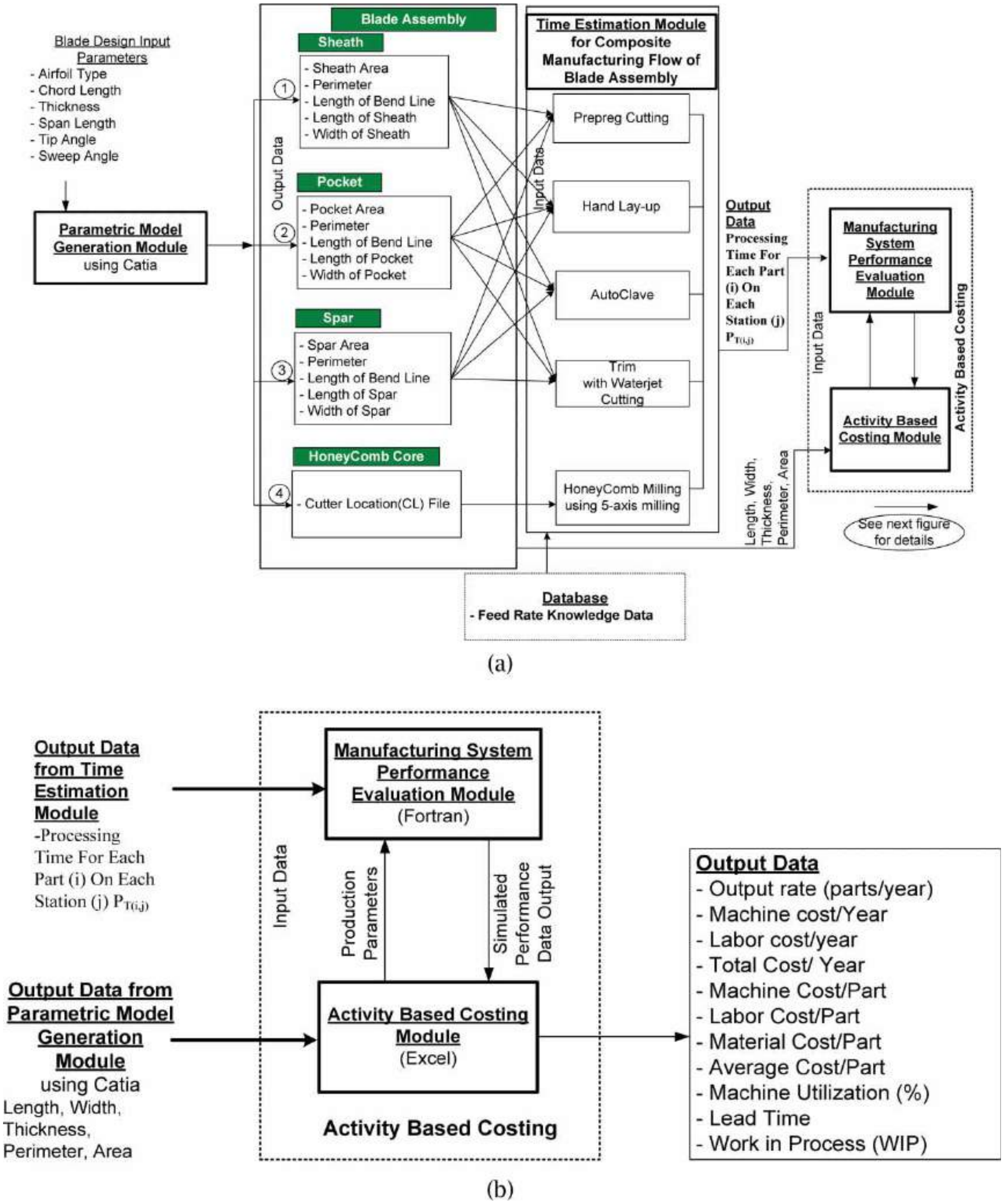

Figure 2. (a), (b) Input-Output data of the developed modules [8].

L2, L3), chord length, twist and tip sweep angle (by leading edge) are shown in Fig. 3.

2.1.2. The class function/shape function transformations method (CST)

The blade surface represented with lofting by three airfoil cross sections. The Class function/Shape function Transformations method (CST) has been used for airfoil representation. The CST method is based on analytical expressions to represent and modify the various shapes. The components of those are shape function and class function. The shape function provides the ability to directly control the key parameters of the geometry. Fig. 4 describes the representation procedure based on the CST method [1] [2] [5].

By using the CST method, the curve ordinates are distributed by the following equation:

$$y(x/c) = C_{N2}^{N1}(x/c) \cdot S(x/c)$$

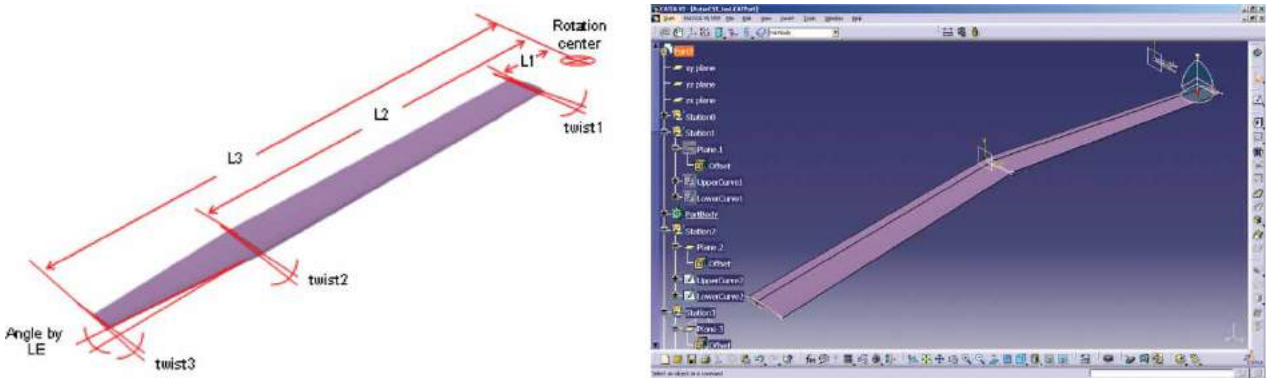

Figure 3. Main geometrical and planform parameters of the blade surface.

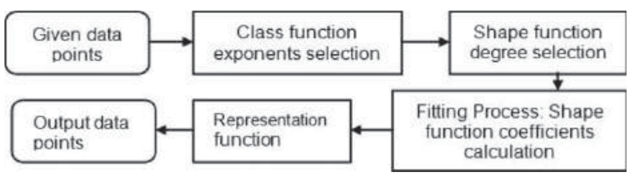

Figure 4. Representation procedure based on CST method [2] [5].

where $C_{N1}^{N2}(x/c) = (x/c)^{N1}(1-x/c)^{N2}$: class function,

$S(x/c) = \sum_{i=0}^{N}\left[A_i \cdot (x/c)^i\right]$: shape function,

N1, N2: exponents

x: non-dimensional values from 0 to 1.

c: curve length

Bernstein polynomials are used as shape functions.

$S_i(x) = K_i x^i (1-x)^{n-i}$

where $K \equiv \binom{n}{i} = \frac{n!}{i!(n-i)!}$: binomial coefficients

n: order of Bernstein polynomial

i: numbers 0 to n

In this study, NACA 0012 is chosen as an airfoil baseline [14] [15]. With the given data coordinate points in Cartesian coordinate space, a curve fit is generated using 4th order Bernstein polynomials. The Class function for the airfoil:

$$C(x) = x^{0.5}(1-x)$$

Airfoil distribution function defined as upper curve and lower curve are presented below.

$$y_l(x) = C(x)\left[\begin{array}{c} A_{lo}(1-x)^4 + A_{l1}4x(1-x)^3 \\ +A_{l2}6x^2(1-x)^2 + A_{l3}4x^3(1-x) + A_{l4}x^4 \end{array}\right]$$

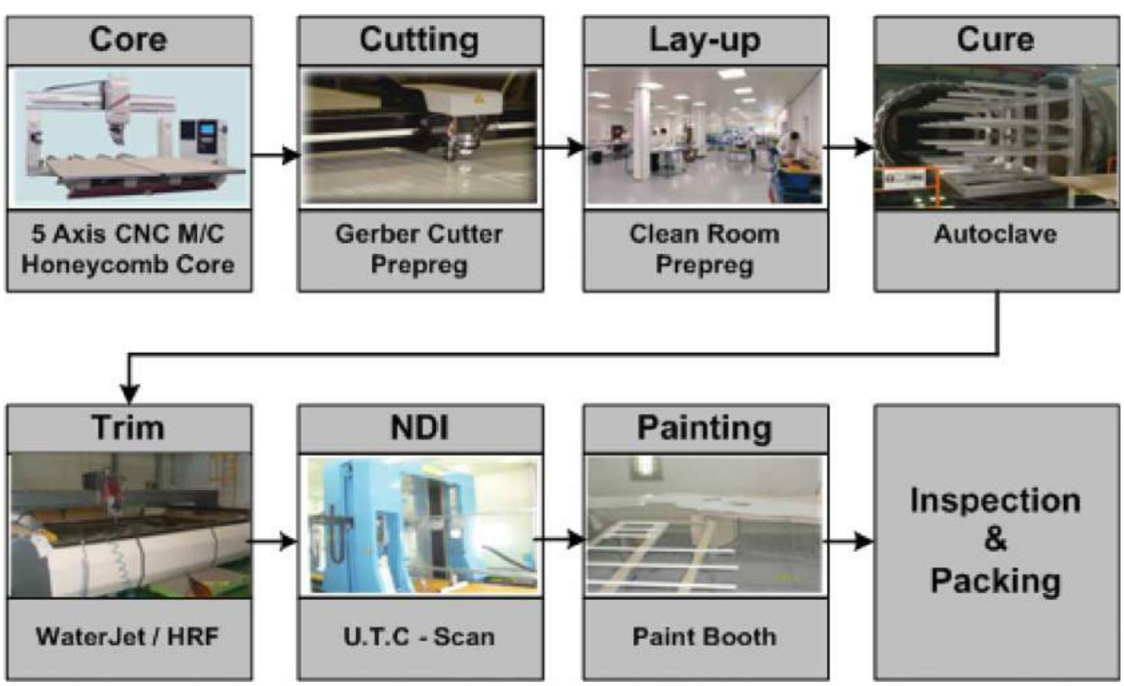

Figure 5. Manufacturing flow for aerospace advanced composite manufacturing. [8][9].

$$y_u(x) = C(x)\begin{bmatrix} A_{uo}(1-x)^4 + A_{u1}4x(1-x)^3 \\ +A_{u2}6x^2(1-x)^2 + A_{u3}4x^3(1-x) + A_{u4}x^4 \end{bmatrix}$$

Where: Au0 = 0.1718; Au1 = 0.15; Au2 = 0.1624; Au3 = 0.1211; Au4 = 0.1671; Al0 = −0.1718; Al1 = −0.15; Al2 = −0.1624; Al3 = −0.1211; Al4 = −0.1671.

2.2. Manufacturing processing time estimation module

Fig. 5 shows the manufacturing flow for aerospace advanced composite manufacturing. In this module, actual processing time estimation models for each manufacturing operation such as Core machining, Prepreg

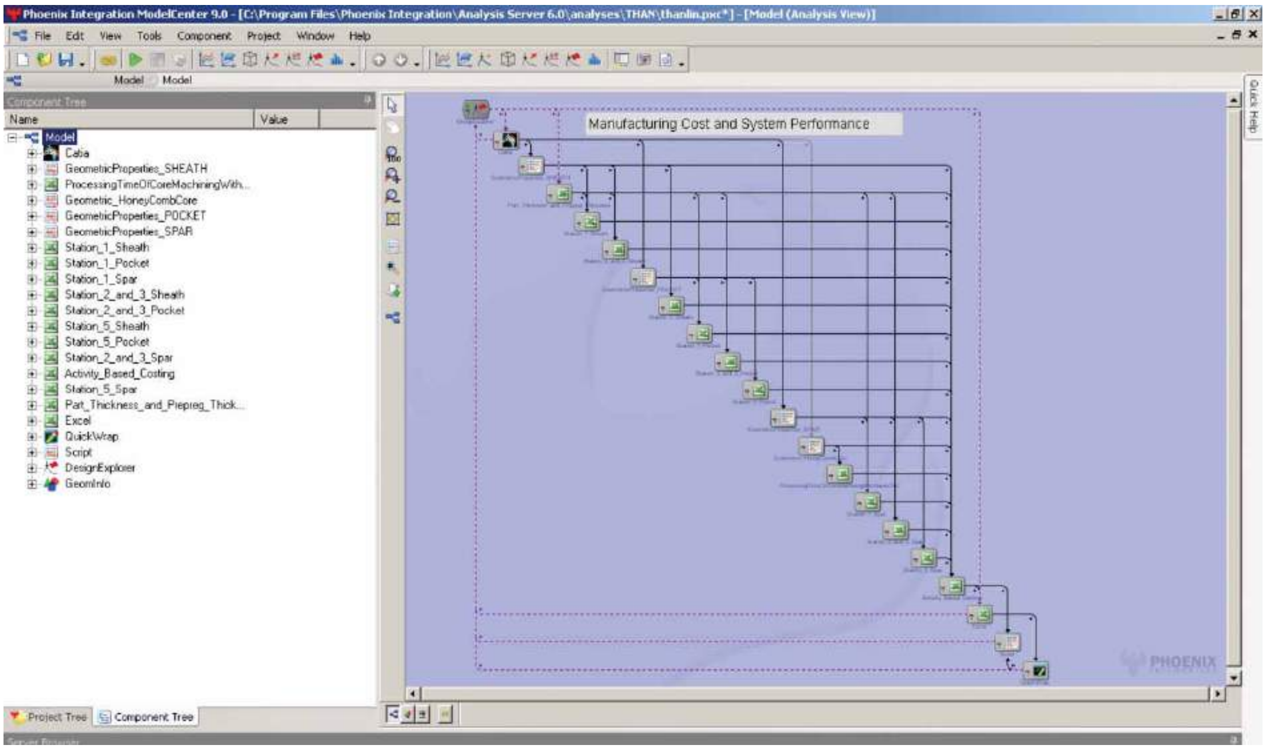

Figure 6. Integrated model for design optimization.

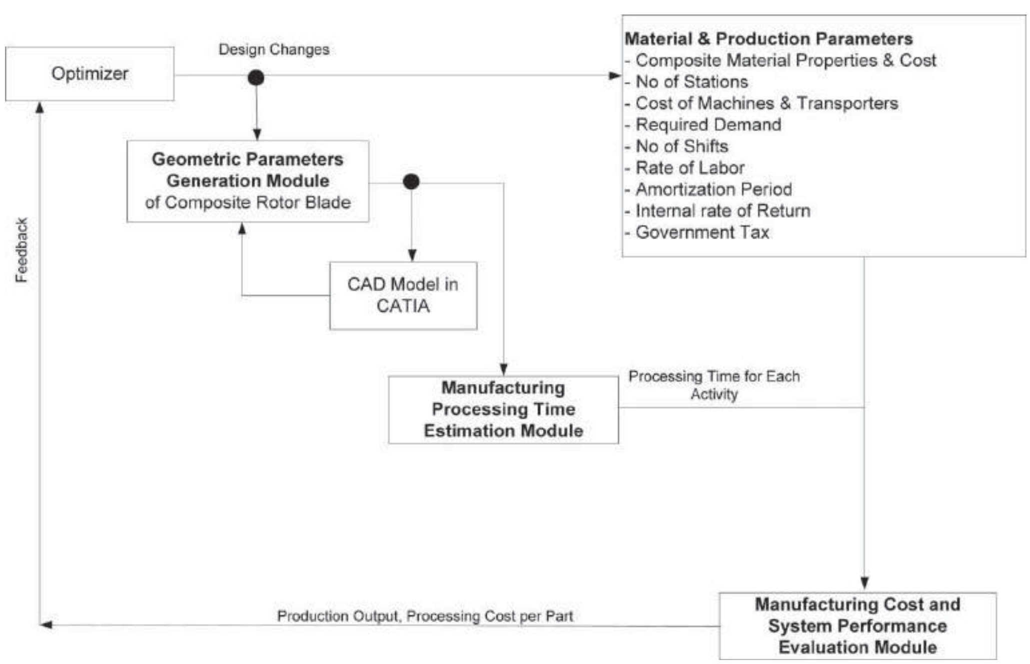

Figure 7. Optimization loop for the design for manufacturing.

cutting, Lay-up, Autoclave and Trim are required to implement regarding to integrate with other modules. Fig. 5(a) (b) describes the input-output data of the developed modules for manufacturing processing time, manufacturing cost estimation and manufacturing system performance modules. Details are presented and discussed by author in [8] [9].

2.3. Manufacturing cost estimation module

Part area data is transferred automatically from the module of Geometry. Part thickness is user input value. Density, Cost and utilization are from the database. The Cost of Labor, C_L used may also be determined for each process activity listed in the process plan. For each activity/process time, the cost of the labor resources consumed is calculated by multiplying that time by the cost rate for the labor resource as obtained from the employee code rate database. Individual items are then summed for the total labor cost included in the product. Cost of Equipment, C_E used may also be determined using the direct process activity rate multiplied by the machine cost rate. The machine cost rate for each production machine is calculated based on maintenance costs, operating cost,

Table 1. Objective function, design variables and constraints.

		Optimum Results	Baseline		
	Objective Function ($)	1281	1353	Lower Bound	Upper Bound
Design Variables	AU0	0.0570	0.1718	0.05	0.35
	AU1	0.051	0.15	0.05	0.35
	AU2	0.2005	0.1624	0.05	0.35
	AU3	0.2767	0.1211	0.05	0.35
	AU4	0.1794	0.1671	0.05	0.35
	AL0	−0.2218	−0.1718	−0.3	−0.05
	AL1	−0.0656	−0.15	−0.3	−0.05
	AL2	−0.0627	−0.1624	−0.3	−0.05
	AL3	−0.2907	−0.1211	−0.3	−0.05
	AL4	−0.2091	−0.1671	−0.3	−0.05
	Chord	0.6107	1.0	0.61	1.0
	Twist	0.9539	1.0	0.3	1.0
	Taper ratio	0.5097	1.0	0.5	1.0
	Taper position	0.5155	1.0	0.5	1.0
Constraints	Production Output Rate/Year (unit)	2283	2160	1000	5000
	Blade Surface Area (m2)	0.215	0.323	0.25	0.5

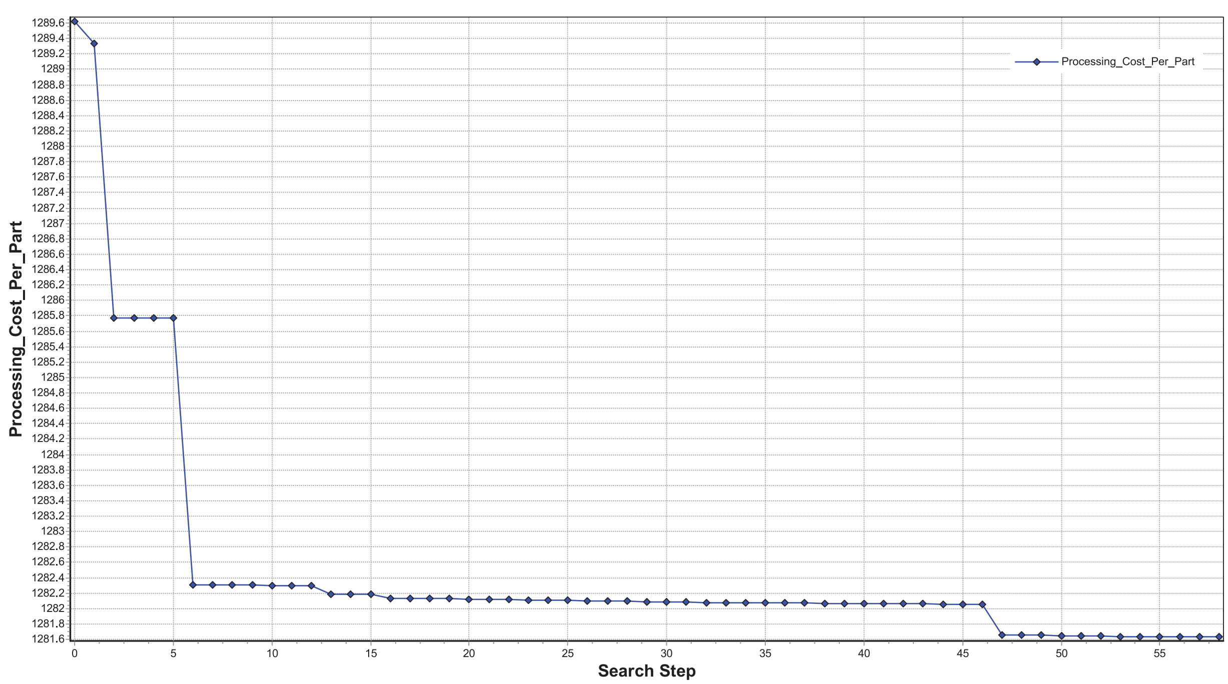

Figure 8. Convergence graph for the objective function (To minimize the manufacturing cost).

equipment asset and the number of machine hours. For each activity/process time, the cost of equipment resources is calculated by multiplying the job time with the cost rate for that equipment resource. Processing cost, C_P is a summation of C_M, C_L and C_E. This module is developed by author and described details in [8][9]. The input-output data of the integrated modules are shown in Fig. 5 (a) and (b).

2.4. Manufacturing system performance evaluation module

Manufacturing system evaluation module is implemented using Microsoft Visual Fortran. The computer aided queuing network model is considered and applied for conceptual design stage as details are not known in this stage. The details are presented by author in [9]. The

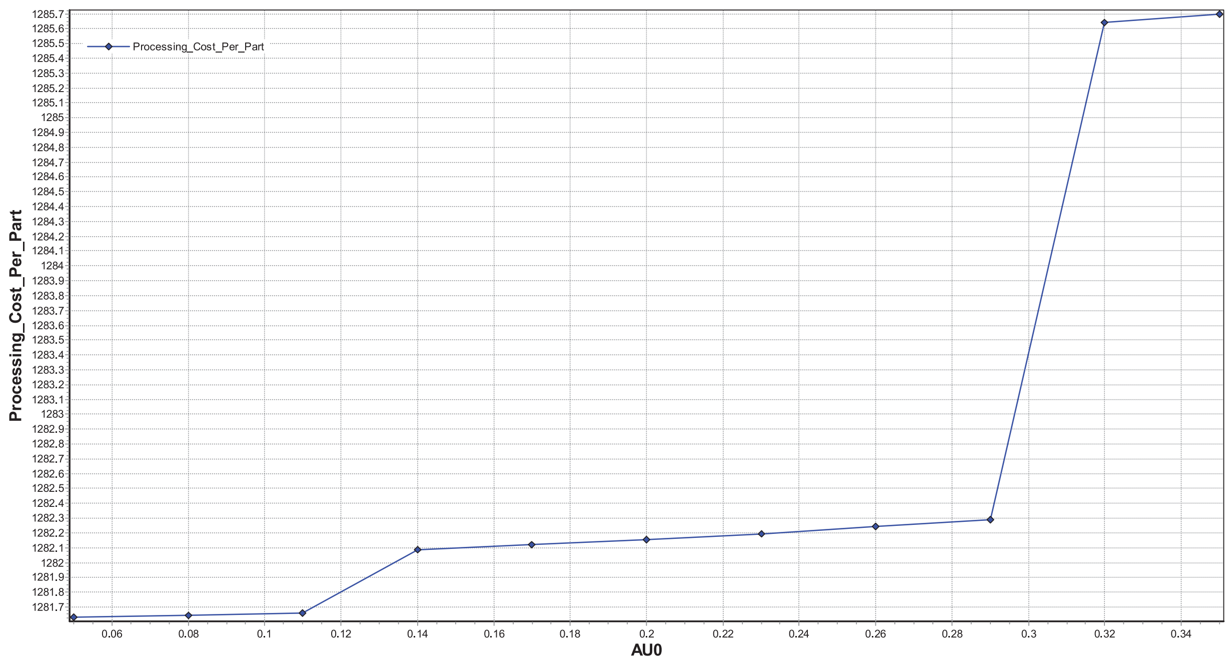

Figure 9. AU0 vs processing cost per part.

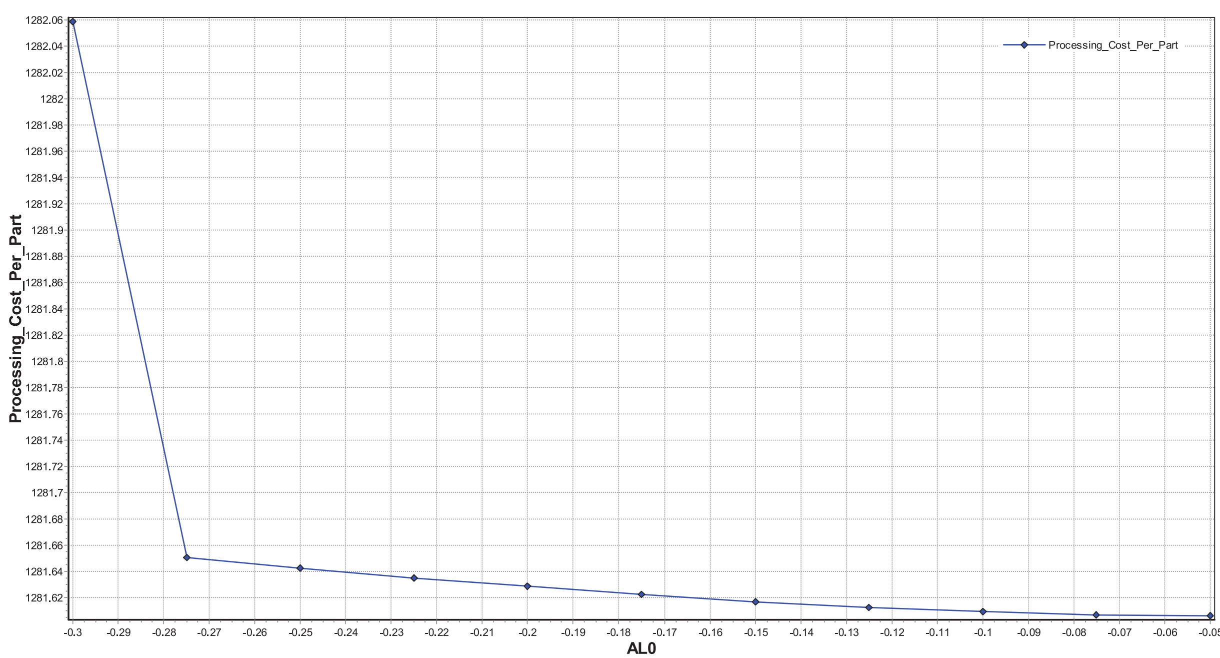

Figure 10. AL0 vs processing cost per part.

input-output data of the integrated modules are shown in Fig. 5 (a) and (b).

2.5. Optimizer

Fig. 6 presents the integrated model for design optimization. Genetic algorithm (GA) is used as optimization method for this study. ModelCenter® [10] controls input data, execute analysis, and retrieve output data. By automating and simplifying these tasks, ModelCenter® makes the design process more efficient, saves engineering time, and reduces the chances for error in the design process.

3. Design for optimization

Designing for manufacturing (DFM) is a strategy frequently used by manufacturers to reach a manufacturing

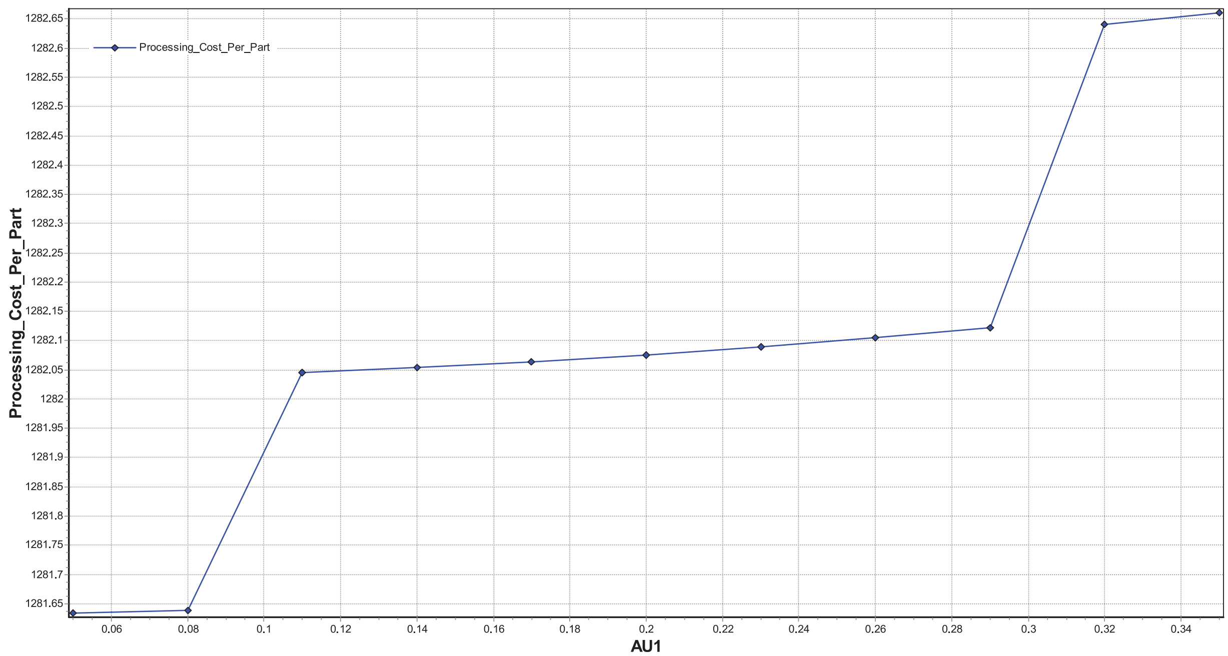

Figure 11. AU1 vs processing cost per part.

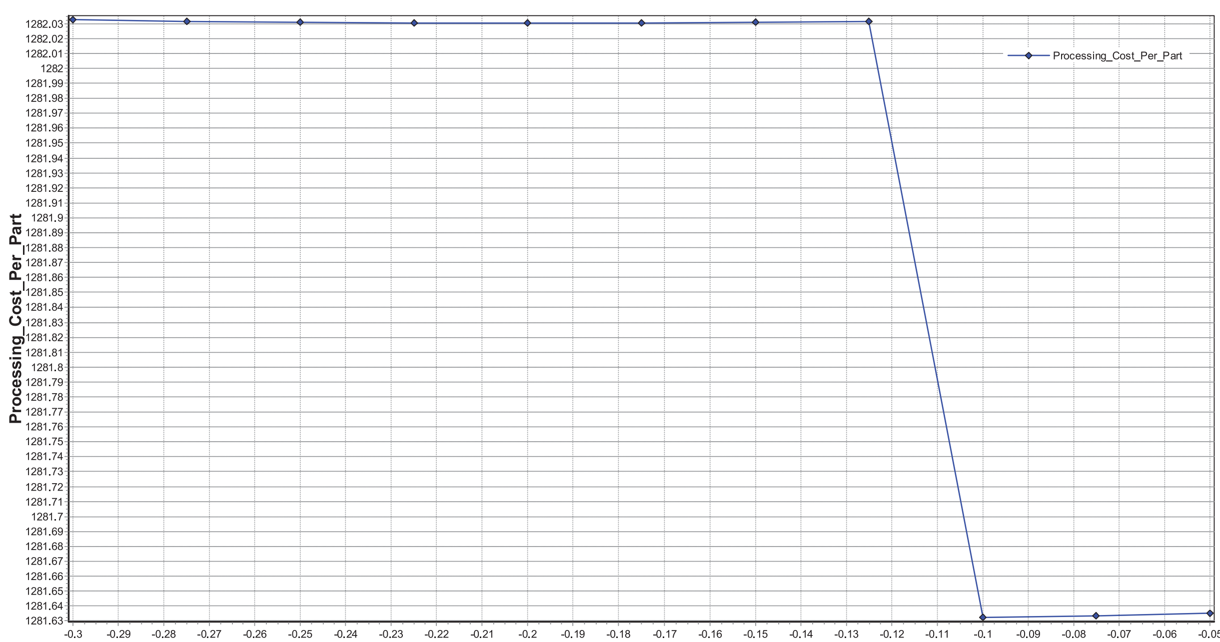

Figure 12. AL1 vs processing cost per part.

cost reduction through design optimization. Rather than design a product and set up the machines and production processes to best fit the design, designing for manufacturing works the other way around. The idea of manufacturing cost reduction through design optimization is to make money and reduce the overhead. Keeping the manufacturing process simple, reducing the costs of materials and increasing the efficiency of the manufacturing process are the best ways to do this. Fig. 7 shows the optimization loop for design for manufacturing.

3.1. Optimization formulation

3.1.1. Design variables

The design variables are maximum pretwist, taper ratio, point of taper initiation, blade root chord, A0 to A4

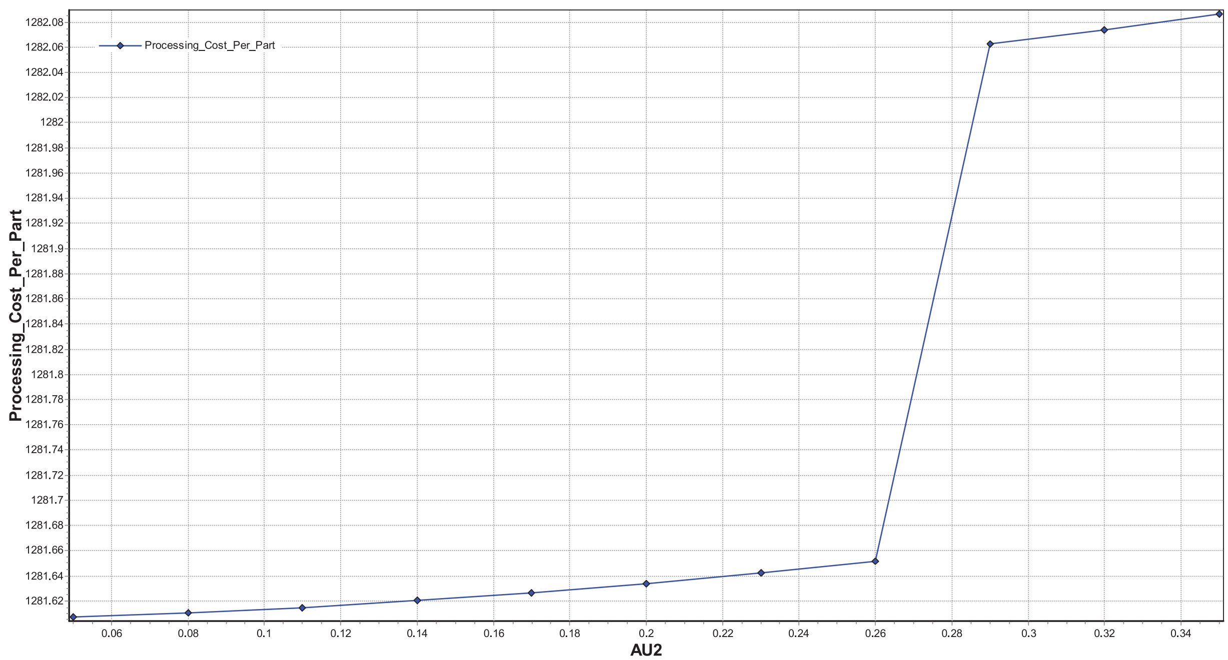

Figure 13. AU2 vs processing cost per part.

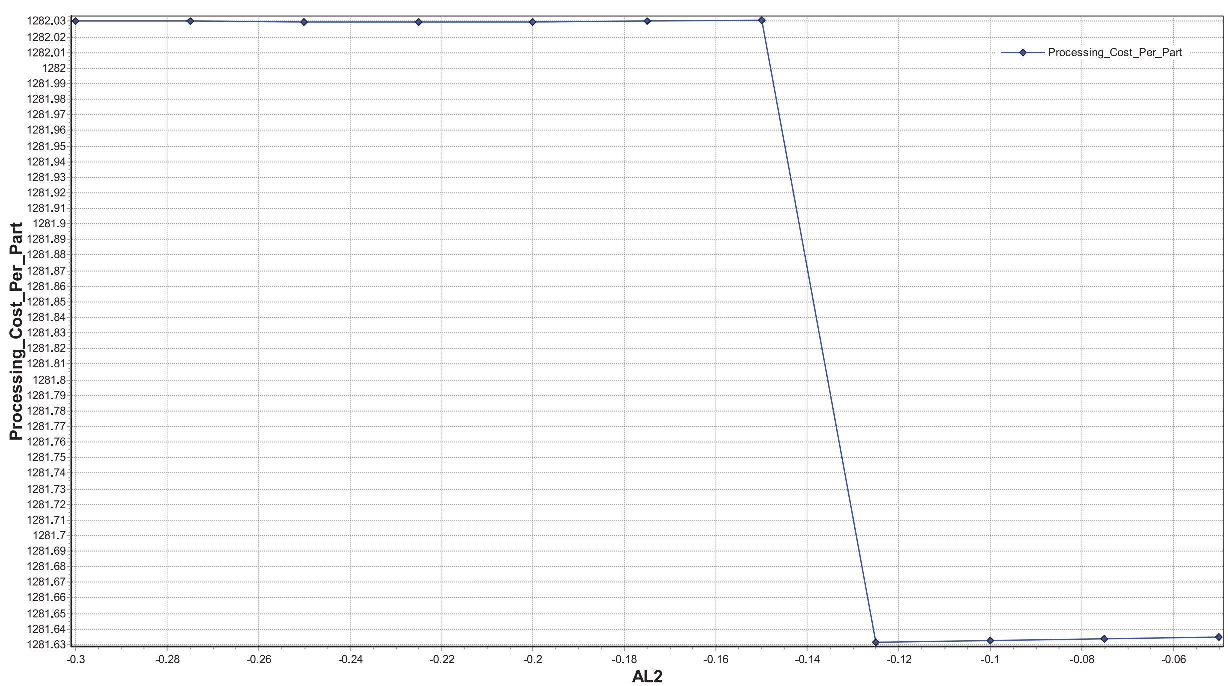

Figure 14. AL2 vs processing cost per part.

coefficients of airfoil distribution function. The blade is rectangular to station of the point of taper initiation and then tapered linearly to the tip. The twist varies linearly from the root to the tip. NACA0012 was chosen as baseline airfoil. See Tab.1 for the objection function, design variables and constraints.

3.1.2. Constraints

The requirements are the followings:

- Production output rate per year
- Blade Surface Area

3.1.3. Objective function

Manufacturing cost and system performance evaluation module provides the objective function to reduce the manufacturing cost of a composite rotor blade.

To minimize

Manufacturing Cost of a composite blade, $C_P = C_M + C_L + C_E$

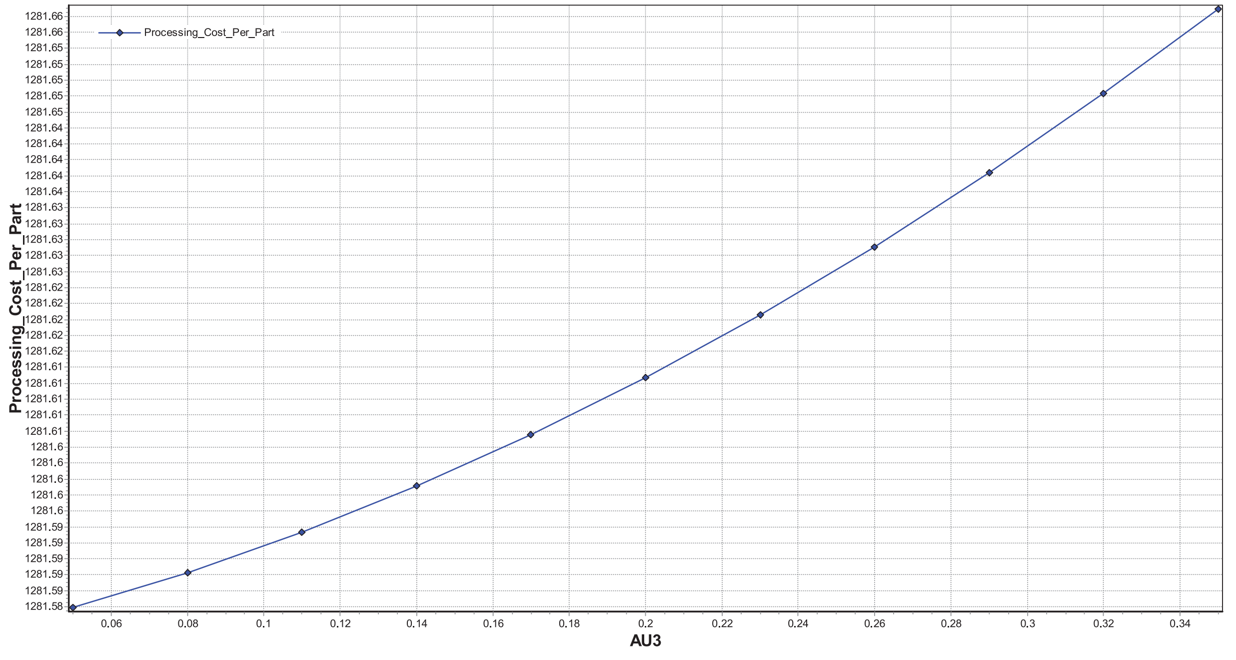

Figure 15. AU3 vs processing cost per part.

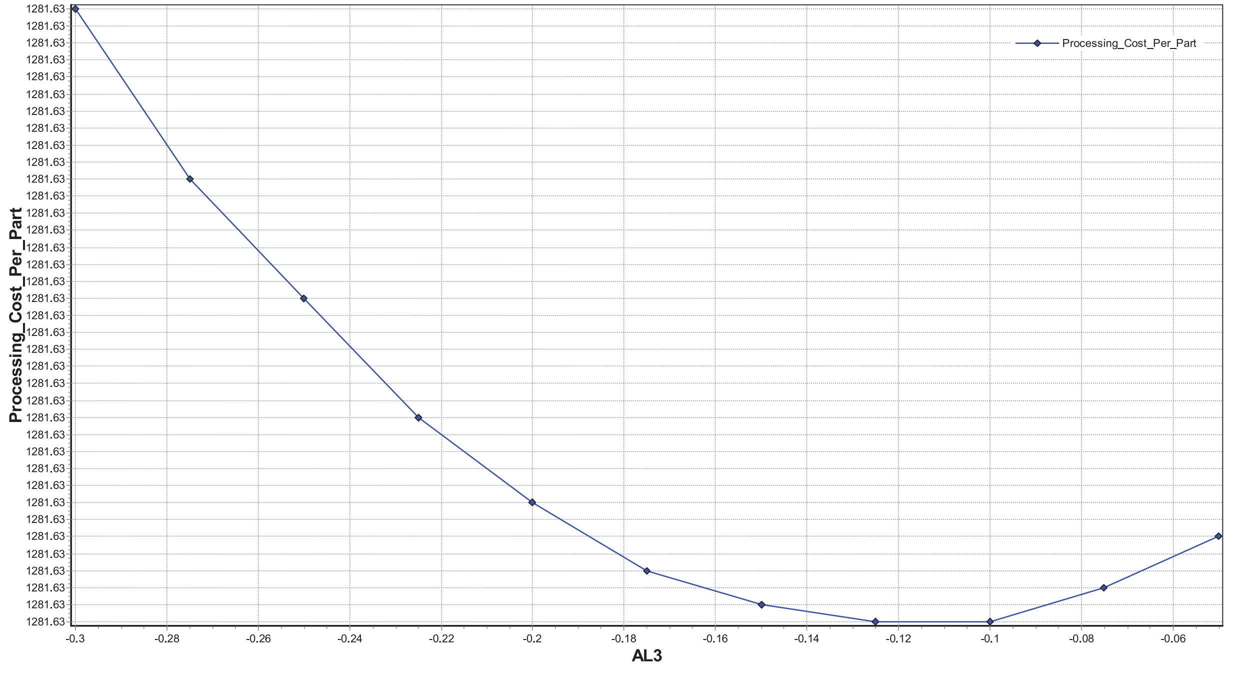

Figure 16. AL3 vs processing cost per part.

Where, C_M = Material Cost, C_L = Labor Cost, C_E = Equipment Cost

4. Results and discussion

Tab. 1 shows the optimization results and baseline. The objective function reduced 5.3%. The history of convergence and sensitivity analysis of design variables are shown in Fig. 8–21. We could analyze the variation of manufacturing cost based on the effect of design parameters. Based on the optimum design parameters, 3-CAD model has been updated itself under the integrated framework. This model can be connected with Aerodynamics module and etc. The concept of integrated design is studied using parametric CAD model. It is demonstrated that the cost of an engineering product can be

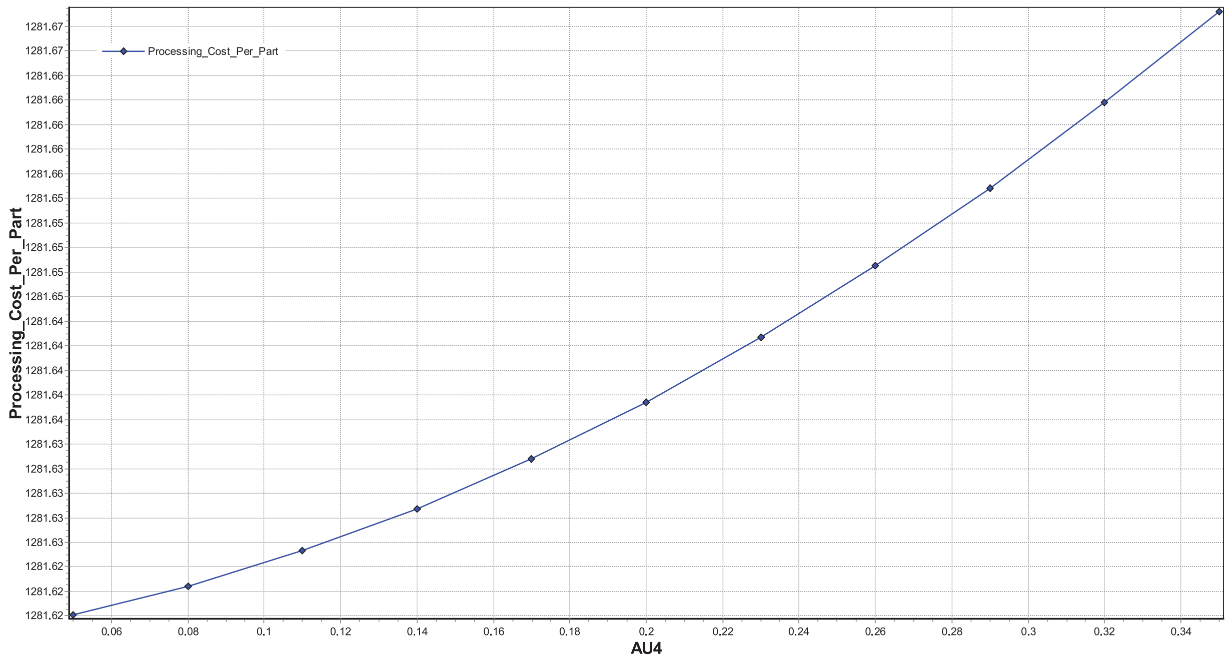

Figure 17. AU4 vs processing cost per part.

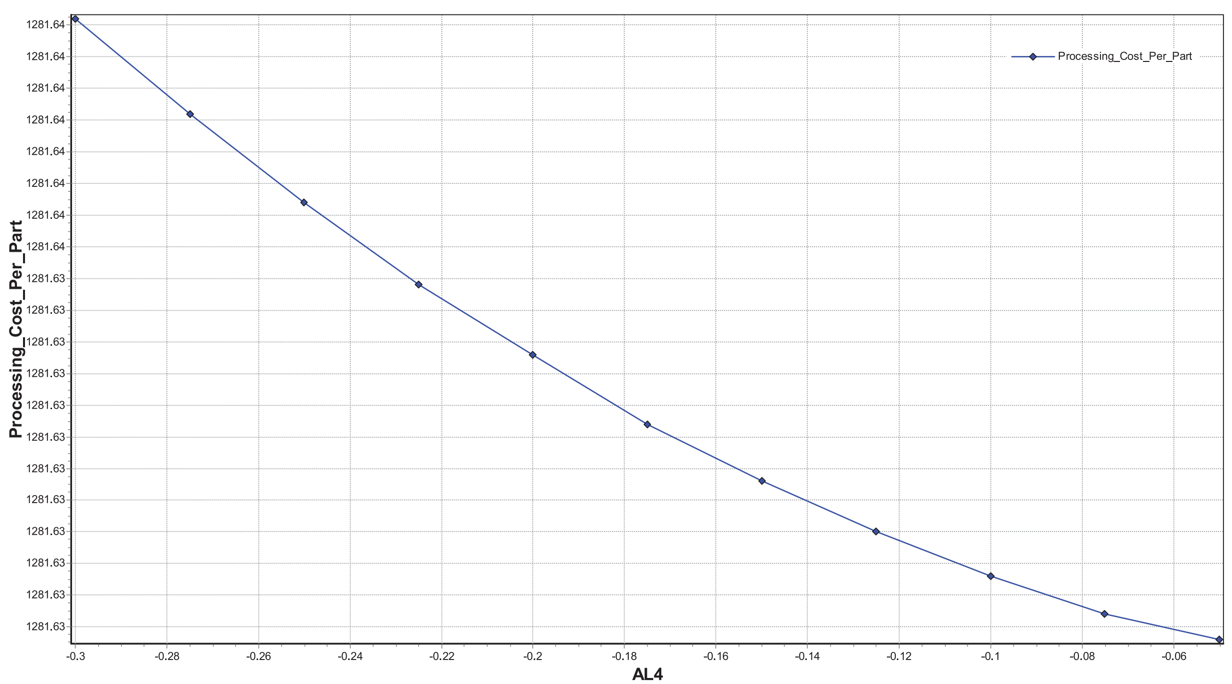

Figure 18. AL4 vs processing cost per part.

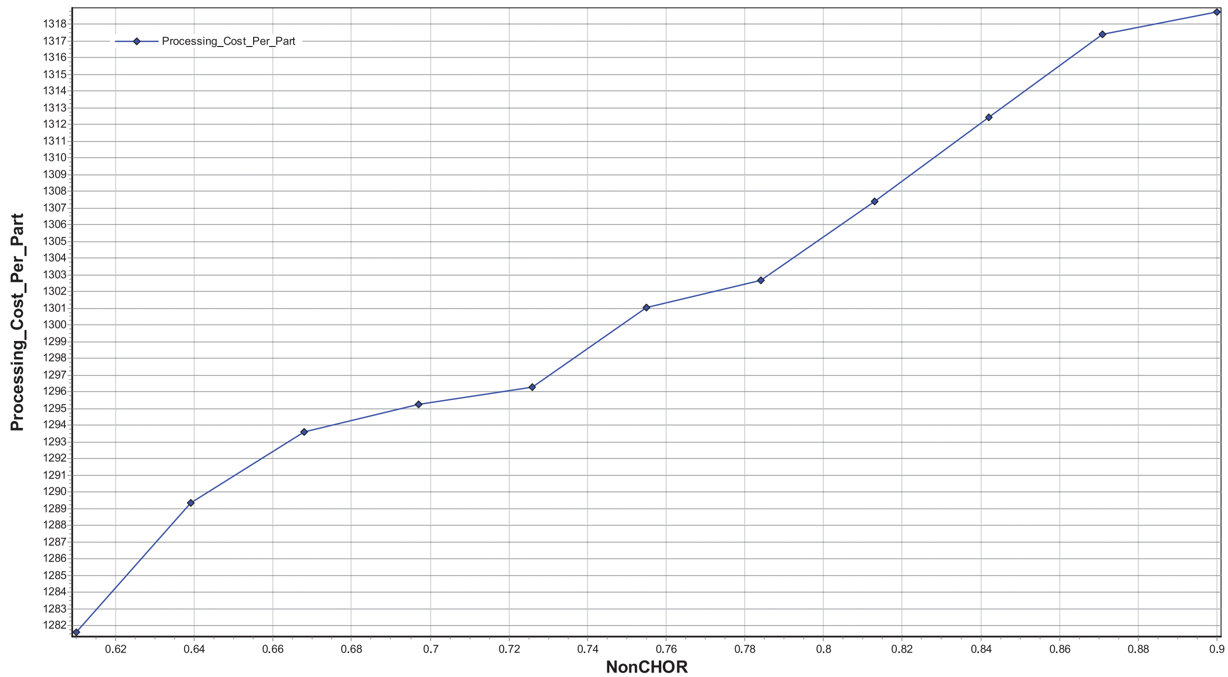

Figure 19. Chord vs processing cost per part.

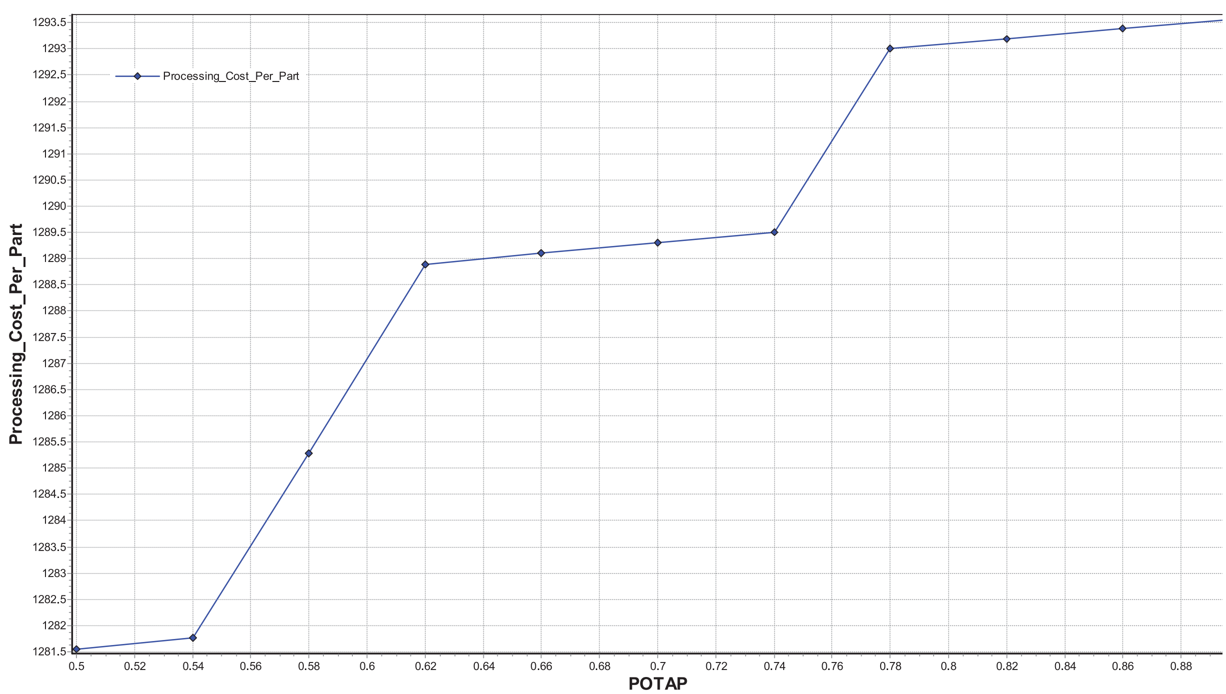

Figure 20. Taper position vs processing cost per part.

integrated to selected design parameters in CAD and manufacturing process parameters for design optimization purpose.

5. Conclusions

This study aims to provide a realistic and effective tool in generating cost driven designs supporting better decision making in the product development process and shows a novel approach for design optimization. The methodology proposed here is intended to shorten the lead time in acquiring the cost estimates. The methodology can be used to design more sophisticated parts than the present model. The developed model can be upgraded and integrated other related engineering analysis modules towards multidisciplinary design optimization. This

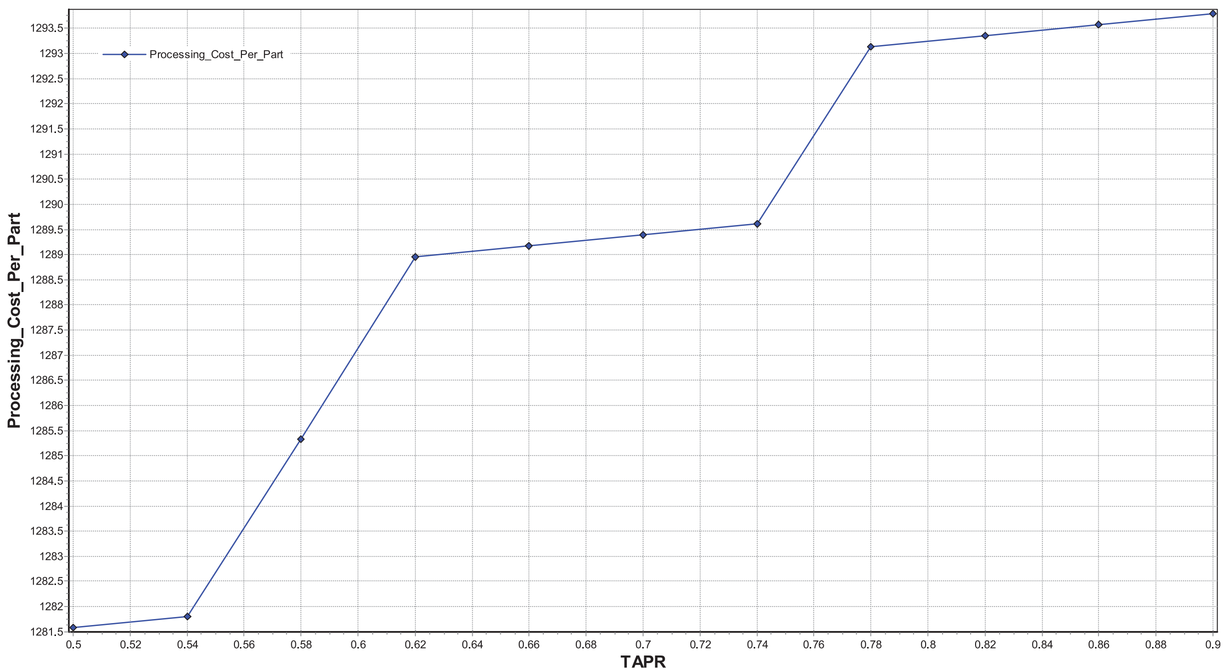

Figure 21. Taper ratio vs processing cost per part.

approach would be applied in the near future for design more sophisticated parts than the present component to appreciate the efficacy of this tool.

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