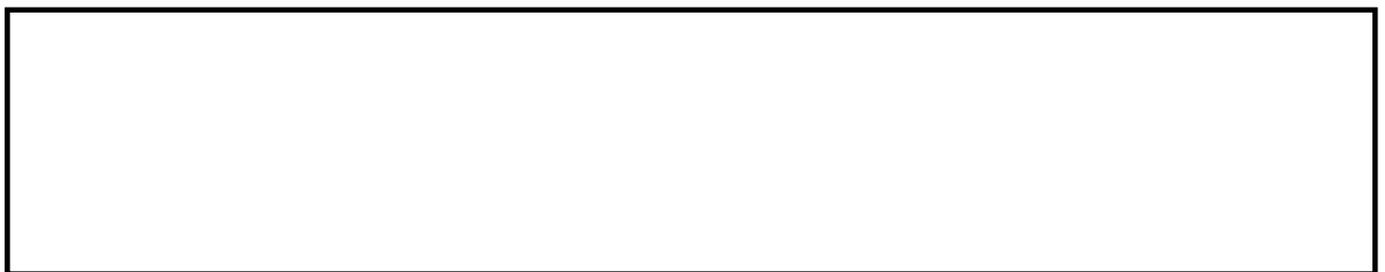


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A digital twin study for immediate design / redesign of impellers and blades: part 1: CAD modelling and tool path simulation.

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A Digital Twin study for Immediate Design / Redesign of Impellers and Blades: Part 1: CAD Modelling and Tool Path Simulation

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Abstract

This paper presents a digital twinning study conducted for an immediate design / redesign and manufacturing of on impellers & blades. It is by accomplished by developing (i) CAD automation methods, based on the standard modelling procedures and (ii) Manufacturing automation based on the 3/3+1/3+2/5 axis milling process. Initially, the CAD model of impeller / blade is created by utilizing the dimensional parameters obtained through standard design calculations / data. It is then parametrized and converted to an automated model through simple dimensional rules and geometric algorithms developed for the purpose. After this stage, the CAD model is analyzed for manufacturing automation where the process planning data comprising cutting tools, process parameters and setups are selected. Here, the tool paths are generated for 3/3+1/3+2/5 axis milling considering a CNC Vertical Machining Center (VMC) to digitally twin milling process. Both the CAD modelling and manufacturing process plans including tool path generation are captured through journaling and customized / improved using the Application Programmable Interface's (API's) to suit the present scope. In this paper, the first part on CAD modelling and manufacturing simulation methodologies are discussed through validating the digital twinning concept in a virtual environment. The work is developed with the focus to help industries moving towards Industry 4.0 and requiring a constant design improvement in their products. It is by emphasizing the importance of digital twinning concept where a concurrent verification of design and manufacturing process can be achieved.

Keywords: Digital Twin, CAD Automation, Process Planning, Machining, Simulation, Impellers, Blades

1. Introduction & literature review

Digital Geometry or Computer Aided Design (CAD) model and its interoperability with Computer Numerical Control (CNC) machines / G&M codes will be challenging if a product requires an immediate design / redesign based on the constant change with customer requirements [1-3]. This will become highly tedious if the design change requires (i) major addition / deletion / modification of features in a CAD model and (ii) to be verified concurrently for a new manufacturing process plan different from the existing ones. Again, the complexity will be multi fold if the same is applied to a series of assembly digital / CAD models or for complex freeform parts such as impellers and blades seen in aerospace / automobile / oil and gas domains. Mostly in these domains, constant improvement in their design / CAD model is a criterion for their business success. They also seek high precision in their parts and requires full digital verification of the design to manufacturing processes before being sent for a final production. Even a minor change or missed detail in (i) intricate internal dimensions (e.g. fillet radius, hole diameter, chamfer length, taper angles etc.) (ii) assembly allowances (e.g. overlapped tolerances, angle variations, aligning relations etc.) (iii) GD&T details etc can lead to manufacturing mismatches such as (i) change with process plans (ii) improper / overlapped toolpaths (plunging, associated tool movements, sudden retraction etc.) (iii) cutting tool / workpiece collisions and (iv) setup / fixture alignment issues. The list will be lengthier as the manufacturing complexity will vary and increase based on other factors such as part complexity, capability of CNC machine, orientation, material etc. 'Digital Twin' is one among many Industry 4.0 technological concepts [1-3] which help to predict the faults on intricate changes on

design dimensions, assembly and manufacturing process plans. This is through highlighting the problems immediately wherever applicable and by allowing the user to make necessary changes thereby maintaining a real time interoperable design to manufacturing environment [1-5]. At present, there are software's providing support to make the changes using their API's, but digitally twinning them requires a logical development of complex algorithms in the form of IF-THEN rules and integrating various technologies. This includes (i) CAD (ii) Computer Aided Manufacturing (CAM) (iii) Computer Aided Process Planning (CAPP) (iv) software programming (e.g., C#.Net, JAVA, Python etc) (v) Internet of Technologies (IoT) (vi) Machine Learning and (vii) sensor-based CAD to CNC machine transfer. Combining all these technologies to develop a consolidated algorithm is an overwhelming task but is achievable through a stage-by-stage completion. This work considers the above-mentioned problem on immediate design / redesign by analysing all the other issues by studying CAD and manufacturing automation for digital twinning. It is by thoroughly analysing the design and manufacturing methods considering two complex profiles namely (i) impeller and (ii) blade adopted in various industrial applications. Before proceeding further, it is necessary to review the past works on these profiles as they have been extensively researched for their design and manufacturing complexities. The forth coming paragraphs are presented on these lines first by giving a brief literature review on digital twin and the later on CAD/CAM/CAPP aspects.

Brief literature on digital twin: Asma Ladj et.al [2] described a knowledge-based digital shadow for machining industry considering a digital twin perspective. Their aim is to adopt data analytics (based on unsupervised learning) on a knowledge inference engine for incidents to be detected in a manufacturing environment. Albrecht Hänel et.al [3] developed a digital twin for machining processes and applied for an application in aerospace industry. They integrated the mathematical models with various algorithms and verified the process parameters for milling process. Weichao Luo et.al [4] proposed a hybrid predictive maintenance approach for CNC machine tool driven by digital twin concept. The work focused on developing a hybrid predictive maintenance algorithm based on digital twin model and to find faults in CNC machines. Simulation algorithm of a digital twin for manual assembly process is presented by Hasan Latif & Binil Starly [5]. They developed a data-driven simulation algorithm for modelling the complex and manual manufacturing process by considering the production schedule followed in a complex defence weapon system. Yongli Wei et.al [6] developed a consistency retention method for digital twinning of CNC machine. They verified the method on wear prediction and sliding guide rail which affected the performance attenuation of CNC machine. Shimin Liu et.al [7] developed a bio inspired digital twin modelling method based on biomimicry for machining aerospace components. They verified the digital twin by developing three sub models namely (i) geometry (ii) behaviour and (iii) process on an air-rudder used in the aerospace structure. An intelligent scheduling of a feature-process-machine tool super network based on digital twin workshop is presented by Zhifeng Liu et.al [8]. They adopted a feature similarity matrix and developed an intelligent scheduling method for workshops to generate process plans rapidly and efficiently. Zhiheng Zhao et.al [9] developed an Internet of Technology (IoT) and digital twin enabled smart tracking for safety management. The work has been verified to detect abnormal motionless behaviour and self-learning genetic positioning in a real-life air cargo terminal. They considered both the physical and cyber world implementation to demonstrate the feasibility and effectiveness of the proposed techniques. Gabriel Fedorko [10] proposed a digital twin for testing and measuring of transport belts for pipe conveyors by adopting the concept of Industry 4.0. They implemented a FEM model with digital twins and measured the key properties and characteristics of the rubber-textile conveyor belts. A digital twin for bending operation by adopting finite element analysis has been conducted by E.P.Hinchy [11]. They developed the digital twin considering three elements (i) the machine (ii) the product (iii) the process and successfully verified the product stress, the residual stress and bend angle post-bending.

Brief literature on impellers and blades: Gouge avoidance utilizing a tessellated model (of a free-form surface) as the input has been attempted by Susan X Li and Robert B Jerard [12]. In their method, they prevented collision and reduced gouging by adjusting the tool orientation. C. Xu & R. S. Amano [13] developed a full 3D centrifugal impeller and analyzed it's capability on both structure and flow. They carried out calculations for the model and showed that a full 3D blade is both advantageous in a structure vibration and an aerodynamic performance. Gang Zheng et.al [14] presented an approach on flank milling of impeller by employing the side of a cutter to touch the desired surface. In their work, they developed two envelope surfaces which are swept by the cutter and conducted simulations to generate an interference-free tool paths. A simple and practical polynomial-based blade leading edge geometry design method is proposed by Weihao Zhang et.al [15]. They redesigned a mature blade profile named Hodson-Dominy (HD) blade and examined the validity of this method with a series of simulations to evaluate the impact on the flow. Linjian Yang & Jinchun Feng [16] presented a multi-axis CNC Integrated machining method for a blade in large Francis turbine. In their work, they generated data points and performed a three-point straightening method for blade machining. They adopted a 5-axis machining environment and simulated with VERICUT software.

From the literature study conducted, and through the gaps noticed it has been decided to focus the work on digital twin for immediate design / redesign addressing (i) automated CAD model design / redesign of impeller / blade and (ii) manufacturing automation of process plan / toolpaths for 3 / 3+1 / 3+2 / 5 - axis milling considering setup / fixturing aspects. The forth coming sections explains the CAD and manufacturing automation methods adopted for validating the digital twin concept. Owing to page restrictions parameterization of both profiles are not presented in this article.

2. Design & CAD model generation of impellers

Basically, impellers are used to pump the flow of gas or fluid as centrifugal pump / turbines / pumps belonging to oil and gas (O&G), aviation and power generation domains. Based on the flow regimes [17], there are two types of impellers (i) Radial flow (modelled for this work) (Fig. 1(a)) which impose essentially shear stress to the fluid and (ii) Axial flow [18] (Fig. 1(b)), which impose essentially bulk motioning and giving increased fluid volumetric flow rate. This work considers radial flow impeller by calculating first the ‘Meridional representation’ values following standard procedures for construction [17,19].

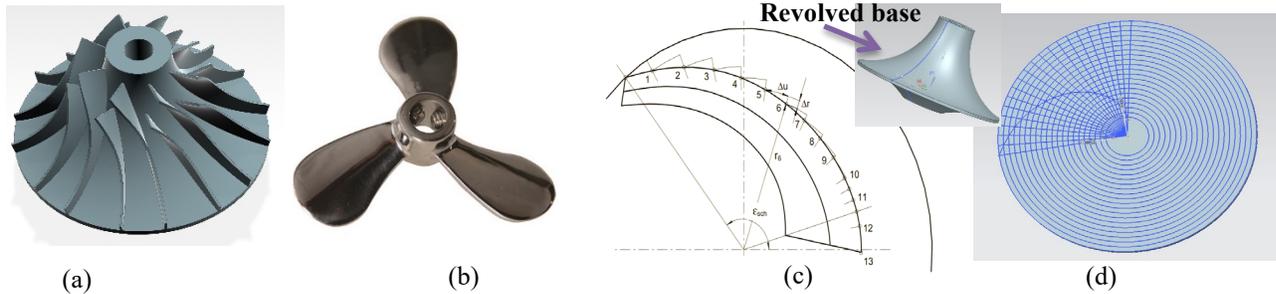


Fig. 1. (a) Radial flow impeller (b) axial flow impeller [18] (c) impeller blade design using Kaplan method (d) curve drawn by joining the intersection points

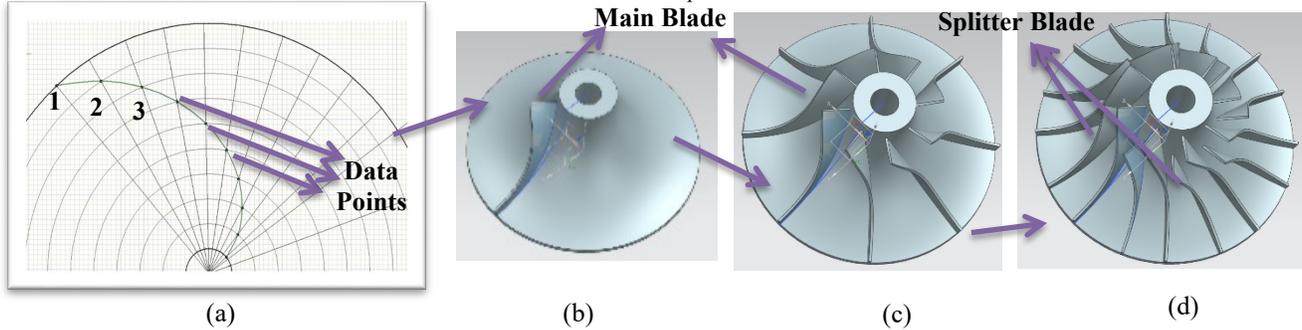


Fig. 2. (a) Data points from the intersected curve (b) impeller with single blade (c) impeller with 8 blades & (d) impeller with splitter blades (8+8)

After these calculations, the impeller base is completed by revolving two inner and outer circles about 360° with the hub surface (Fig. 1 (c)). Now the above calculated values are utilized and impeller ‘vane’ profile is generated over the surface of the hub. Construction of profile is based on the Kaplan method [17] and is similar as circular arc method (Fig. 1 (c)). Initially, two circles with inner and outer diameter are drawn. Then about 10 concentric circles (will vary with different impellers) are drawn with an incremental radius varying from inner to outer circle (Fig. 1 (d)). Then 10 radial lines were drawn with an incremental angle of 10° and the intersection point named as ‘data point’ (mentioned as 1,2,3...13 in Fig. 2(a)) is calculated from the point of intersection of the first circle with the first radial line. Similarly, the other values are obtained considering i^{th} concentric circle and i^{th} radial line to get the i^{th} data point. These data points are aligned using B-spline curve to obtain the vane profile projection over bottom surface. Using the control points from the above procedure a B-spline curve is drawn with a degree of 3. After this stage, the intersection curve obtained on the bottom hub surface is extruded normally to the top hub surface. Here, the blade height normal to hub surface is varied from entry to the exit i.e., from top to bottom. Thus, a single impeller main blade profile is obtained

and the same procedure is followed to construct the other main and splitter blades. Splitter blades are smaller ones and constructed in between the main blades. The construction process and final profile is shown from Fig's. 2 (b) - (d).

2.1. Design calculation of impeller

Once impeller is modelled, the impeller blade profile is parameterized in terms of control points and knot vectors. As explained in the previous section, the basic profile of impeller blade is constructed using B-spline curve based on the equations developed for the profile dimensions. The parameterization stage requires the B-spline parameters mainly the knot vectors, which are obtained from the data points generated in the design stage. These points located on the intersection of circles and lines with incremental length= r' mm and angle = θ° are considered and the following basic equations are solved to get a final equation to suit the data points:

$$\text{Circle equation: } x_i^2 + y_i^2 = r_i^2 \text{ ----- Eq. (1)}$$

$$\text{Line equation: } y_i = (\tan \theta_i) \times x_i \text{ ----- Eq. (2)}$$

By substituting the equations Eq. (1) in Eq. (2) and the following is obtained

$$x_i = \frac{r_i}{\sqrt{1+(\tan \theta_i)^2}} \text{ ----- Eq. (3)}$$

Substituting equation Eq. (3) in Eq. (2)

$$y_i = (\tan \theta_i) \times x_i$$

$$y_i = (\tan \theta_i) \times \frac{r_i}{\sqrt{1+(\tan \theta_i)^2}} \text{ ----- Eq. (4)}$$

Thus, data points obtained are

$$(x_i, y_i) = \left(\frac{r_i}{\sqrt{1+(\tan \theta_i)^2}}, \frac{r_i \times (\tan \theta_i)}{\sqrt{1+(\tan \theta_i)^2}} \right) \text{ ----- Eq. (5)}$$

$$(x_i, y_i) = (r_i \times \cos \theta, r_i \times \sin \theta); \text{ Where, } r_i = i \times r; \theta_i = i \times \theta,$$

Based on this equation 5, Table 1 is presented with the data points (partially given owing to page restrictions) obtained from the base curve of the impeller blade profile. It also explains the geometrical representation of data points by the intersection of the line with the curves ending up with the outer circle.

Table 1 Data points from the representation of data points (partially given)

r (mm)	θ (degrees)	X	Y
100	0	100	0
200	10	196.9646	34.71221
300	20	281.9259	102.5562
400	30	346.4632	199.908
500	40	383.1359	321.2582
600	50	385.8759	459.456
700	60	350.3218	606.0319
800	70	274.0817	751.5845
900	80	156.9107	886.2161
1000	90	0.796327	999.9997

As explained above, B-spline is the essential part of the almost any modern graphics development. In our case B-spline is predefined and it is only required to provide control points and obtained using Kaplan method. Now the basic B-spline curve which is defined by the Eq.6 (as given below) is utilised and a general equation for this profile is obtained for parametrization. The following calculations are performed, and the final Eq.8 is obtained to suit the impeller profile. (Owing to page restrictions brief calculation is shown here)

$$C(u) = \sum_{i=0}^n N_{i,k}(u)P_i \text{ ----- Eq.(6); Where, } N_{i,k} \text{ are B-spline basis functions of degree k, (k=3)}$$

$P_i = \{P_0, P_1, P_2 \dots, P_n\}$ are control points (obtained from geometry) and

$U = \{u_0, u_1, u_2 \dots, u_m\}$ is a knot vector. Where, $m = n + k + 1$; Here $N_{i,k}$ represents the basis function.

$$N_{i,k}(u) = \frac{(u-u_i)N_{i,k-1}(u)}{u_{i+k-1}-u_i} + \frac{(u_{i+k}-u)N_{i+1,k-1}(u)}{u_{i+k}-u_{i+1}} \text{ ----- Eq. (7)}$$

The control points calculated as given below: $B_0 = (100, 0)$; $B_1 = (196, 34)$; $B_2 = (281, 102)$; $B_3 = (346, 199)$; $B_4 = (383, 321)$; $B_5 = (385, 459)$; $B_6 = (350, 606)$; $B_7 = (274, 751)$; $B_8 = (156, 886)$; $B_9 = (0, 1000)$

Chord lengths: $C_1 =$ distance between B_0 and $B_1 = 101.84$; $C_2 =$ distance between B_1 and $B_2 = 108.85$

$C_3 =$ distance between B_2 and $B_3 = 116.76$; $C_4 =$ distance between B_3 and $B_4 = 127.48$

Similarly continued until C_5 to C_9 i.e., $C_9 =$ distance between B_8 and $B_9 = 193.21$; $\sum_{i=0}^n c_i = 1280.30$

Knot vectors for the given data points: $u_0=0$; $u_1=u_0+\frac{c_1}{\sum_{i=0}^n c_i}=0.080442$

$u_2=u_0+\frac{c_1}{\sum_{i=0}^n c_i}=0.165363$; Similarly continued till u_9 ; i.e., $u_8=u_0+\frac{c_1}{\sum_{i=0}^n c_i}=0.849115$; $u_9=u_0+\frac{c_1}{\sum_{i=0}^n c_i}=1$

Table 2 is presented with a partial list of chord lengths and normalized knot vectors.

Table 2 Chord lengths and normalized knot vectors

r in mm	θ in degrees	in radians	x	y	C	u	6*u
100	0	0	100	0	0	0	0
200	10	0.174444	196.9646	34.71221	102.9907	0.080442	0.482652
300	20	0.348889	281.9259	102.5562	108.7255	0.165363	0.99218
400	30	0.523333	346.4632	199.908	116.8009	0.256592	1.539553
500	40	0.697778	383.1359	321.2582	126.7705	0.355608	2.133646

After this calculation, the final equation is obtained as

$$C(u)=B_0N_{0,5}(u)+B_1N_{1,5}(u)+B_2N_{2,5}(u)+B_3N_{3,5}(u)+B_4N_{4,5}(u)+B_5N_{5,5}(u)+B_6N_{6,5}(u)+B_7N_{7,5}(u)+B_8N_{8,5}(u)+B_9N_{9,5}(u) \quad \text{----- Eq.(8)}$$

The above equation for the B-spline curve is determined using 10 data points and order of 5 is linked with the expressions in the 3D CAD model. A total of 15 knot vectors is used to determine the curve equation. Open uniform knot vectors are used in the curve equation. After the B-Spline equation generation, the dimensions of the base curve are parameterized. Data points are generated using the parameters and utilized to construct B-spline curve. The completed model and the associated final drawing sheet are given in Fig. 3 (a) and (b).

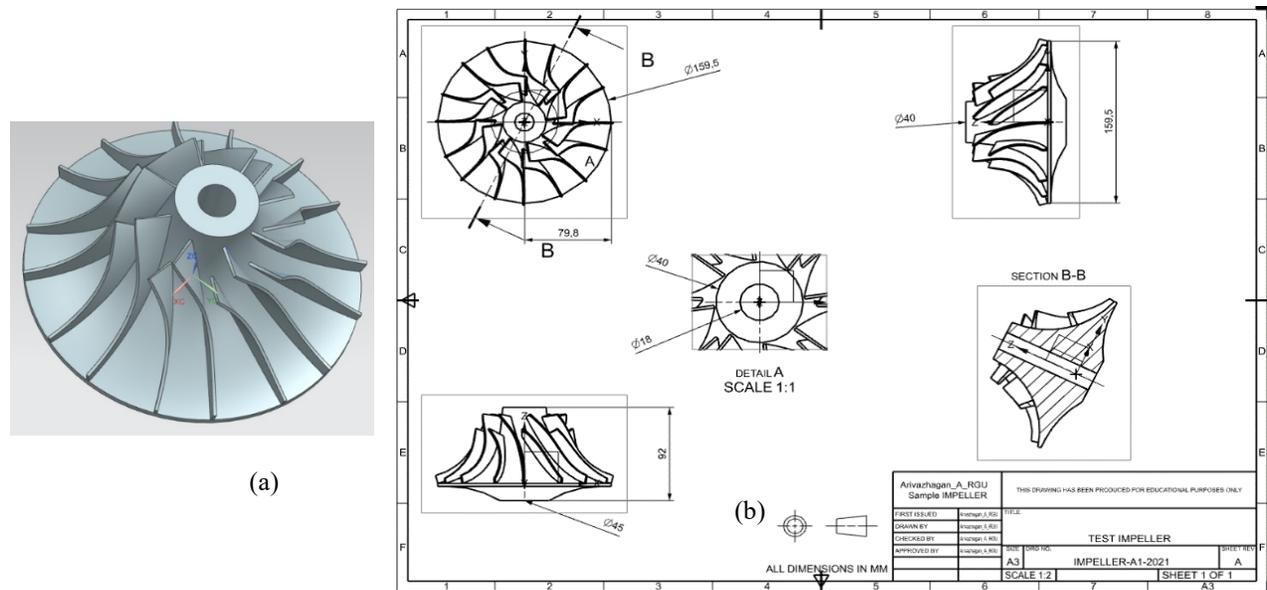


Fig. 3. (a) Final CAD model and (b) associated drawing sheet of the impeller

3. Design & CAD model generation of blades

The blade is an integral part of impeller or fan or blisk [16, 17]. From top to bottom, the blade consists of 12 multiple parameters associated with 12 complex cross-sectional profiles (CSP's) with varying dimensions at different levels of section. These parameters make the blade a complex design to obtain a free form shape associated with the CSP's. The parameters and values associated with a blade (partial list) as obtained from standard book sources [17] are shown in the Table 3 (some are assumed to suit the present requirement to design a standard aerofoil shape). Initially, to construct a single CSP, the values of 12 parameters (X, β , α , θ , etc.) are utilized and a master circle with radius Ra is sketched. Then, small concentric circles are constructed with their radius and center(s) based on the values associated with the intersection of percentages (X %) of arc length. Finally, CSP's are generated by connecting the

tangents of concentric circles belonging to a particular CSP. A schematic representation of the blade profile with A-A section with the dimensional parameters and the 3D model is shown in Fig. 4 (a) and (b).

Table.3 Partial details of parameters belonging to 12 CSP's

Parameter	CSP-1	CSP-3	CSP-7	CSP-12
Ra	231.3	266	353	398.8
X	240.6	239	235	23.2.5
f	19.57	19.16	15.65	12.77
β	52.50	46.70	38.50	32.90
α	37.5	43.3	51.5	57.1
θ	52.10	46.57	38.3	32.90
Z	101.28	101.20	100.98	100.27
p	32.70	25.81	16.08	8.65
X[%]	X in % of Arc length			
1.25	4.34	2.82	1.90	1.61
2.5	6.12	3.98	2.68	2.28
5.0	8.44	5.48	3.69	3.14
7.5	10.18	6.61	4.45	3.78

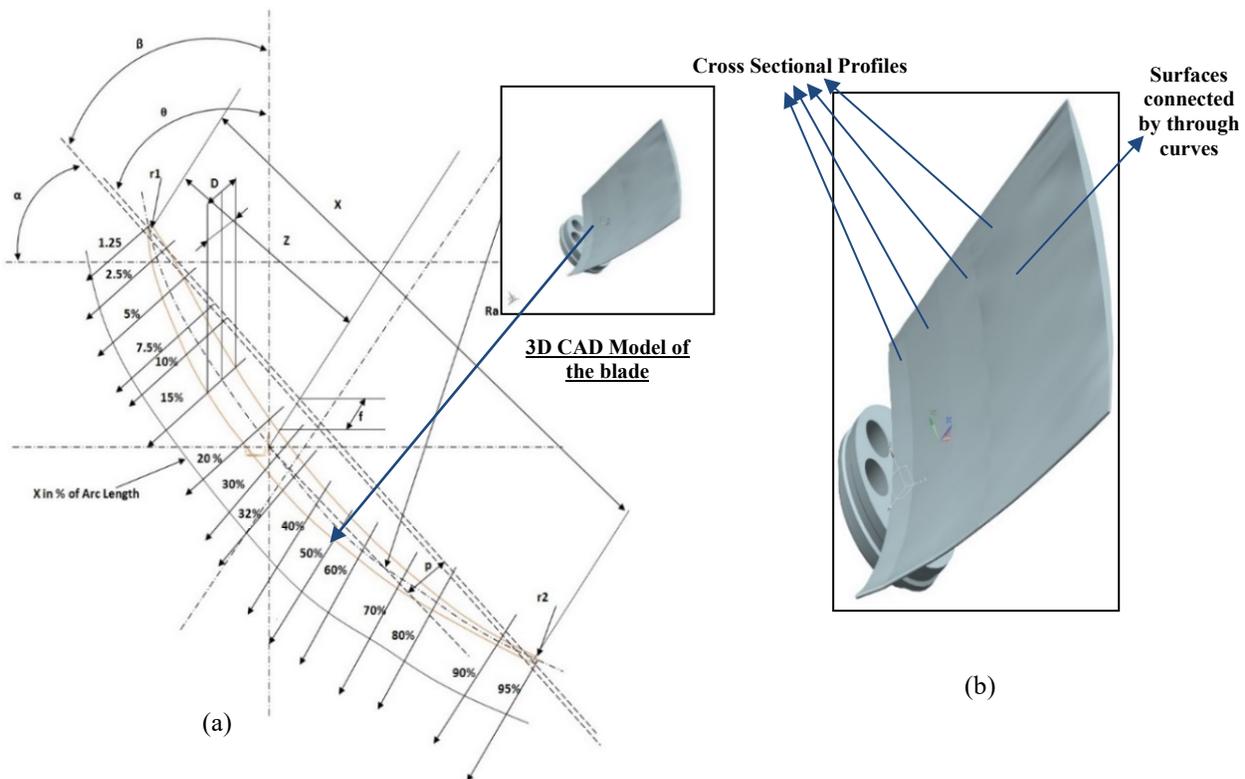


Fig. 4. (a) Blade profile with a single cross A-A section and (b) 3D model of the blade

3.1. Design of blades

As mentioned earlier, the construction procedure of a single A-A blade profile is complicated and is different from the impeller. To parametrize the model, the construction procedure must be understood first, and a high-level procedure is given in the previous section. The Fig's. 5 (a) - (c) are presented with the main construction steps, which aligns with the modelling of a single profile. Some important points on the construction include (i) drawing the circles (Fig. 5(a)) corresponding to the values given in Table 3 and (ii) drawing tangents of the circles to complete the outer sketch of blade profile (Fig. 5(b) & (c)). Based on this procedure, the final model and the associated drawing sheet is given in Fig. 5 (d). Once completed the parametrization task is taken up by considering the parameters directly from the dimensions linked with the CAD model. The parametrization procedure is not as complex when compared with impeller as most of the values are completed by linking a particular cross-sectional profile to the main expression.

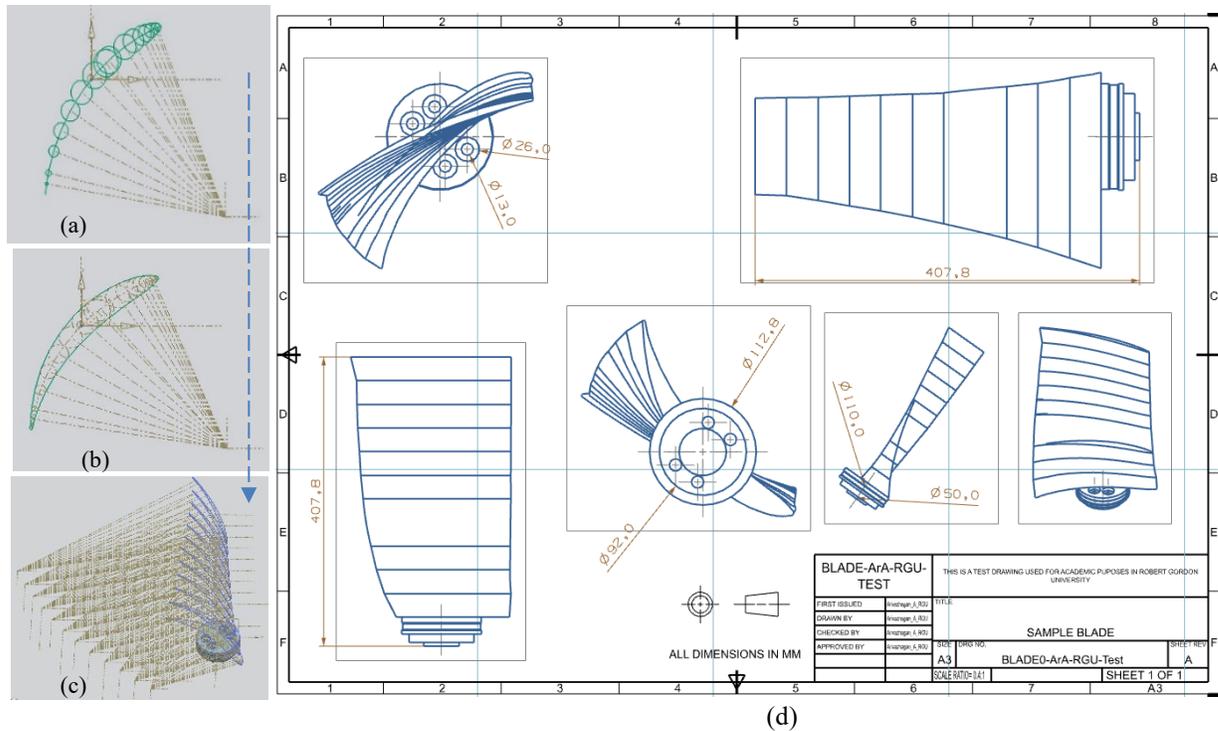


Fig. 5. Main construction steps (a) construction of circles (b) construction of tangents (c) completion of full profile of blade (d) associated drawing sheet of the blade

4. Digital twin-based automation of impellers and blades for immediate design / redesign

Automation is the process of designing models without the use of graphical environment. Models can be generated using any computer language and an API linked to the CAD package. In this research, Siemens NX Open API [20] is adopted for automation by recording the procedures through journaling. NX Open API is a collection of routines that allows programs to access and affect the NX Object Model. Based on these routines the following algorithms are developed to automate the CAD model generation considering the digital twin concept for immediate design / redesign of impellers & blades.

4.1. Automation algorithm of impeller

1. Initialize the program through API.
2. Create a new part file using the function "UF_PART_new (part_name,UF_PART_ENGLISH, &part)". (Define part name in the beginning generate the part tag as ID provided to the part file)
3. Obtain working coordinate system tag to determine the plane on which sketch needs to be developed; use wcs_tag using function "UF_CSYS_ask_wcs(&wcs_tag)"
4. Get the identifier for the matrix of objects attached to an object i.e., the data required to draw a line using function "UF_CSYS_ask_matrix_of_object (wcs_tag, &line1_coords)" (Wcs_tag is obtained in the previous step; line1_coords tag is assigned to the object identifier data. The start point and end point of the line are defined using line tags data structure.)
5. Get the identifiers for all the lines and curves that are required to be sketched and revolved.
6. Create a line using object identifier and assign an object tag 'line' to the result by using function "UF_CURVE_create_line (&line1_coords, &line[0])". (The data tags are declared at the beginning of the program.)
7. Similarly make all the necessary sketching to obtain the hub surface using lines and curves.

8. Enclose, all the lines and curves obtained in a list and assign a tag 'loop_list' to the list of objects using function "UF_MODL_create_list (&loop_list)".
9. Create a revolved surface from the sketch using function "UF_MODL_create_revolution (line, 5, trim_data, body_limit, offsets, origin, false, true, origin, direction, mode_sign, &objects, &obj_count). (The output after the revolution gives an array of revolved feature tags and number of features returned. The base part i.e., the revolved feature of the impeller part is now obtained).
10. Construct the blade profile, using the data points obtained for the blade base.
11. Join the data points obtained using the function "UF_CURVE_create_line (&line1, &objarray [0]);" and extract the line object data with the resultant line assigned with a tag to 'object_array'.
12. Create a link among the list of objects, the lines generated earlier and assign a tag 'loop_list2' using function "UF_MODL_create_list (&loop_list2)".
13. Create an extrusion over the sketching of blade profile using function "UF_MODL_create_extruded (loop_list2, taper_angle, limit1, ref_pt, direction, create, &features); The parameters involved in extruding a profile are the list of objects that to be extruded, taper angle i.e., the angle of inclination of extruding surface and base profile surface, limits i.e., offset to be provided for the extrusion from sketching surface along with the length of extrusion, direction axis to which the extrusion is to be made, the sign of the operation to be performed.
14. Save the part using function "UF_PART_save ()" and terminate the program using function "UF_terminate ()". An impeller with one blade over hub surface is automatically modeled using the above algorithm. Then the complete profile is generated and verified for various dimensions.

4.2. Automation algorithm of blade

1. Draw the half sectional view of base profile by drawing lines using line function UF_CURVE_create_line.
2. Revolve the half section about the axis using revolve function using UF_MODL_create_revolution.
3. Make a counter bore in the base profile using function UF_MODL_create_c_bore_hole; Draw a plane on the top of base using UF_MODL_create_plane.
4. Enter the plane no from 1 to 12. (for 12 CSP's); Define the coordinate system using UF_CSYS_ask_wcs.
5. Draw a line at given distance 'M' and angle from origin using line function; Draw another line at given distance L-M and angle from origin using the same line function; Draw a line with the offset value of 'P' from the line drawn before.
6. Draw another line, inclined at some angle to the previous line.; From the same point draw a circle with a radius R.; With the same radius R draw a circle from the other end of line P.
7. With the same radius R draw a circle from the intersection point; Create and Tag the reference point and reference curve.; Draw the lines from reference point to the trailing and leading edges of the arc using function UF_CURVE_create_line; Draw reference lines from the reference point to the reference curve.
8. Draw the circles with diameter as the thickness given on the points where the lines are meeting curve using function UF_CURVE_create_circle.; Creating a look up table containing the values of radius of circles to be drawn on the points of reference curve.
9. Drawing Tangents using UF_tangents.; Similarly draw all 12 profiles by generalizing and using a FOR loop.; Join all the profiles and generate the 3d model by using command UF_mesh_point_type.
10. Finally check the code by editing the values for a varied profile.

5. Graphical simulation of machining module for digital twin

5.1. Simulation of impeller and blade

After the CAD automation, complete manufacturing process plan is automated for impeller and blades. This section explains the manufacturing automation completed for milling process by journaling and customizing various steps to suit the impeller and blade machining. Owing to page restrictions only the simulation part is presented here.

Impeller: The strategy adopted for machining / generation of tool paths for radial impeller is based on (i) Cavity mill method for roughing (ii) Area mill method for semi finishing and (iii) Impeller hub / Blisk hub methods for finishing

operations. It is simulated for a Vertical Machining Center (VMC) XYZ 710 with a 5-axis capability considering ball end mills of sizes 12mm, 8mm, 6mm and 3mm. Table 4 presents the full process plan of machining the impeller with the exact process parameters (speed & feeds) and the stepover distance. Fig. 6 represents the free body simulation of the impeller highlighting the roughing, semi finishing and finishing operations. As the impeller blades are intricate free form shapes, special impeller machining methods are adopted in the finishing operations. Fig. 7 shows the exact digital twin model of the VMC machine simulated with the tool movements (fixture hidden) as the verification for final machining.

Table. 4 Process plan details of the impeller

S.No	Parameters	Roughing operation	Semi roughing operation	Semi Finishing operation	Secondary Semi Finishing operation	Finishing operation	Finishing operation
1	Type of Operation	Cavity mill	Cavity mill	Area mill	Area Mill	Impeller Hub Finish	Blisk Hub Finish
2	Diameter	12mm	8mm	6mm	3mm	3mm	3mm
3	Type of mill	Ball end mill	Ball end mill	Ball end mill	Ball end mill	Ball end mill	Ball end mill
4	No of Flutes	6	6	6	4	4	4
5	Length	75mm	75mm	75mm	75mm	75mm	75mm
6	Cutting Speed	100 mm/min	100 mm/min	100 mm/min	100 mm/min	25 mm/min	25 mm/min
7	Spindle Speed	1061 rpm	3979 rpm	5305 rpm	10610 rpm	2653 rpm	2653 rpm
8	Feed rate per tooth	0.2 mm/tooth	0.1 mm/tooth	0.2 mm/tooth	0.1 mm/tooth	0.03 mm/tooth	0.03 mm/tooth
9	Step over Distance	10mm constant	4mm constant	10% of Tool Diameter	1mm constant	10% of Tool Diameter	20% of Tool Diameter

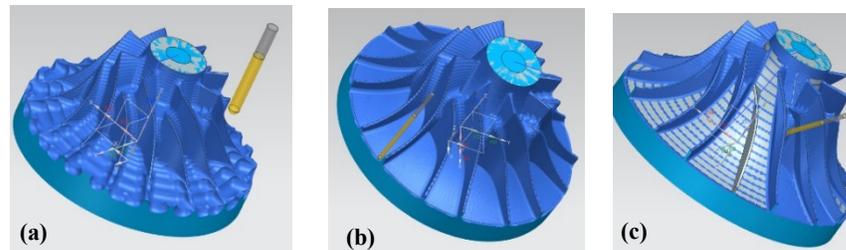


Fig. 6. Tool paths generated for milling of complete profile (a) roughing operation (b) secondary semi finishing and (c) finishing

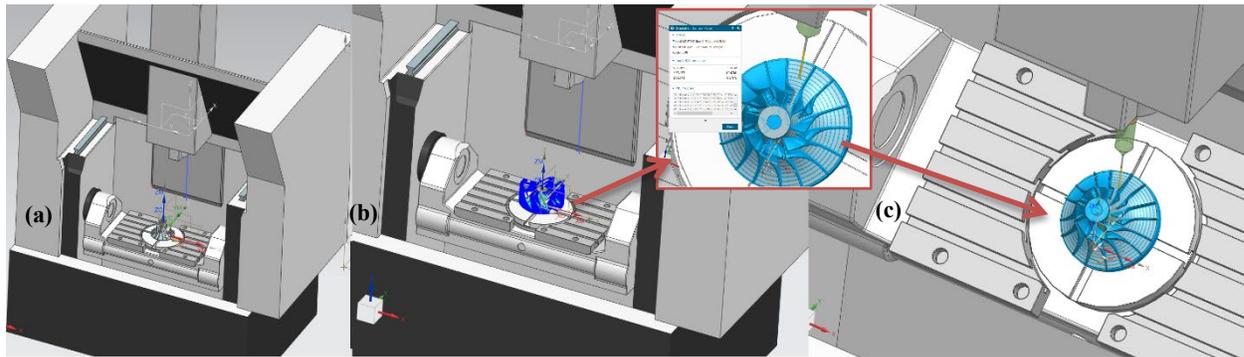


Fig. 7. A digital twin model of the actual vertical machining center with simulated toolpaths (fixture hidden) (a) setup of impeller (b) finishing toolpaths (c) simulation of the finishing toolpath in the exact machine

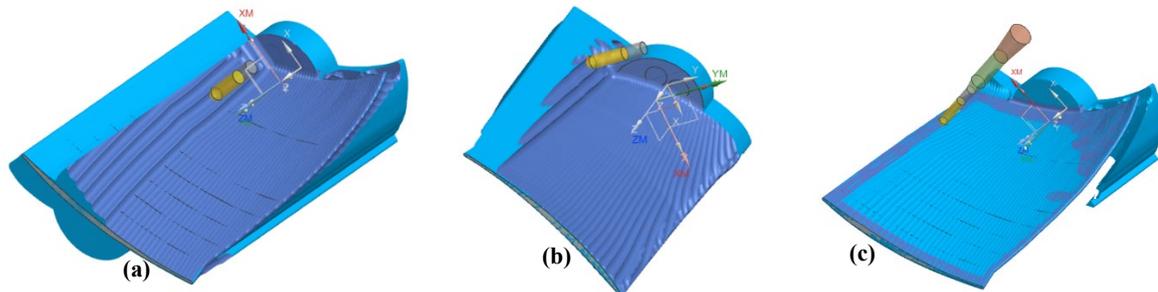


Fig. 8. Tool paths generated for milling of complete profile (a) roughing operation (top) (b) roughing operation (bottom) and (c) finishing

Blade : The strategy adopted for machining of blade profile is by (i) Cavity mill method for roughing operations (Top and bottom) and (ii) Area mill method for finishing operations (top and bottom). Owing to the nature of the blade profile the top bottom portions are machined separately and in a single setup. The same CNC machine tool simulated for impeller is adopted here as well. i.e., Vertical Machining Center (VMC) XYZ 710 with 5 axis capability. This is by considering ball end mills of sizes 16mm and 12mm. Table 5 provides the full process plan details of machining the blade with the exact process parameters (speed & feeds) and the stepover distance highlighting the roughing and finishing operations. Fig. 8 is presented with the free body simulation of the blade highlighting the roughing and finishing operations. Fig. 9 shows the exact digital twin model of the VMC machine simulated with the tool movements (fixture hidden) as the verification for final machining.

Table. 5 Process plan details of the blade

S.No	Parameters	Roughing operation (Top)	Roughing operation (Bottom)	Finishing operation (Top)	Finishing operation (Bottom)
1	Type of Operation	Cavity mill	Cavity mill	Area mill	Area Mill
2	Diameter	16mm	16mm	12mm	12mm
3	Type of mill	Ball end mill	Ball end mill	Ball end mill	Ball end mill
4	No of Flutes	6	6	6	6
5	Length	75mm	75mm	75mm	75mm
6	Cutting Speed	100 mm/min	100 mm/min	100 mm/min	100 mm/min
7	Spindle Speed	1989 rpm	1989 rpm	1061 rpm	1061 rpm
8	Feed rate per tooth	0.3 mm/tooth	0.3 mm/tooth	0.1 mm/tooth	0.1 mm/tooth
9	Step over Distance	15mm constant	15mm constant	10% of Tool Diameter	10% of Tool Diameter

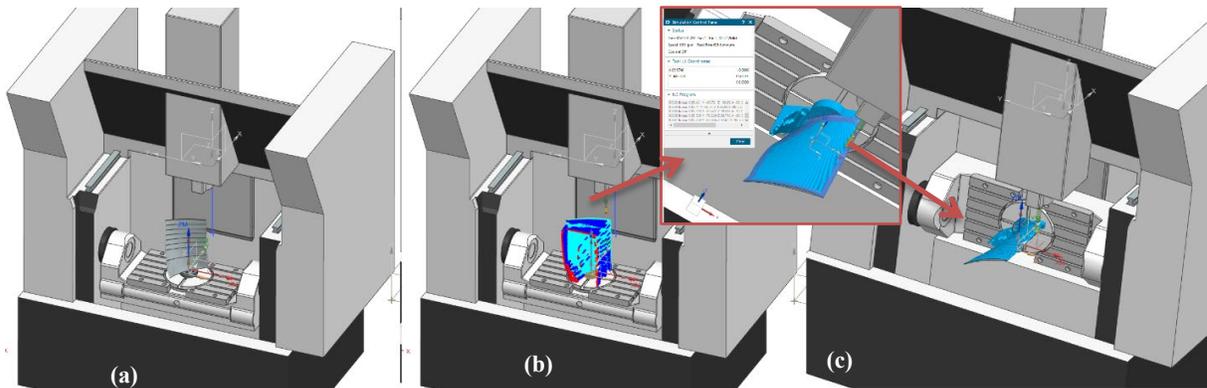


Fig. 9. A digital twin model of the actual vertical machining center with simulated toolpaths (fixture hidden) (a) setup of blade (b) finishing toolpaths (c) simulation of the finishing toolpath in the exact machine

6. Conclusions & Scope for Future Work

This work presents an initial study conducted for a digital twin capability through developing design and manufacturing methodologies considering immediate design / redesign of impeller and blade. This is by automating (i) CAD models and (ii) Manufacturing process planning activities of milling process. These tasks are accomplished by first recording the journals and later customizing them for the considered profiles i.e impeller and blade. The customization consists of four sub functions namely (i) automated design (ii) automated process planning (iii) automated tool path generation and (iv) automated simulation & verification. All these functions are linked with a main Graphical User Interface (GUI) developed in this work for immediate design / redesign considering required parameters. A user can select/ modify various impeller / blade parameters (presently limited to few features and their design) as suited for their industrial needs and can generate the complete set of data required for digital twinning. Options are being added for the user to upgrade the functions with different types of profiles available from various engineering domains. The work is ongoing with a planned scope of future work covering the aspects of obtaining live cutting tool forces, stresses / strains, vibrations, GD&T data through IoT based sensor integration.

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