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Research Article

Implementation of Computer Aided Engineering for Francis Turbine Development in Nepal

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The expansion of the existing industries involved in the production of components of hydropower to the Francis turbine manufacturer up to 5 MW unit size has been recognized as one of the most promising business models in Nepal. Given the current fact that the development of Francis turbines with the manufacturers of Nepal has not been done yet, due to lack of designing expertise and limitations in the available technology, this paper presents the use of different available manufacturing technologies, which is suitable in the Nepalese hydropower market. This is an experience based paper, in which the advanced manufacturing process implementing Computer Aided Simulation (CAS), Computer Aided Design (CAD), and Computer Aided Manufacturing (CAM) is introduced for turbine manufacturing. Moreover, CAD from Solidworks, 3D printing from Rapid Prototyping Machine (RPM), and manufacturing of three designs by three different methods, dye casting, lost wax casting, and forging in a local workshop, have been described. The outcome of this work is the identification of suitable Francis turbine development methodologies in context of Nepal, incorporating industrial revolution through research based products.

1. Introduction

Nepal is considered as a country having tremendous water resources. Despite the huge prospects of hydropower development, the past 100 years has shown a very poor track record in this country, with only about 2% of the total feasible potential harnessed so far. With the growing energy demand escalating worldwide, most of the hydropower development projects are shifting towards the unexplored regions of Asia and South America. Apart from the economic and political instabilities, the countries in these regions bear their own specific technical challenges with the prominent sediment erosion of turbine components.

Nepal has an inevitable problem of erosion wear of turbine parts due to abrasive sediments present in rivers, with high amount, particularly in Monson seasons. This has created several challenges in operation and maintenance of turbines causing financial losses [1]. Nepal also lacks competence to design and manufacture electromechanical components required for hydropower projects. In particular, Nepal does not have any experience of turbine manufacturing above 100 kW size. Both developers and manufacturers have identified need of local competence to design and fabricate turbines for future hydropower development in Nepal.

It has been forecasted that the demand of electrical energy in Nepal will reach 3,600 MW by 2027. Most of the turbines installed in Nepalese hydropower projects are imported from European manufacturers. Some of the power plants have also started using Korean and Chinese runners due to financial benefits, especially in small power plants. There are around 27 manufacturing companies developing micro hydro turbines (less than 100 kW size) in Nepal, but with competences only in the area of Pelton and Crossflow turbines. However, according to a survey [2], in Nepal, more than 50% of turbines under construction fall under the unit size of 1–5 MW, majority of which falls under low speed number (0.2–0.3) type of Francis turbines, which are compact and highly efficient types. In coming years, Nepal will also need such turbines with unit size up to 25 MW in significant number.

With the advancement in the manufacturing industries and technologies in the field of hydropower that has been observed, growing rapidly over the past few decades, Nepal has to catch up the pace by implementing technologies relevant to its economic condition. This paper has sought

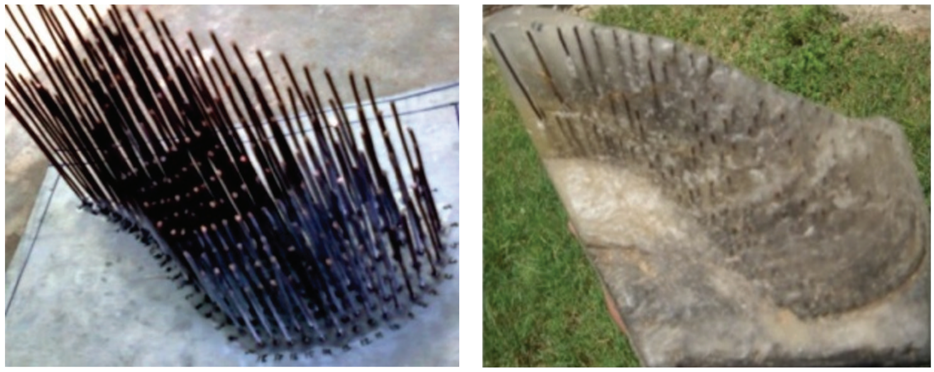


Figure 1: Wax pattern for visualization of Francis blade.

to discuss some recent endeavors carried out in design and manufacture of Francis turbines blending some state-of-the-art technologies with traditional approaches as a sensible path to move ahead.

2. Worldwide Evolution of Francis Turbine Design and Manufacturing

Experiments on the mechanics of reaction wheels were initially commenced by the Swiss mathematician Leonhard Euler and his son Albert in the 1750s. Later in 1826 Jean Victor Poncelet of Francis proposed the idea of an inward flowing radial turbine, the direct precursor of the modern water turbine. This machine has a vertical spindle and a runner with curved blades that was fully enclosed. A similar machine was patented in 1838 by Samuel B. Howd; this design was later improved by James B. Francis in 1849 by adding stationary guide vanes and shaping the blades so that water could enter at the correct angle. This design was named as Francis water turbine [3].

In the initial phase, Francis turbines were designed based upon specific requirements with no intense research related to the change in the blade shapes due to varying operating conditions. Gradually, the need of optimizing the efficiency with the working condition was felt, which resulted in implementing mathematical relations and numerical calculations in an iterative loop so as to obtain satisfactory values by changing the variables within the allowable range. However, during those times, the testing of the designs could not be done in virtual environment, nor could they be visualized three-dimensionally. Hence, the analytical methods could only be complemented through manufacturing. The turbine manufacturing trend has shifted from riveted plates and casting to fully automated manufacturing [4].

The manufacturing was performed in the form of single casting or part casting and assembly by unitary process. They were made of iron, steel/bronze. Most common methodology was to develop partly by sheet metal and partly by cast metal and unite them. C* Blade S.p.a. Forging and Manufacturing, an Italian company from 1963, implemented forging technology during its starting phase for power turbine manufacturing [5]. This forging technology is a component of the part casting where blades are forged whereas hub and shroud are casted and assembled together [6]. Figure 1 shows a wax model developed from radial and axial view coordinates of blade to create pattern for profile. Although this method is a type of traditional Prototyping Technology by using wire supports, it gave a useful understanding of how the relative velocity distribution in the blades results in the complex profiles along the stream-wise direction.

The traditional technologies had obvious limitations in terms of time consumption, accuracy, efficiency, and problems related to cavitation and vibrations. Hydraulic turbines and, especially, Francis turbines are considered to be tailor-made designs, where the profile of the runner blades, guide vanes, and stay vanes changes with the hydraulic design parameters. Hence, the design and manufacturing process was needed to be integrated with modern and suitable technologies for quality and time relevant designs.

Current design trend implements advance and more reliable process for turbine design and development technology. The modern trend used CAD/CAM/CAE integrated environment to increase the blade quality and decrease the time consumed for the design and the manufacturing processes. The use of CAD also enhances the ability of an organization to work in competitive environment to design site specific turbine [7]. There are various processes involved in blade manufacturing, including the development of solid model, testing, and optimization using numerical techniques and experimentations [8]. In order to carry out the manufacturing, a complex five-axis milling machine is used to develop the surface profile of the runner with high precision [9]. Figure 2 shows turbine manufactured by this process and Francis turbine of 700 MW installed in Three Gorges Power Plant (22.5 GW). These pictures show that the world has exhilarated rapidly in terms of manufacturing turbines by introducing new technologies within the past few decades.

3. Possibilities of Turbine Design and Manufacturing in Nepal

The feasibility study of turbine manufacturing in Nepal has shown that Nepalese manufacturer has an amiable future in the field of Francis turbine manufacturing [2]. At present,

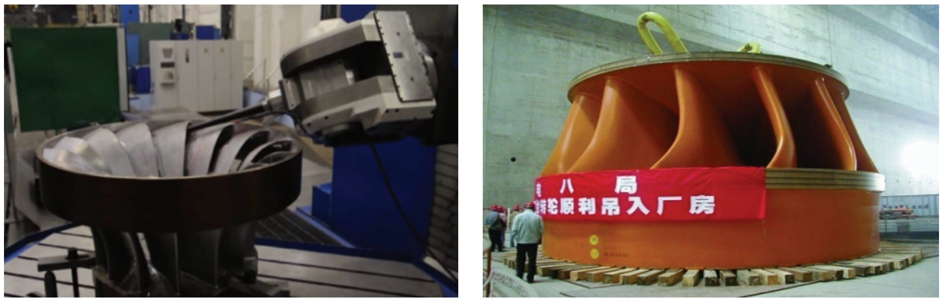


Figure 2: Francis turbine manufacturing with new technologies [23] and the turbine in Three Gorges Power Plant of China [24].

(a) Turning turbine component

(b) Casting turbine blade

(c) Assembling runner hub, blade, and shroud together

Figure 3: 92 kW Francis turbines manufactured at NHE, Nepal.

the Francis turbines installed in the power plants of Nepal are being imported from manufacturers abroad. It is understandable that the turbines in the large hydropower plants need a certified company, equipped with design expertise and technological advancement. Although Nepal has around 27 manufacturing companies working in the field of hydropower sector and some of them having the capacity and motivation to manufacture turbines up to 5 MW, they are quite reluctant to bear the risk of Francis turbine manufacturing due to lack of competences.

At this moment, Nepal has developed sufficient background and technical competency to start up turbine manufacturing business. Kathmandu University has been putting its effort into development of hydro turbines in Nepalese context. Research for hydro turbines at KU had started in the late 90s with two miniature turbine laboratories named as Pico Turbine Laboratory and Waterpower Laboratory. Later in 2009, a new Turbine Testing Laboratory (TTL) was constructed with financial support from Norway. This lab possesses a long term goal of creating an excellence for turbine design, testing, and manufacturing Francis turbines in Nepal. It has performed several research based studies addressing the challenge faced by Nepalese hydropower plants, especially due to sediment erosion. Most of the computer aided technologies described in this paper was commenced from the research activities carried out in the lab, mostly in collaboration with Waterpower Laboratory at NTNU, which has experience of turbine testing for almost 100 years.

Some of the manufacturing experiences in Nepal have also shown that some manufacturing companies in Nepal have good competences in the field of Francis turbine manufacturing. Figure 3 shows processes involved in manufacturing a 92 kW Francis turbine at Nepal Hydro and Electric Company Pvt. Ltd. (NHE). The design of the turbine was carried out at TTL, with the motive of comparing the performance of conventional design with the optimized design, in terms of efficiency and erosion through testing. Although it was for the purpose of testing only, this turbine happens to be the first Francis turbine that was designed and manufactured in Nepal.

This initiation of turbine manufacturing has led to a need of endeavors for expanding the manufacturing arena of Nepal to another level. The processes used in manufacturing the turbine in the figure are discussed in latter sections of this paper.

4. Design and Computer Aided Simulation

4.1. Hydraulic Design. Turbine Testing Lab, since its earliest days of concept formulation, has good relationship with Water Power Laboratory, Norwegian University of Science and Technology regarding the technology and faculty exchange. Particularly, in the field of the design of Francis turbines, there have been close cooperation and activities between these partner institutions. With a combined effort of academic exchange program, the institutions were able to design a MATLAB based code called *Khoj* [10]. The prime design stage in Francis turbine is the iterative simulation for the suitable result. The head and flow are the two major design parameters which use additional supporting design variables like tangential component of velocities and their angles. Manual iteration for the suitable design outcome is complicated; hence it requires integration with state-of-the-art programming. In this case MATLAB based GUI system is developed for hydraulic design of Francis turbine. This step reduces the bulky iteration stage, since all the calculations will be performed with the selection of iteration driver.

4.2. Hydraulic Design Simulation. Once the design is developed from the design tool, it is also essential to interpret the performance of the design by simulations. The fluid domain involved in the turbine passage is simulated using Computational Fluid Dynamics (CFD). They are the numerical simulation on the discretized flow field for estimation of the performance. Although there is always certain level of deviance in the result compared to the experimental study and the actual condition, the result of CFD gives a comparative idea for estimation. Commercial tools or in-house codes can be used for this kind of fluid flow simulations. They use the basic governing equation from Navier Stokes equation with turbulence model along with the boundary conditions on the discretized geometry of the turbine system. The design given by the MATLAB code is imported to these solvers, where various parameters such as turbine efficiency, erosion, and cavitation can be observed in varying conditions [11]. Using this technology, a large range of the designs can be tested at low cost and based on the result; a design optimization can be carried out to proceed into the manufacturing process.

4.3. Mechanical Design. Along with the hydraulic performance, the rigidity of design is another significant prospect. Whereas the hydraulic simulation provides the pressure acting on the blade due to the water flow, the structural simulation shows whether the blade is able to withstand the pressure or not. This depends on the mechanical properties of the blade, such as its density, elasticity, geometry, and orientation. A separate computer simulation including Fluid Structural Interaction (FSI) is performed to relate the fluid flow with the structure [12]. Figure 4 shows some of the results of the Computer Aided Simulation done in the premises of ANSYS.

Once the result of iterative design and simulation is satisfactory in terms of performance, flow, and structural rigidity, the design is adopted and further processed for CAD development.

5. Computer Aided Design (CAD), Modeling, and Workshop Drawing

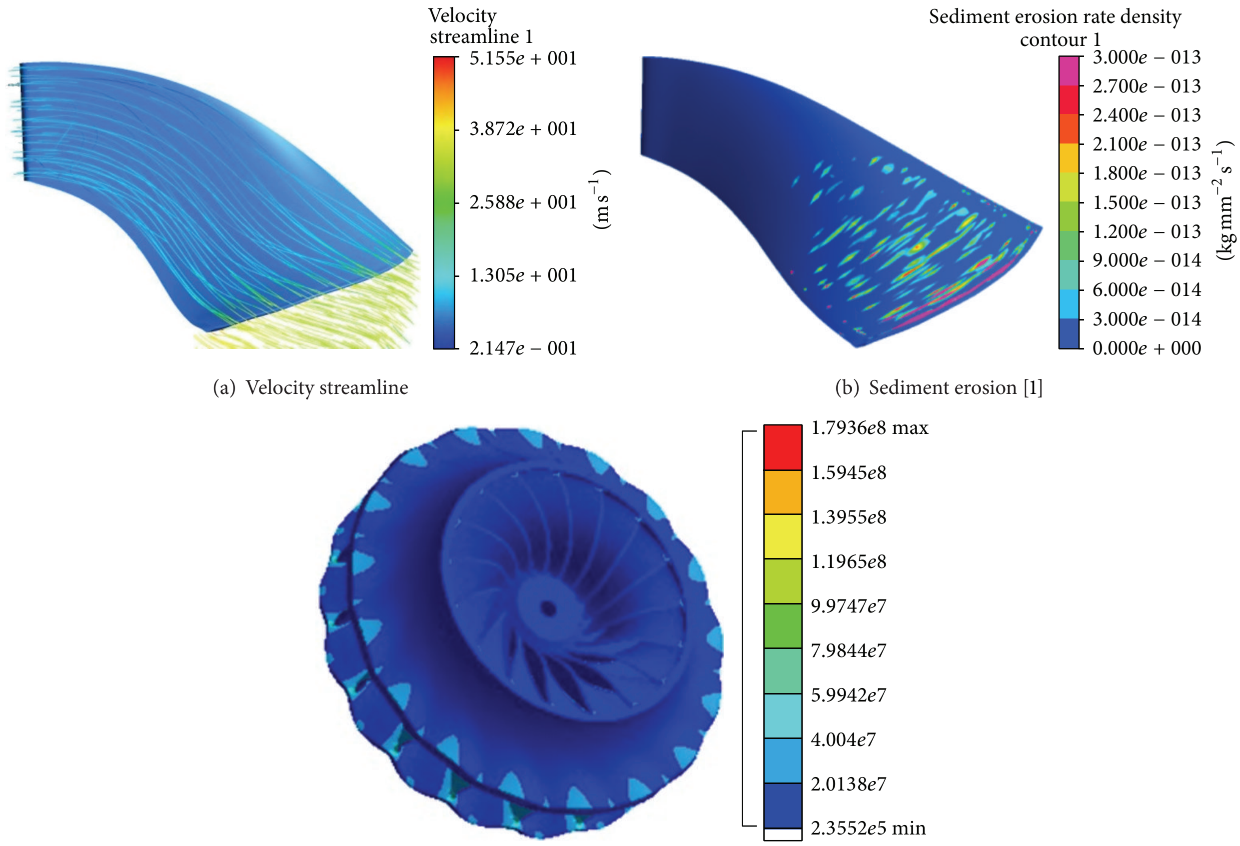
This is the stage in which the design performed is expressed in the form of 3D which latter is projected to 2D drafting. The main objective of this stage is expressing the design in the understandable form. 3D CAD visualizes the design and drafting creates comfort in the manufacturing.

5.1. 3D Drawing. The accepted hydraulic design with the allowable stresses on the thickness provided is primarily drawn in 3 dimensions in order to visualize the position and finalize the assembly in more realistic form. The features of the 3D CAD software allow us to predict the material use to preestimate the cost effectiveness of the design [13]. This operation is performed under the premises of Solidworks with easy and comfortable interface. Each component of the system is developed referencing the common origin in different files called part files. These files are later combined together in the assembly window of the workspace. The major features like sketch extrusion, revolution, reference, pattern, sweep, blend, and so forth are used for the 3D CAD.

5.2. Drafting. The next step in CAD is the design drafting. It is the process of the drawing that is understandable by the manufacturer. The standard guideline of either third angle or first angle is implemented for projection of the 3D drawing. The drawing window of the program produces the projection drawing in the relevant scale. The main advantage of adopting this kind of feature instead of traditional method of direct development of 2D is to prevent probable mistakes in the drawing since they are developed from 3D after observation and visualization of design. Figure 5 shows the difference in 3D modeling and drafting, in relation to the presentation of descriptive process in this method.

6. Computer Aided Manufacturing and Workshop Manufacturing

6.1. Computer Aided Manufacturing. This is the physical replication and product development stage involved in the manufacturing process. As discussed in the earlier sections, Francis turbine blades, guide vanes, and stay vanes are complex designs which need to be physically replicated as



(a) Velocity streamline

(b) Sediment erosion [1]

(c) Stress distribution on the runner

FIGURE 4: Computer Aided Simulations, [25].

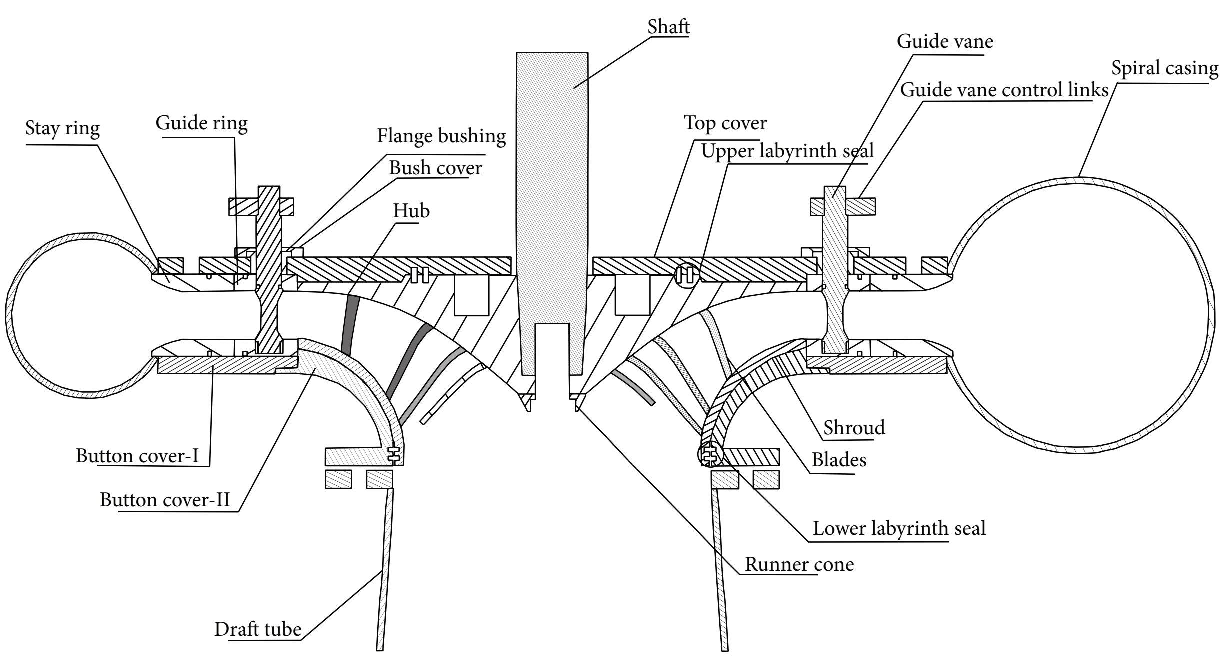


FIGURE 5: 3D modeling and drafting of a Francis turbine.

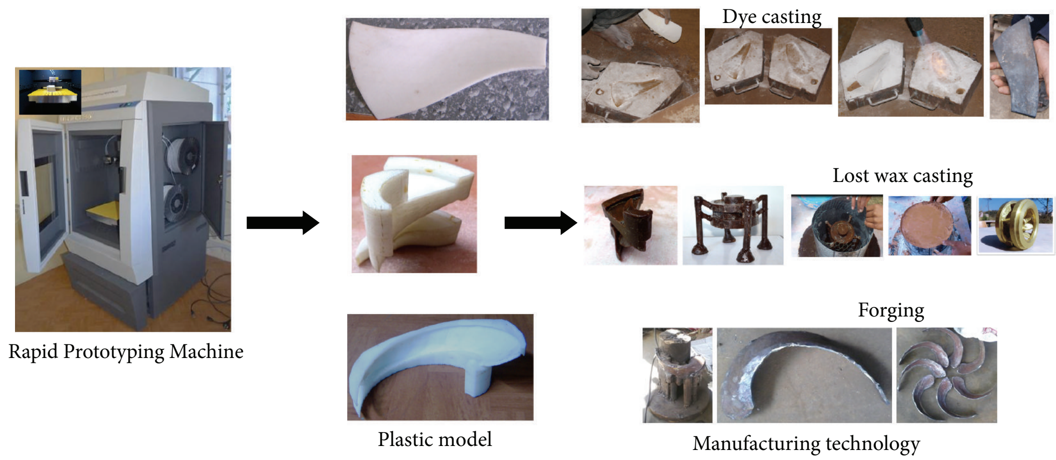


FIGURE 6: Computer Aided Manufacturing and Workshop Manufacturing.

accurately as possible for the expected performance. Hence, another advanced method called Computer Aided Manufacturing was needed, which performs Rapid Prototyping (RP) of a 3D model. RP is frontier technology which reduces time and increases accuracy for design verification by producing solid model from 3D CAD [14].

The complex geometry like runner blades or the entire runner is casted. To ascertain the design reliability accuracy of the designed CAD and its physical replication, dye plays the major role [15]. In such a scenario, Rapid Prototyping proves to be an efficient machine which helps to replicate the designed models in the form of plastic, which can be later converted into metal pieces at a nominal cost [16]. RP helps in minimizing the risks and maximizing the quality to overcome the gap of experience.

Currently, TTL acquires Inspire D290 3D printer which operates on Fused Decomposition Modeling (FDM). FDM is an additive process that involves heating a thermoplastic material's wire filament which is fed to a moving head and squeezing out of tube, which traces the area of the layer and deposits the filament on the surface. FDM is regarded as one of the effective RP techniques for fast, cost effective, and dimensionally correct product development. This method has been found effective in aerospace applications [17]. Once deposited, the material solidifies and adheres to the previous layer. The table moves through small distance in vertical direction (Z-direction) to create space for the formation of new layer while printing head is moving in X-, Y-direction. The material used in our case is Acrylonitrile Butadiene Styrene (ABS) polymer [18]. The product thus created will be very suitable for developing the mould in investment casting. So far the practices have showed that FDM plastic products have proven themselves to be effective casting molds [19].

The 3D design of the blade developed in Solidworks is now provided with required tolerance and file is converted into *.stl* file, which is readable to the printer. The printer has an integrated computer interface for printing arm initialization, height definition, fineness, temperature control, and so forth. Once the model is loaded, the major operations are performed to export the design to the SD card installed in the printer. Now, the printer displays the estimated time and materials for the printing permission. Once every requirement is defined, the printing starts. The printing device uses software packages: model wizard for 3D model processing, which is 3D slicing software. Table 1 shows the specification of the Rapid Prototyping Machine, which is at TTL.

TABLE 1: Specification of the Rapid Prototyping Machine.

Particular	Description
Build volume	$320 * 290 * 255$ mm (23.7 litres)
Layer thickness with 1-nozzle layer	100 microns/0.1 mm
Layer thickness with 2-nozzle layer	150 microns/0.15 mm
System size in mm	$720 * 850 * 1650$ ($W \times D \times H$) mm
Support material	ABS (Acrylonitrile Butadiene Styrene)
Operating speed	5–60 cm^3 adjustable
Power	220–240 V, 10 A
Software compatibility	Windows* XP/windows* 7/windows* 8

6.2. Workshop Manufacturing. The physically replicated guide vanes, stay vanes, and blades through the RP machine are then processed for manufacturing. The guide vanes and stay vanes are comparatively easier geometry; hence either of the casting technologies can result in a fine product with further possibility of postmachining. However, with the runner and the blade geometries, several constraints are to be considered, either single casting or part casting.

In this section, three of the major experiences of Turbine Testing Lab are presented.

A 92 kW runner designed under a NORAD funded project was manufactured by integrating two technologies.

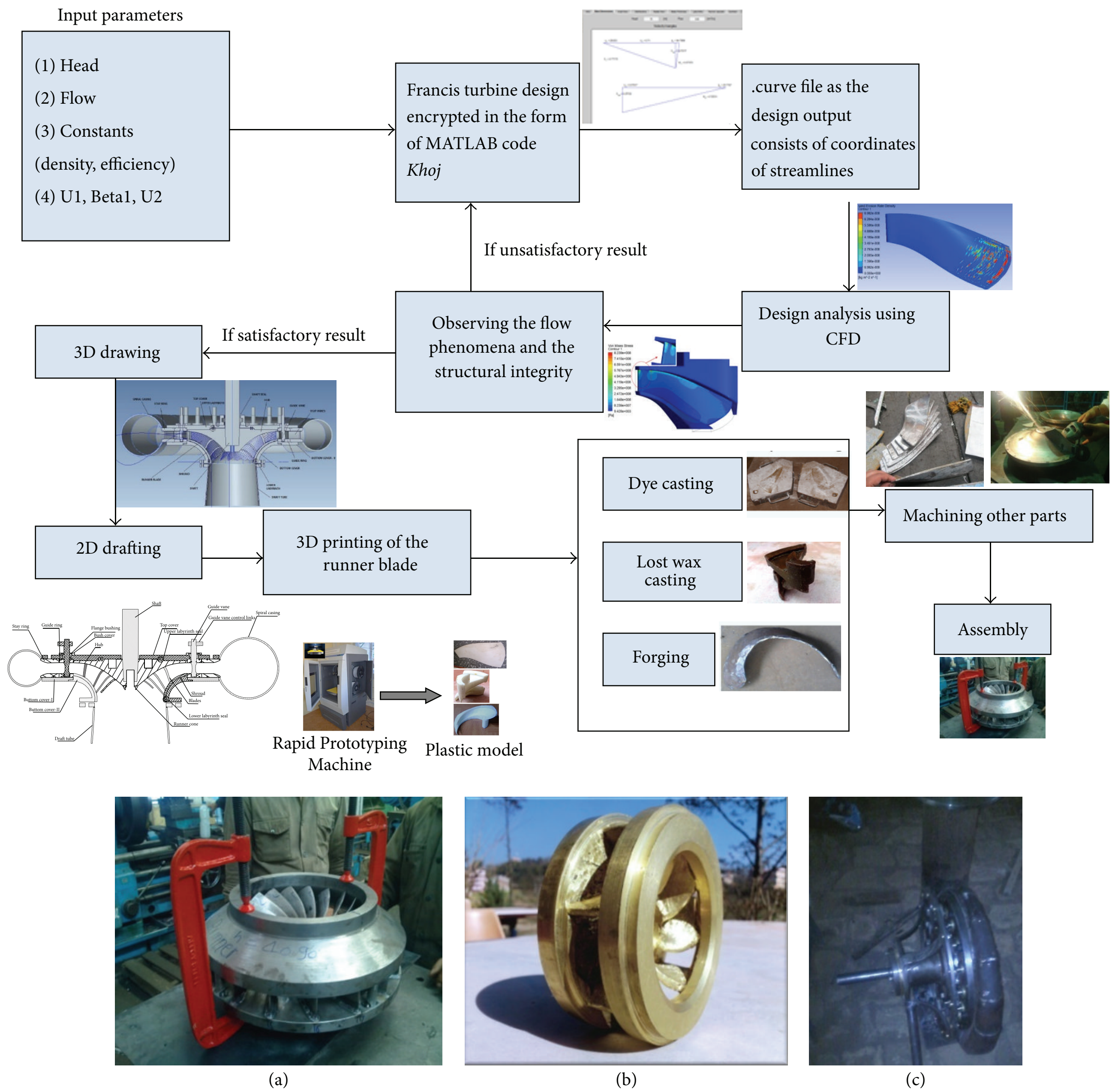


Figure 7: Flowchart of the methodology adopted in Francis turbine manufacturing and the turbine manufactured through (a) dye casting, (b) lost wax casting, and (c) forging.

The hub and shroud are machined and blades were dye casted. Later all these three sets of geometries were combined using welding technology [20].

In another activity for feasibility study of turbine manufacturing company in Nepal, a 2 kW Francis runner was casted using lost wax casting technology and finally buffed for surface finishing.

In one of the recent projects of 1.6 kW Reversible Pump Turbine the blades geometries were almost semicircular; hence it was very difficult to follow either of the above two technologies. Hence, a different but comparatively more traditional approach of forging was implemented, where the prototyped blade pattern was used as the quality control agent for forging. Figure 6 explains all three technologies implemented [21, 22]. All the other supporting components associated with Francis turbine are machined and finally assembled. Thus manufactured turbines will be assembled to the main turbine component comprising of spiral casing, guide vanes, stay vanes, and draft tube. Since the casting moulds and forged blades are created with allowance, postmachining allows for the assembly within the preestimated dimensions. The paper focuses on the manufacturing implementations; hence, performance-wise effectiveness of the process has not been considered.

7. Summary

This paper discussed possibilities of implementing Computer Aided Engineering in Francis turbine manufacturing in Nepal. It was discussed that, in the course of few years, most of the new hydropower plants in Nepal will need Francis turbines, based on the operating regime assessed. As the manufacturing companies presently available in Nepal have not manufactured Francis turbines, the future endeavor in making an attempt of up to 5 MW turbines can thrive the industries and hydropower market in Nepal. The design competences possessed by Kathmandu University can be blended with the available technologies discussed in this paper to manufacture turbines in much cheaper rates. Also, with the design optimization techniques, the turbines can address local problems of erosion, which would otherwise not be possible in the case of imported turbines. The different aspects of turbine manufacturing discussed in this paper are summarized in Figure 7. The experiences shared in this paper of manufacturing three different types of turbines from three methods urge the expansion of the manufacturing arena of Nepal to another level.

This work is more focused on uplifting the micro hydro status of Nepal by developing Francis turbine manfacturing facility in Nepal. The proposed methodologies can be implemented for turbine manufacturing by adopting the design and Rapid Prototyping facility available at Turbine Testing Lab. The manufacturing facility available with the local manufactueres is sufficient to manufacture it.

The future research should focus on the performance of the turbines manufactured with different processes. Additionally, economical and simple assembly design for promoting local manufacturing should be prioritized.

Conflict of Interests

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

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