




Augmenting mechanical design engineering with additive manufacturing

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Abstract

In the prevailing education system, the present method of learning involves retaining theoretical concepts, math-based problem-solving, and depiction or realization of design through two-dimensional pictorial representations, thus lacking a hands-on experience of the product development and the manufacturing process. The future belongs to product design management via additive manufacturing/3D printing. Giving hands-on experience to students during the course work is the need of an hour for competing with the world of manufacturing automation with quick response strategies. The current work describes the method of augmenting 3D printing technology into the traditional deductive approach of design process learning using case studies that involve real industry-based scenarios to develop a product for a specific operation, allowing students to experience an entire product design cycle. The cases reported under this project-based learning are fastening nut; knuckle joint; rolling contact bearing; Venturi meter; spur gear; epicyclic gear train; Pelton turbine and connecting rod. This paper presents the proposed approach's effectiveness in improving critical thinking, design cognition, motivation, and the preparedness of the students for the industry. Also, the results of an empirical assessment performed on a small group of students show the impact and adaptability of the method toward students, and the scalability of the proposed approach to other disciplines. It was also observed that the student's learning, understanding of concept, creativity, imagination, confidence, and designing ability were effectively improved after augmenting 3D printing which was validated with the results of the selected group in internal and external examinations of the Institute and in the competitive examinations. Further, these selected students have also been placed in highly reputed companies in the design and automobile engineering domain.

Keywords 3D Printing integration · Evaluation methodologies · Improved classroom teaching · Collaborative learning

1 Introduction

In the general run of things, engineering education especially in the domain of designing has been enlightened in 2D space that starts off with abstract theory, overemphasizes the use of formulas and math-based problem-solving, shows the pictorial representations of concepts, and lacks practical measurement and product-based outputs, leading to

conceptual misinterpretation. The need is felt to modernize the existing learning approaches by adding real-life application tools and enabling students to experience and deal with various situations existing in the professional set-up. Supplementary practical knowledge along with an understanding of theoretical concepts is required to make students sociable and self-confident when they are engaged in industrial applications. The exigency to update the instructing methodology in engineering to pace up with continuously evolving technological advancements prevails in almost every field and society, with the primary focus to preserve the student's skills and generate intrigue in their learning [1]. The cognizance of design process and its application is a fundamental learning objective for all engineering students during their undergraduate education.

Mechanical Engineering is a discipline with robust activity in instructing, investigating, and practicing. Mechanism

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of machines, machine drawing, machine design, fluid mechanics, and hydraulic machines are recognized as fundamental core courses for mechanical engineering since the beginning of engineering practice that every student must undergo for developing lucrative systems that operate in the mechanical world of human beings. The existing way of commanding in these courses is mathematical and analytical, and students are somewhat humdrum academically disengaged and deficient in the latest technologies and in critical thinking skills [2]. Pedagogy for design courses impacts design cognition along with experience and awareness of students about the phases of product development [3].

The contrast between the learning methods and the real-life applications involved in designing is the prime reason for the incompetency of the current instructing methods in preparing industry-fit students in that the students are unfamiliar with the actual products and in what they design or develop [4, 5]. In general, students are unable to discover a way how to transform their logical skills or learning in product development to real-life applications through critical thinking, although having the capability to create and innovate [6]. Student adaptation to computer-based technologies and interactive learning environments develops self-confidence combined with professional skills [7]. The use of physical models of machines and engineering elements to demonstrate the theoretical concepts are considered as a fundamental tool of design and have been used to assist in the learning process of design courses which will help the students to facilitate product development decisions and business strategies in industries [8, 9]. Particularly, prototypes and models developed through 3D printing serve several purposes, including providing a demonstrative form of the final products and allowing feedback for revision and improvement within the design process. The conventional methods to make these models are costly and take a lot of time and effort though. This is where the 3D printing technology comes into the picture, with its rapid prototyping process which eases the fabrication of design models for the students. Even after 30 years of its inception, the benefits of 3D printing are still unknown and under-utilized for the good of the society. Snyder et al. [10] have presented an overview of 3D printing technology and its applications in education, engineering, manufacturing, and science.

Comprehending spatial material can be exceptionally difficult through traditional learning methods and textbooks with two-dimensional pictures of complex three-dimensional information, leading to a reduction in grasping and retaining new information [11]. In general, students are constrained of having limited necessary tools at their disposal and are unable to make the transition to a hands-on approach. Thus, creating an atmosphere where students can work on 3D CAD with great visualization options will help them to get a superior overview of mechanical or technical

aspects of designing for different parts, whereas the 3D process will allow them to calibrate and refine parts quite efficiently [12, 13]. Proficiency, in parametric design software and 3D printing, is now a requisite component of modern design and engineering, which not only adds several technical skills under their belt but also provides courage and confidence to the students.

The vast range of applications of 3D printing and the curiosity to experience this game-changing technology has resulted in a dramatic rise in its use in educational institutions, by both teachers and students, as a tool for rapid innovation [14, 15]. The technology is utilized for printing scaled physical models by teachers for a demonstration to aid in learning, as well as printing parts for project works by students. Thus, it seems highly reasonable to incorporate this technology into the academic curriculum from school level up to engineering undergraduate courses [16]. The labs in school level have been started to benefit from 3D printers and with the use of digital technologies, students find an easy connection with their subjects. The advent of 3D printing technology has provided enhancement in students' engagement via hands-on learning opportunities through enabling them to print 3D physical models which are easy, quick, accurate and less costly using 3D CAD models. For example, one of the universities namely Dayalbagh Educational Institute provides ample opportunities to the students to experience 3D printing technology and work in this domain to keep them updated with the latest advancements in the field [17]. The variation in various parameters of 3D printers, such as infill design pattern, infill degree and orientation, density, etc., can result in a wide range of values for strength and surface finish for the fabricated parts and students can get desired properties in the printed parts by altering the process parameters [18–20]. These knowledge and experience on 3D printed prototypes provide a way for students to explore their designs, inspect the existing models, and easily produce different prototypes in a short period of time. The use of 3D Printing will further generate curiosity in students to explore different aspects of designs and improve their abilities to visualize the design in a physical form, resulting in a boost in their creative and innovative capabilities [21–23].

The utility of additive manufacturing in supplementing the design learning process for engineering students is now well established and we can see continuous research and study being done in this area to improve the teaching method and structure of design courses [24]. There are several studies attempted to evaluate the impact of direct access of 3D printing or additive manufacturing on education at various levels ranging from high school students [25, 26] to those enrolled in a master's program at a university [27, 28] where a number of different parameters were investigated. For example, the study conducted by Tian Chen, et al. on the

impact of an additive manufacturing exercise on student's design skills showed conclusive evidence of the effectiveness of AM process in helping the students to create feasible designs and fabricate functional products [29]. However, this study is limited to only a single project which is not related to real industry-based problems. The present research takes one step further in utilizing AM techniques for better learning of design courses by allowing students to 3D print real industrial products being taught in their current curriculum. Also, the current work has been inspired by the study of M. A. Seif et al. on teaching design courses through a practical approach using some case studies [30] and its multifaceted merits. In the current paper, case study-based product development has been investigated through 3D printing which allows students to get exposed to the product development cycle being implanted at professional level in the industry. The eight case studies used here to integrate additive manufacturing and design learning process are introduced to students with the objective of providing them with sufficient exposure to 3D printing, CAD designing, and industrial applications [31, 32].

The adoption of Industry 4.0 practices in the professional work set-up has made it crucial for engineering students to have some experience of the industrial works. The project-based learning approach utilized for this research would be ideal for this purpose [33, 34]. The uniqueness of this present research comes from the fact that apart from considering factors, such as student feedback, motivation, and project results, this study also emphasizes on the performance of the students with respect to industry for further evaluation. It represents efforts to integrate additive manufacturing (3D printing) into existing knowledge delivery method for designing courses by exposing students to the actual cases of product design prevalent in the industry. The existing method of knowledge delivery for mechanical design courses is shown in Fig. 1 which lacks the provision to expose students to the physical development of design, one of the key objectives of this study. This is achievable using carefully designed case studies which are undertaken by a limited number of students to get an insight into the impact of 3D printing technology in teaching of mechanical engineering design. The purpose of this work is to revamp the undergraduate mechanical engineering curriculum, focusing on the design process, creativity skills, and methodologies and also making explicit connections for student perceptions about what an engineer is expected to do in the real world [35]. Incorporating 3D printing in design courses will enhance experiential learning and affects the practicality of engineering design pedagogy to a superior level in terms of performance and learning outcomes of students.

This work will serve as the basis for setting up the foundation of a novel teaching method involving the inclusion of 3D printing technology into fundamental core design

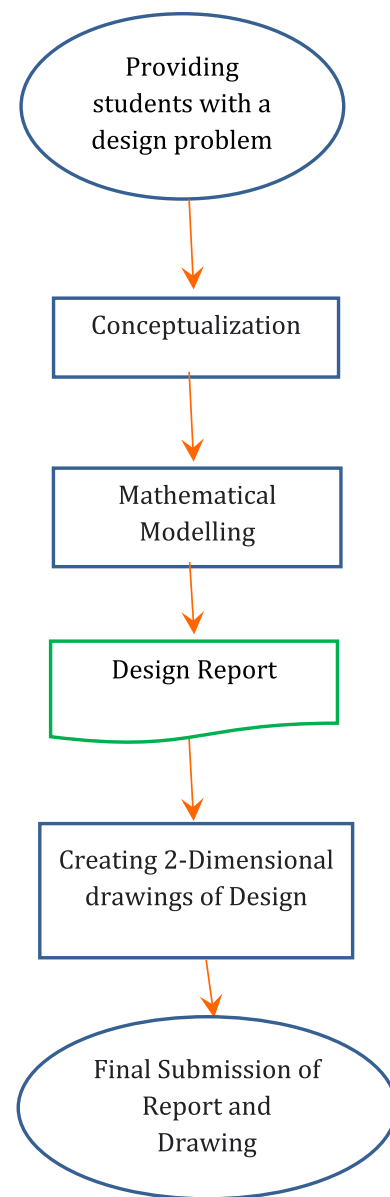


Fig. 1 Flow Chart of Conventional Learning Model for design courses

courses for undergraduate students in the mechanical engineering curriculum, e.g., engineering drawing, machine drawing, mechanism of machines, fluid mechanics, hydraulic machines, and machine design. This will allow the physical realization of concepts and analyze the designs and their functions, thus encouraging students to get intrigued in complex courses and extending theoretical knowledge to practical hands-on experience.

The traditional model of teaching for mechanical design courses depicted in the form of a flow chart (Fig. 1) involves conceptualization, mathematical modeling followed by creation of drawings and report; however, this chalk and talk method of teaching does not enable students to physically

realize the design or develop their design work on the paper into a feasible product. Instead, they just create 2D illustrations of the design rather than fabricating design which prevents them from learning valuable skills useful in the industries.

The approach followed for this research encourages action-based hands-on and eyes-on learning exploration and innovation in mechanical engineering design by harnessing the capabilities of 3D printing technologies to visualize concepts, verify different hypothesis/process parameters, do experiments with shape geometries, and turn own innovative ideas into reality via product development by making artifact. Therefore, the proposed approach improves students' learning which were constrained under the traditional manufacturing pedagogy. By this way, students can experience an entire product design cycle which enhances their concepts, critical thinking ability, and experience related to professional practice, making them further industry-fit.

2 Research methodology

The methodology followed in the present work is based on an experiential learning model that involves the integration of mathematical designing with CAD and 3D printing to create physical models along with theoretical reports. The project-based learning approach was adopted for the study that involves an elaborate process to develop a product and thus enhancing participation of students in the learning process [36, 37]. The purpose was to provide an insight to the students about the way products are designed for easy manufacturing and assembly, and to help them understand better the issues related to reliability and maintenance, as well as enlighten them about the phases of a product life cycle. The research methodology here comprises case studies of real-world problems, the solutions to which must be designed using technical knowledge, computational tool, and design software, followed by 3D printing a prototype of the CAD model to provide a hands-on experience to students along with conceptual learning.

The students working in teams of four are allocated a particular case study out of the eight test cases reported in this paper, namely design of fastening nut, knuckle joint, rolling contact bearing, Venturi meter, spur gear, epicyclic gear train, Pelton turbine, and connecting rod depending upon the courses instructed to them in that year. The students are asked to mathematically design, represent the same design by drawing on a sheet, further create a CAD model, and end up by creating the prototype solution of model problems using 3D printing. The prototypes obtained via 3D Printing focuses on three key aspects, namely craftsmanship, design quality, and scale (proportion).

The incorporation of 3D modeling and printing into the designing methodology was first implemented in 2019 in which a selected group of 20 students from the first-year batch were chosen randomly from a pool of 200 students. Using a similar approach, the 20 students were introduced to this innovative method of learning and were asked to undertake a designing exercise involving a real industry-based problem in the form of a case study that required critical thinking, technical knowledge, use of computational tool, design software, and additive manufacturing technology (3D Printing).

These 20 students were evaluated in their design course in the same manner as their counterparts and were informed to take this assignment as a supplementary project along with ensuring voluntary participation of students. In contrast to the conventional design practice which involves the use of mathematical, technical, and factual knowledge to develop a theoretical design and then producing 2D drawings for this design, the students were tutored to follow a novel design methodology to develop a preliminary report in the same manner as earlier. Based on this report, a CAD model is generated and analysis for force, strength, etc. is carried out on this virtual model using appropriate software and finally this CAD model is used for the fabrication of 3D Printed prototypes which can then be tested physically to analyze the performance of the design under given conditions. This design model consists of provisions for evaluating the design through inspection and analysis, thus ensuring an accurate design that functions in a manner as envisioned by the student. However, this was not the case for the conventional models where no data regarding the performance of design are available, resulting in no scope for revision of design.

Each four-student team was provided with a 3D printer to ensure that it has all the required facilities for the project work at their disposal and to provide complete liberty to them while fabricating prototypes and models. The students were also guided regarding the materials available for 3D printing and different features of 3D printers to enable them to make optimum use of technology [38, 39].

The components of each case study were carefully worked out to ensure integration of the knowledge and practice in modeling, prototyping, and 3D printing with the existing model of evaluation involving mathematical designing. By this way, technical and contextual knowledge, competencies of practice, laboratory and design experience, professionalism and ethics were considered in the involved students [40]. This excessive exercise provided students with insights into the design processes and during this approach, it was observed that students corrected their design errors easily through CAD that were missed while creating mathematical design. Also, the students had a chance to investigate the performance of their designed product through various tests.

This research comprising project-based model development work was mapped out for a duration of 4 years (2019–2023) that is the entire duration of B. Tech Mechanical Engineering course of the 2019 batch of undergraduate engineering students at our Institute. Initially starting with a group of 20 students, the sample size of the research was continuously expanded in the following years by allowing more students from each upcoming batch to become a part of this research. These data are depicted in graphical manner in Fig. 2.

It can be easily inferred from Fig. 2 that 20 and 32 students from 2020 and 2021 batch respectively undertook this case-based model development exercise. The students from each batch were provided with appropriate facilities to undertake the product development work for all the eight case studies mentioned during the duration of research. Each 4 students' group from 2019 batch was able to work on a greater number of case studies as compared to groups from 2021 as they were a part of this research for longer duration. The objective was to rope in as many students as possible to experience this innovative technique of learning design problems to perfect a learning model and implement it in curriculum of mechanical engineering in which 3D printing technology become an integral part of designing process. A spectrum of courses involving designing, such as Theory of Machines 1 (MEM404), Automobile Engineering (MEM603), Machine Design 1 (MEM601), etc., is offered at the Institute. The inclusion of 3D Printing technology in these courses for prototyping is significantly helpful in preparing students for professional practice in industries.

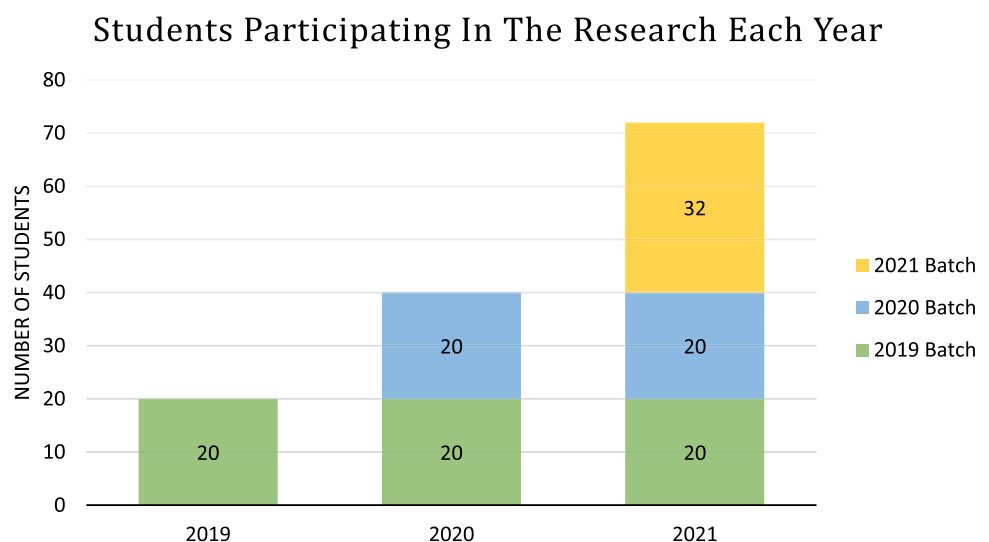
3 Phases of case study-based product development

This new proposed way of teaching consists of designing as per the traditional method & then implementing it through designing software, physically testing, and printing them via a 3D printer. Here, the work is concerned completely with designing & producing products by the students which automatically creates and develops a sense of attentiveness and creates interest when they themselves produce or generate a product [41]. This also provides them with the platform to explore new innovations.

The students who are volunteering to be part of this research are required to undertake product development work in the form of a case study and manufacture a 3D printed product in a systematic and structured approach. The structure of the work is planned to evaluate and improve the fundamental knowledge and skills, ability to make judgments under uncertain conditions, capacity to engage in professional practice, and capability to learn through experience. The student working on a specific case problem will be required to develop the following four components for successful completion of the project involving product development:

1. Introduction Report—This is the initial design report drafted using the theoretical and technical information including several assumptions and estimations to find the theoretical design parameters. It also consists of diagrams and literature survey regarding the case study. The students are encouraged to keep an inductive approach and identify the concepts most suitable to understand and solve the problem.

Fig. 2 Graph depicting the number of students participating in the research each year



2. CAD Modeling and Force Energy Analysis—This stage of assessment involves the use of design software to create a virtual model from the valid drawings produced earlier in the report. This provides a spatial realization of the design to the students and helps them to focus on every parameter of the design problem, some of which might have been overlooked otherwise. The students also learn the effect of different parameters on the geometrical and physical properties of the model. They also perform Force and Energy analysis on the CAD model to ensure the feasibility of the design under given conditions and to eliminate any localized point of failure present in the model to ensure uniform distribution of stress in the model.

3. Prototyping using Additive Manufacturing—This third stage involves the fabrication of a real solid design model using an additive manufacturing technique such as Fused Deposition Modeling (FDM). The prototype might be having original dimensions as the design or scaled down by a suitable factor. The purpose is to provide an insight to students about the way products are designed for easy manufacturing and assembly as well as help them study issues related to reliability and maintenance. This also helps the students to investigate certain aspects of the model which had not been considered during designing, such as tolerances and surface finish, which are critical for the optimum performance of the product [42]. The students use the knowledge of critical parameters involved in additive manufacturing to produce prototypes with desired properties [43].

4. Final Report—Each component of the assessment mentioned above has a provision for evaluation, feedback, and revision and the duration for each one of those components is allotted keeping these provisions in mind. The final report component of assessment consists of a detailed report containing cumulative data of all the previous components along with the results of evaluation of these components, revisions or updates made after each unsuccessful iteration, as well as a comparison between the initial design (generated using theoretical data) and the final design (generated after modeling, prototyping, testing, and revising the design so that the design performs the requisite functions efficiently). Since the case studies consist of real-engineering design problems, thus the students can compare their judgment and decision in the final report with those made by the professionals by looking at the designs of the product used in the industry and can obtain a brief idea of how products are designed professionally.

The design case studies here are structured to allow students to learn designing of products for effortless manufacturing and assembly, and make them aware of issues in

reliability and maintenance and compare their models with the industrial developed products [44, 45]. The design case structure is also formulated to simulate the mind and creativity of students, thus widening their grasp of the subject matter and the product [46]. Integrating 3D printing in science classrooms (on students' science, technology, engineering, and mathematics) will motivate them to achieve higher with respect to future carriers [47].

On the other side, the lack of critical manufacturing properties like tolerance, surface finish, etc. in the design under traditional system is addressed in this model as the prototyping and inspection phase allows students to get familiar with these properties and their influence on the design. This learning method also inculcates teamwork among students, as the students are required to work on a specific problem in groups, which enhances their role from a learner to creator in the domain of engineering and provides them with valuable lessons to avoid setbacks during the duration of professional practices.

The flow of work to be done by the group of four students undertaking a particular design case study is depicted in Fig. 3 which includes all the stages or phases involved in the product development cycle for a particular case study, starting from conceptualizing a creative and imaginative solution to the given problem to the demonstration of the fabricated product and overall report of the design.

The flow chart depicted in Fig. 3 also describes the various inputs required at each phase of product design, such as empirical data, information related to tolerances, etc. Various decision-making steps along the workflow were also shown in Fig. 3 with the proper channels for improvement in case of a decision not to go forward with the present work. The closed loop channels for improvement in the work done at a particular stage enable the students to derive the most feasible design or product after multiple iterations. The four major components or phases of the case study-based product development cycle described above have been clearly shown in the flow chart (Fig. 3) in a chronological order along the direction of workflow.

4 Case studies

There are eight case studies taken into consideration that are designed in such a manner to provide a broad perspective to students in short time with a realistic context. It can also help the students in studying the design process and the stages of a product life cycle through experiential learning. The cases are planned considering that these students have no prior experience in designing or prototyping thus this supplementary work should not overburden them and they have ample time to focus on their curriculum. The students are guided to design solutions for each of the following real problems

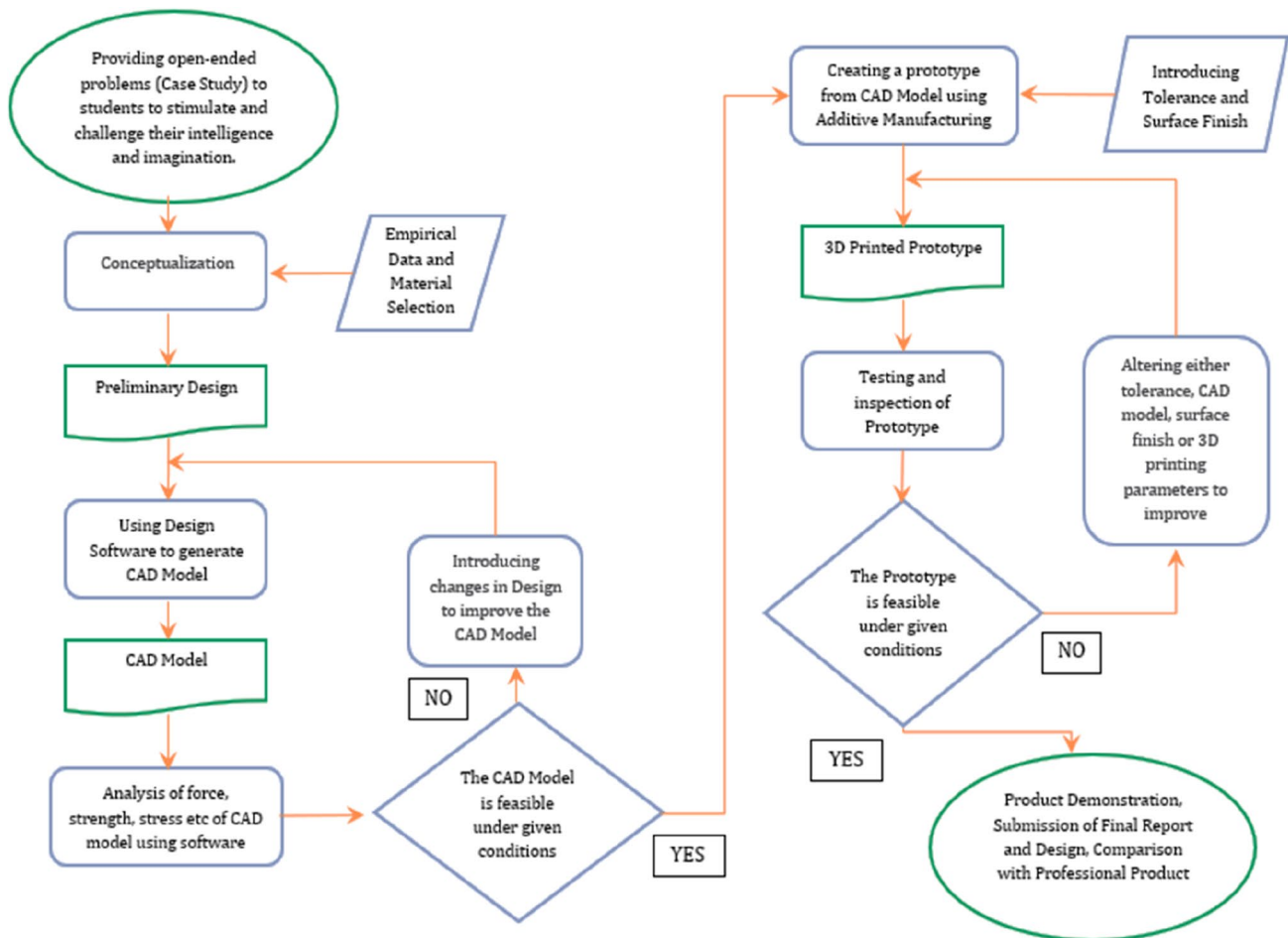


Fig. 3 Flowchart depicting phases of case-based product development cycle

and fabricate the designed product through 3D printing in accordance with the work structure described earlier. The creativity and imagination of students were also encouraged in the case study exercises with flexibility provided to them so that they can work on innovative designs to achieve optimal functions. In addition, the design parameters varied for the eight case studies for each group while keeping the same core product so that the students can look at 4 to 5 unique designs and prototypes during the final report and demonstration of the products and get a better understanding of the effect of these parameters on the design shape, geometry, and look. The students were also given the liberty to select a suitable scale based on the constraints of the 3D printers and complexity of their designs. The case studies undertaken by some of the groups are described below with illustrations and pictures showing glimpses of the work done by them in duration of this research.

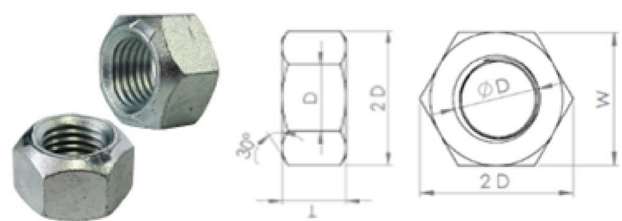


Fig. 4 Nut and its illustration

4.1 Case-1: Nut

The nut, Fig. 4, is a very important fastener that is used alongside a mating bolt in almost every machine to provide a temporary joint between parts and has a wide range of applications in various fields, such as automotive, electrical, aerospace, etc. Hence, pursuing courses are being taught to the undergraduate students in mechanical, automobile, electrical, aerospace, and manufacturing; namely,

Machine Design 1 (MEM 601), Machine Design Practice 1 (MEM 602), Graphic Science (MEM 101) and Engineering Drawing 2 (MEM 203).

4.1.1 Problem statement

In this case, a student must design a nut with 20 mm as the nominal diameter of the bolt and pitch of 2.5 mm.

4.1.2 Preliminary designing

The conventional way of imparting knowledge about this machine element to engineering undergraduate students is to provide them with the knowledge of empirical relations and formula involved in determining the design dimensions of the product. Also, illustrations of the design, Fig. 4, and actual product are shown to the students to improve their visualization abilities.

The mathematical model of nut is described as follows:

Let, D = Nominal diameter of bolt = 20 mm and p = pitch of thread = 2.5 mm.

Then, by empirical relationship,

Thickness of nut, $T = D = 20$ mm.

Width across flats, $W = 1.5D + 3$ mm = 33 mm.

Angle of Chamfer = 30°

Radius of chamfer arc, $R = 1.4D = 28$ mm.

Distance across diagonal = $2D = 40$ mm.

After mathematical calculations and determining the dimensions of the nut, the 2D drawing, Fig. 5a, is prepared as shown below.

4.1.3 CAD modeling and prototyping

The mathematical designing procedure and theoretical study of the element will not answer all the questions since students cannot physically realize the element; for example,

at what point the chamfering must be given, and how the internal threads look like, etc. For the better understanding of the concept, students prepare the CAD drawing as shown in Fig. 5b. During the CAD designing, the students are informed about tolerances for standard metric thread, such as $\pm 0.05D$ for width across flat (W) and $0.016D + 0.012$ for nut thickness (T). The students further proceed to print this design via 3D printer which also contributes to learning different designing software as well as the operation of the 3D printer itself.

After 3D printing the part, shown in Fig. 5c, students can physically realize and visually interpret how the part looks like and check the functionality of the product by comparing it with a standard $M20 \times 2.5$ metric nut. Also, they can find out the load bearing capacity by performing strength-based tests and the critical dimensions where the designed part can fail and thus acquire comprehensive knowledge of all the phases from designing to production. All these factors provide a better understanding of the part which is not possible just by designing it on a piece of paper.

4.2 Case–2: knuckle joint

Knuckle joint is a commonly used part to connect the rods because of its design to permit the misalignment. This joint is used to connect two shafts whose axis lies on the same plane and are under tensile loads. It is being taught to UG students of mechanical engineering in courses, namely Machine Design 1 (MEM 601), Machine Design Practice 1 (MEM 602) and village industries (RDC 781).

4.2.1 Problem statement

To design a knuckle joint that transmits 160KN and take stress as 80 MPa in tension, 70 MPa in shear and 160 MPa in compression.

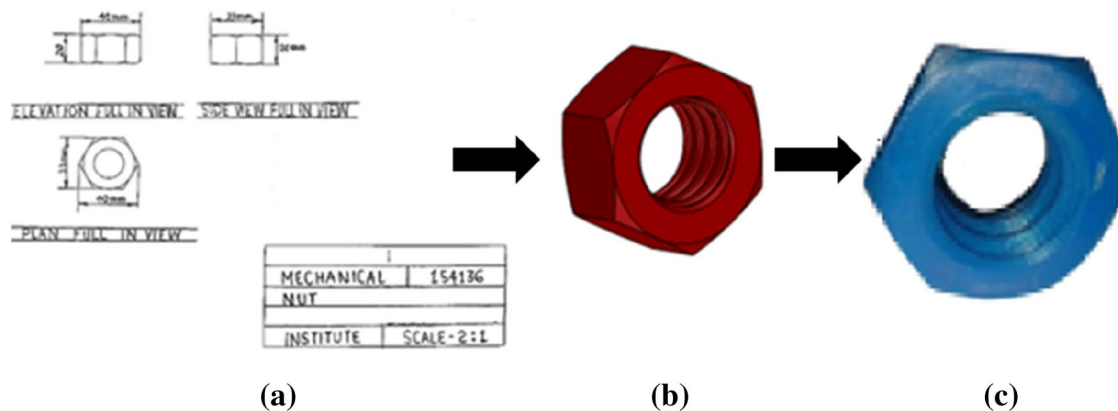


Fig. 5 Sequence of the designing a nut a Engineering drawing of Nut b Solid works drawing of Nut c 3D printed Nut

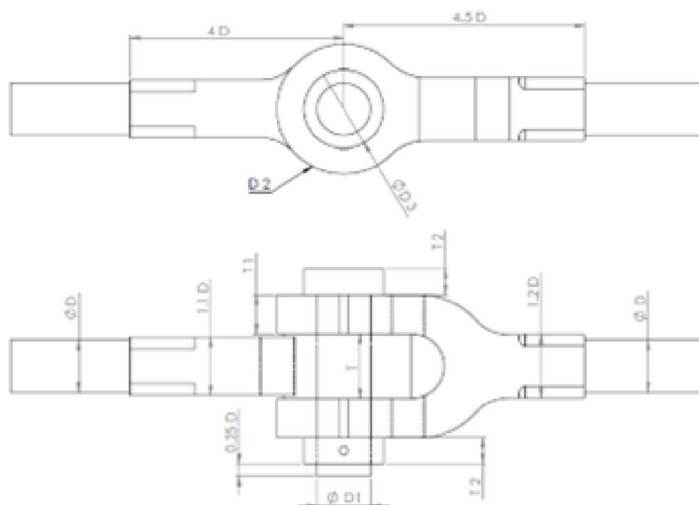


Fig. 6 Knuckle Joint and its illustration

4.2.2 Preliminary design

The students are guided regarding the formula and empirical relations involved in designing the knuckle joint, Fig. 6. The illustrations and actual knuckle joint are shown to the students and its parts and operation are explained.

In this case, some parameters like maximum load that the joint can transmit, and various stresses are considered for mathematically designing the knuckle joint as follows:

Let D = Diameter of Rod and σ = permissible tensile stress.

We know that the transmitted load, $P = \frac{\pi}{4} D^2 \times \sigma$

$160 \times 10^3 = \frac{\pi}{4} D^2 \times 80 = 62.83 D^2$

$D^2 = 2546.55$

$D = 50.463 = 50.44 \text{ mm} = 54 \text{ mm (adopted value)}$.

Now from empirical relationships, the dimensions of all the parts are calculated, some of which are described as below:

Diameter of Knuckle Pin, $D_1 = D = 54 \text{ mm}$.

Outer diameter of eye, $D_2 = 2D = 108 \text{ mm}$.

Diameter of Knuckle pin head and collar, $D_3 = 1.5D = 81 \text{ mm}$.

Thickness of single eye, $T = 1.25D = 67.5 \text{ mm}$.

Thickness of fork, $T_1 = 0.75D = 40.5 \text{ mm}$.

Thickness of pin head, $T_2 = 0.5D = 27 \text{ mm}$.

After mathematical calculation for all the dimensions of the knuckle joint components, the dimensions are checked by taking into consideration the failure of different parts of the joint and comparing the calculated value against the limiting value. The 2D drawing of the joint is made after finalizing the dimensions of the parts as shown in Fig. 7a.

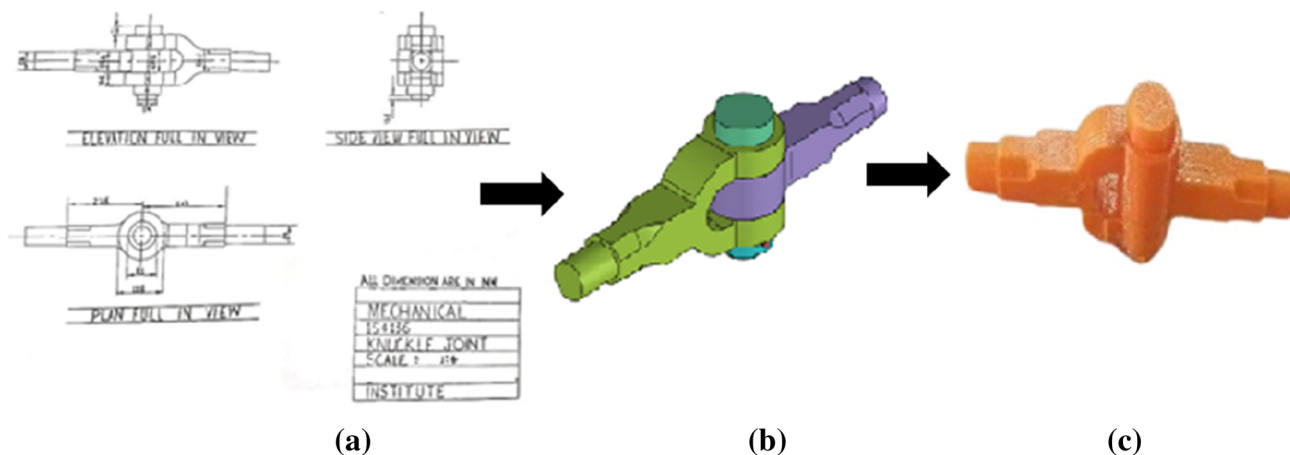


Fig. 7 Sequence of the designing a Knuckle joint a Engineering drawing of Nut b Solid works drawing of knuckle joint c 3D printed Knuckle Joint

4.2.3 Modeling and prototyping

The whole mathematical designing procedure and theoretical study of the element do not contribute to providing answers to all questions, since students cannot figure out how the element looks like, how the fork end and eye end are joined together, at what point the fillet has to be given, etc. For this purpose, students prepare the CAD drawing (Fig. 7b) using Solid works software.

This designing of the part on CAD software helps student to understand better how the actual assembly of the parts is done by identifying the mating parts. Also, the detailed knowledge regarding tolerance of shafts and holes is provided to them so that they can incorporate it in their models. Further finite element analysis of the model can be done through ANSYS or other software to identify shortcomings of the CAD model and rectify them. Then the students proceed to print this design via 3D printer (Fig. 7c) which contributes to learning different software for designing as well as the operation of 3D printer. The parts of the knuckle joint are individually printed and then after removing unwanted materials from printing they are assembled. The joint is then checked by operating and any error during prototyping is spotted and the model is revised and again printed to create a smooth working knuckle joint assembly. The students can also find out the load bearing capacity by performing strength-based tests and are informed about the lubrication and surface finish of the parts and their importance in working of the joint. All these factors provide a better and overall understanding of the part which is not possible just by designing it on a piece of paper.

4.3 Case–3: Rolling contact bearing (ball bearing)

Bearing, Fig. 8, is one of the most important machine elements that is being used to support rotating shafts to

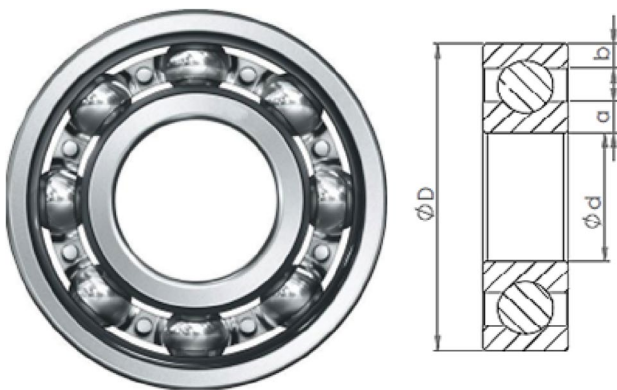


Fig. 8 Roller bearing and its illustration

carry out loads while at the same time minimizing friction. They can support both axial and radial load using rollers placed between two races. This component is taught to every engineering student in courses namely, Theory of Machines 1 (MEM 404) and Machine Design 1 (MEM 601). Therefore, this machine element is of immense importance to students due to its widespread applications.

4.3.1 Problem statement

Design a ball bearing for radial load of 1150 N and tangential load of 3160 N operating at 600 rotation per minute with a 2-year life at full day operation.

4.3.2 Preliminary design

The mathematical model is developed considering the load on the bearing and the life of the bearing. These parameters are used to calculate the dynamic load rating for the bearing and the bearing number through use of standard charts.

So, Dynamic Load = $X \times V \times R$.

Where, R = Resultant Load = $(1150^2 + 3160^2)^{0.5} = 3362.75$ N.

From Data Handbook, $X = 0.56$ and $V = 1$

So, Dynamic Load, $W = 3362.75 \times 0.56 \times 1 = 1883.14$ N = 1.88 KN

Now we consider 2-year Life for full day operation at 600 rpm, Then.

Life in hours = $L_H = 360 \times 2 \times 24 = 17,520$.

Life in Revolutions = $L = 60 \times N \times L_H = 630.72$ million Revolutions.

Now from Data handbook, For 630.72 million Revolutions.

Then, Dynamic Load Rating, $C = W \times \left(\frac{L}{10^6}\right)^{\frac{1}{k}} = 16.28$ KN.

So, using Data Handbook 30BCO3 Deep Groove ball bearing is selected for next high value of $C = 20.99$ KN.

For Deep Groove Ball Bearing of 30BCO3 type.

Bore Diameter, $d = 30$ mm.

Outer Diameter, $D = 72$ mm.

Width = 19 mm.

$C = 20.99 > 16.28$.

And Maximum allowance RPM = 10,000 > > 600.

Hence, Bearing is safe.

After mathematical calculation, the basic 2D drawing of Ball Bearing is prepared (Fig. 9a) depicting the dimensions and views of the ball bearing in two-dimensional set-up.

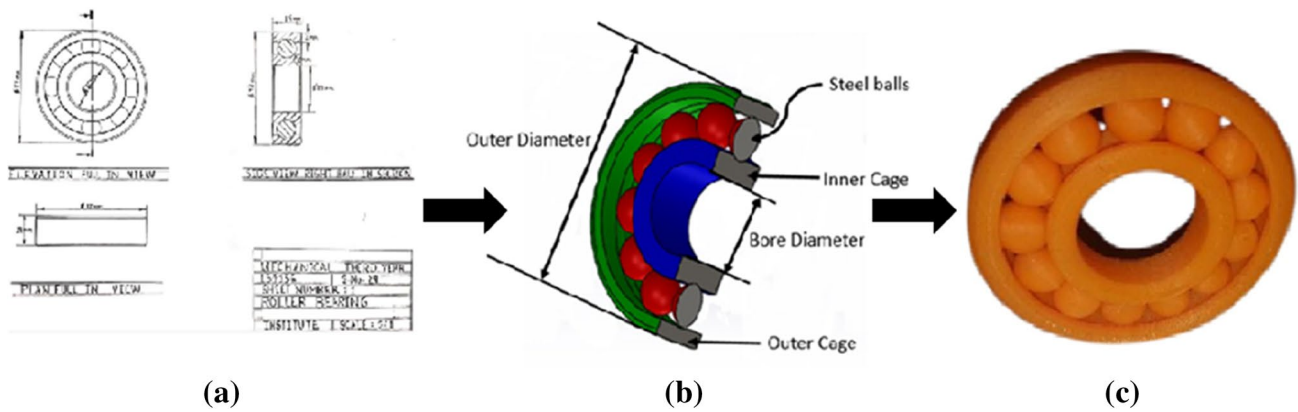


Fig. 9 Sequence of the designing a roller bearing **a** Engineering drawing of roller bearing **b** Solid works drawing of roller bearing **c** 3D printed roller bearing



Fig. 10 Venturi meter

4.3.3 Modeling and prototyping

The next step includes preparing drawing of these parts and designs through various engineering drawing software and then printing it by a 3D printer that aims to provide a clear vision and better understanding of various engineering and non-engineering parts compared to the traditional 2D drawings.

To find out whether the part will be a success in practical cases or not, students prepare the CAD drawing (Fig. 9b) & further proceed to print this design via a 3D printer (Fig. 9c) which contributes to learning different software for designing and the operation of the 3D printer.

After 3D printing the part, the students can visually interpret how the part looks like, how the movement of balls and cages takes place, and how the balls get fitted in the cage or race. Students can also find out the load bearing capacity by performing strength-based tests and measuring the critical dimensions where the part can fail and thus acquire complete knowledge of all the phases from design to production. All these factors provide a better and comprehensive understanding of the part which is not possible just by designing it on a piece of paper.

4.4 Case-4: Venturi meter

Venturi meter, Fig. 10, is one of the hydraulic devices which is studied as an application of Bernoulli’s equation in almost every engineering field. More specifically, it is studied by mechanical/production/civil/manufacturing engineers in courses like Hydraulic Machines and Fluid Mechanics. This apparatus is used to find out the discharge of a liquid flowing through a pipe and mainly consists of three parts: Convergent conical portion, throat, and a divergent conical portion.

4.4.1 Problem statement

A horizontal Venturi meter is designed which has a 160 mm diameter at the throat connected to an oil–mercury gage having a deflection of 351.48 mm, the discharge of oil of 50 L/s, and specific gravity of oil of 0.8. Assuming coefficient of Venturi meter as 1, determine the dimensions and discharge for the prototype.

4.4.2 Mathematical model

The parameters like discharge, head and coefficient of Venturi are given and the dimensions of the Venturi meter can be calculated based on formulas. By further taking a suitable scale, the prototype dimensions and discharge are calculated before developing 2D drawings of the model.

If a_1 is the area at inlet and a_2 is the area at throat then,

$$a_1 = \frac{\pi}{4} \times (.16)^2 = 20.11 \times 10^{-3} m^2$$

Also, the deflection of the mercury gage,

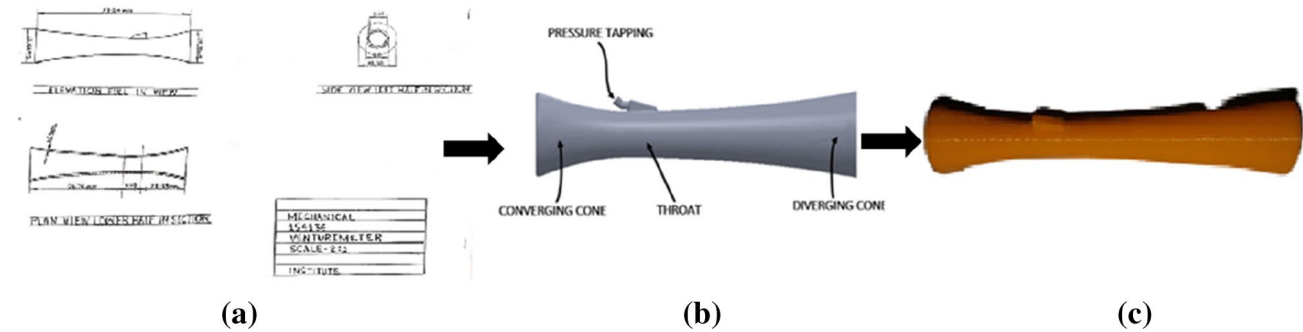


Fig. 11 Sequence of the designing a venturi meter **a** Engineering drawing of venturi meter **b** Solid works drawing of venturi meter **c** 3D printed venturi meter

$$h = \left(\frac{13.6 - 0.8}{0.8} \times 351.48 \right) = 16 \times 351.48 = 5.62 \text{ m of oil}$$

Then discharge through Venturi meter is given by:

$$Q = \frac{C \cdot a_1 a_2}{\sqrt{a_1^2 - a_2^2}} \sqrt{2gh}$$

$$50 \times 10^{-3} = \frac{1 \times (20.11 \times 10^{-3}) \times a_2}{\sqrt{(20.11 \times 10^{-3})^2 - (a_2)^2}} \times \sqrt{2 \times 9.81 \times 5.62}$$

Solving the above equation, we get

$$a_2 = 4.632 \times 10^{-3} \text{ m}^2$$

Diameter at throat = 76.8 mm.

Calculating discharge of the prototype for the given discharge of an undistorted model,

Taking inlet diameter of the prototype $d'_1 = 20.24 \text{ mm}$

Scale ratio of model to prototype = $\frac{1}{s}$ where $\left(\frac{d_1}{d'_1} \right)^2 = \frac{1}{s^2}$

Thus, we get $\frac{1}{s} = 7.9$ or 8.

Throat diameter d'_2 can be calculated by formula

$$\left(\frac{d_2}{d'_2} \right) = \frac{1}{s^2}$$

On putting values, we get $d'_2 = 9.60 \text{ mm}$

Taking q as the discharge of the prototype $q = Q \times s^{2.5}$

Therefore, $q = 50 \times (1/8)^{2.5} = 0.2845 \text{ liters/s}$.

As we have assumed $C = 1$, velocities can be calculated at inlet (v_1) and throat section (v_2) as,

$$q = a'_1 v_1 = a'_2 v_2$$

$$\begin{aligned} q &= .2845 \times 10^{-3} = \frac{\pi}{4} \times (d'_1)^2 \times v'_1 = \frac{\pi}{4} \times (20.24 \times 10^{-3})^2 \times v'_1 q = .2845 \times 10^{-3} \\ &= \frac{\pi}{4} \times (d'_2)^2 \times v'_2 = \frac{\pi}{4} \times (9.60 \times 10^{-3})^2 \times v'_2 \end{aligned}$$

Therefore, $v_1 = .8842 \text{ m/s}$ and $v_2 = 3.93 \text{ m/s}$.

Angle of convergence is taken from 15° to 20° and angle of divergence is taken from 5° – 7°

To avoid the separation of fluid at the throat region, ratio of diameter of throat and the pipe is fixed. This ratio varies from $1/4$ to $3/4$ but more specifically it should be from $1/3$ to $1/2$.

In the prototype designed- $d'_2/d'_1 = 9.60/20.24 = 0.474$, therefore the design can be considered safe.

To avoid the tendency of separation of fluid and to minimize the frictional losses, the divergent cone is made 3 to 4 times longer than convergent cone.

After mathematical calculations, the 2D drawing is prepared, Fig. 11a, shows the basic 2-D drawing of Venturi meter.

4.4.3 CAD model and prototyping

By just looking at a 2D view of any design on a sheet of paper and performing its design calculations, one cannot get the fair idea of the actual working and the importance of various design considerations. By contrast, using a 3D printer and applying model analysis allow us to make a prototype of any model which must be studied. A student can prepare a CAD drawing of the prototype (Fig. 11b), simply print it using a 3D printer and have a clear vision and better understanding of various engineering and non-engineering parts. After printing the prototype of the calculated dimensions by a 3D printer (Fig. 11c), one can visually interpret how the part looks and what the various parts of a Venturi meter are, etc. Using Venturi meter test



Fig. 12 Spur gear

bench, experiments can also be done, and all these factors will provide a deep understanding of the part which is not possible by just drawing it on a sheet of paper.

4.5 Case-5: Spur gear

Spur gear, Fig. 12, is one of the most important machine elements because of its high-power transmission capacity. Also, because of its compactness it is widely used in automatic gear boxes, cutting machines, etc. It is being taught to mechanical, manufacturing, Aerospace, and electrical engineers in courses namely, Machine Design 1 (MEM 601), Machine Design Practice 1 (MEM 602), Machine Design 2 (MEM 706) and Theory of Machines (MEM704).

4.5.1 Problem statement

To design the pinion for a pair of spur gears transmitting 21.6 KW power at 1400 rpm with 20° pressure angle, number of teeth on pinion equal to 20 and allowable static stress

is 200 MPa. Diameter of pinion shaft is 32 mm and length of hub is equal to face width.

4.5.2 Preliminary design

The theoretical design for the gear is developed based on Lewis’s equation. The parameters like power to be transmitted, rotation per minute, number of teeth and pressure angle are given, and the formula are used to calculate the dimensions of the spur gear as follows:

Teeth on pinion gear = $T = 20$.

Permissible stress = $\sigma = 200$.

Pitch line velocity, $v = \frac{\pi m T N}{60} = 1466.08 \text{ m}$.

Taking steady load condition for 8–10 h duration, the service factor is $C_S = 1$.

Tangential load on gear = $W = \frac{P}{v} C_S = \frac{14.73}{m} \text{ N}$.

Velocity Factor = $C_v = \frac{3}{3+v}$

Tooth form factor = $Y_p = 0.175 \frac{0.841}{T} = 0.133$.

Applying Lewis equation,

$W = \sigma \times C_v \times b \times \pi \times m \times Y_p$

Thus, on substituting these values, we get the value of:

Module (m) = 6 mm.

PCD (D) = $m \times T = 120 \text{ mm}$.

Width of tooth, $b = 6 \text{ m} = 36 \text{ mm}$.

Addendum = $m = 6 \text{ mm}$.

Dedendum = $1.25 \text{ m} = 7.5 \text{ mm}$.

Working Depth = $2 \text{ m} = 12 \text{ mm}$.

Tooth thickness = $1.5 \text{ m} = 9 \text{ mm}$.

The two-dimensional drawing, Fig. 13a, of the spur gear is drawn based on the above calculated dimensions as shown below

4.5.3 Modeling and prototyping

Following the mathematical designing procedure and theoretical study of the element, students prepare the CAD drawing (Fig. 13b) & further proceed to print this design via a

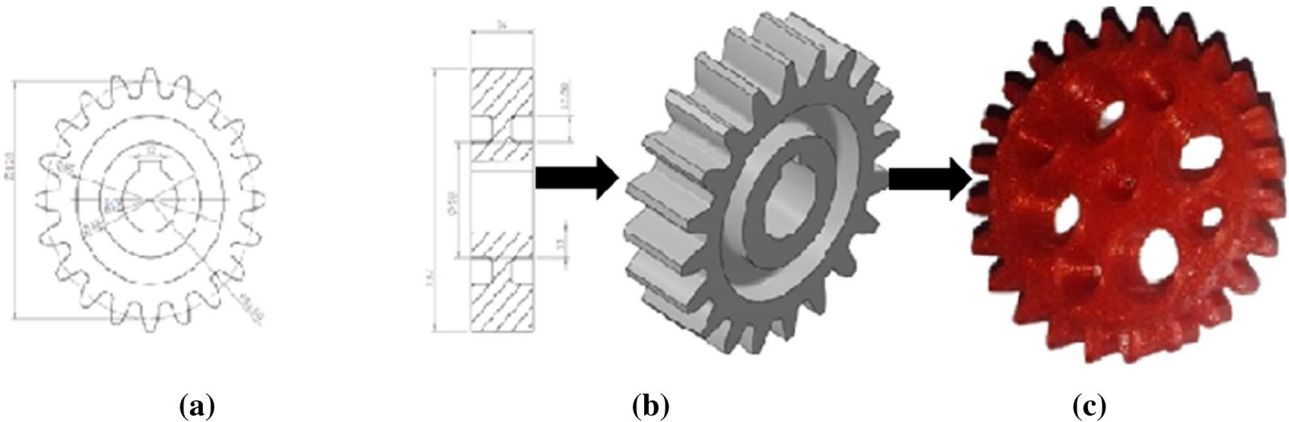
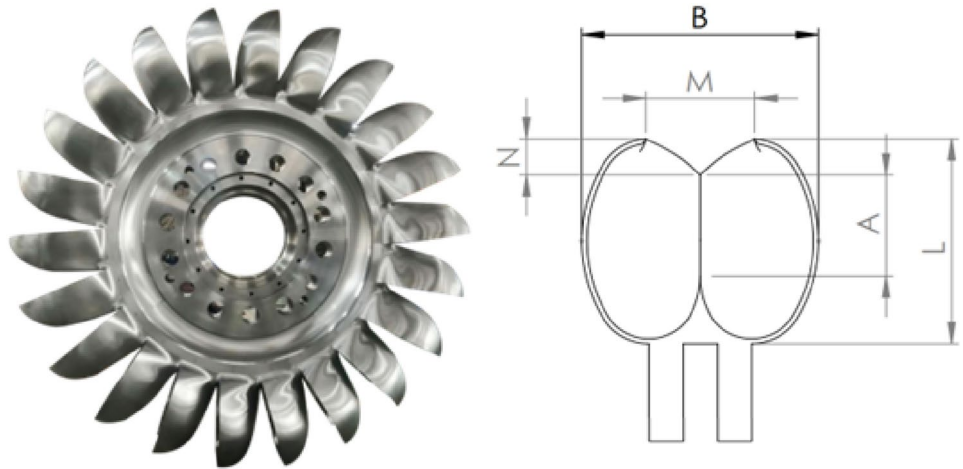


Fig. 13 Sequence of the designing a spur gear a Engineering drawing of venturi meter b Solid works drawing of spur gear c 3D printed spur gear

Fig. 14 Pelton wheel turbine and illustration of pelton wheel bucket



3D printer (Fig. 13c) which contributes to learning different software for designing and the operation of 3D printer. This helps the students in physical realization of the parts and learning about design parameters not undertaken in the mathematical model (e.g., gear tooth profile). It can also run simulation to check if the gear teeth are mating properly and introduce necessary changes in the design. After 3D printing the part, students can visually interpret how the part looks, how the movement of gear takes place, and how the teeth's get engaged. Students can also investigate the part and examine it to ensure the proper functioning of the design.

4.6 Case-6: Pelton turbine

Hydraulic turbine is a device that is used to convert the energy of the fluid (Kinetic energy, potential energy & enthalpy) into mechanical energy. Turbine can be classified into several categories, but the two broad categories of turbines are Impulse turbine and Reaction turbine. Pelton wheel or Pelton turbine, Fig. 14, is the tangential flow impulse turbine in which water strikes the buckets, in the tangent direction of the runner. Turbines are being taught in the engineering branches, such as mechanical/production/aerospace engineering in courses, namely Applied Thermodynamics (MEM 304) and Hydraulics Machinery (MEM 818). Pelton wheels are mainly finding their application where the head is high, and discharge is low. They are usually operated in the conditions where the bucket velocity is half the velocity of the jet.

4.6.1 Problem statement

To design a Pelton wheel running at 1200 rpm, under the head of 10 m, with coefficient of velocity as 1, speed ratio as 0.46 and jet ratio equal to 10.

4.6.2 Preliminary design

The initial design model for Pelton wheel is performed with the help of mathematical equations and empirical relations using the given parameters like net head, discharge, etc. to determine the dimensions of the Pelton wheel to operate on the desired revolutions per minute. The mathematical calculations are described as below:

Head for the turbine, $H = 10$ m.

Coefficient of velocity, $C_v = 1$.

Speed Ratio, $r = 0.46$.

Jet ratio, $m = \frac{D}{d} = 10$,

Revolutions of the wheel, $N = 1200$ rpm.

Velocity of wheel, $u = r \sqrt{2gH} = 0.46 \times 14 = 6.44$ m/s.

Runner diameter, $D = \frac{60u}{\pi N} = 0.1025$ m = 102.5 mm.

Diameter of jet, $d = \frac{D}{m} = 10.25$ mm.

Number of buckets, $Z = 15 + 0.5 m = 20$.

Bucket length, $L = 3d = 30.75$ mm.

Bucket width, $B = 4d = 41$ mm.

Notch width, $M = 1.5d = 15.375$ mm.

Bucket depth, $X = d = 10.25$ mm.

Bucket height, $A = 2d = 20.5$ mm.

Notch depth, $N = 0.5d = 5.125$ mm.

The next process following the completion of preliminary design stage is to develop a two-dimensional drawing (Fig. 15a) of the Pelton wheel turbine as shown below.

4.6.3 Modeling and prototyping

The 3D CAD modeling process followed by prototyping of the design, Fig. 15b, using 3D printers helps students get a clear understanding of design parameters like the shape of the bucket, its appearance and tolerances involved in the design process. After getting the 3D printed part, Fig. 15c, students can visually interpret how the part looks and how the splitter divided the bucket into two parts. The student

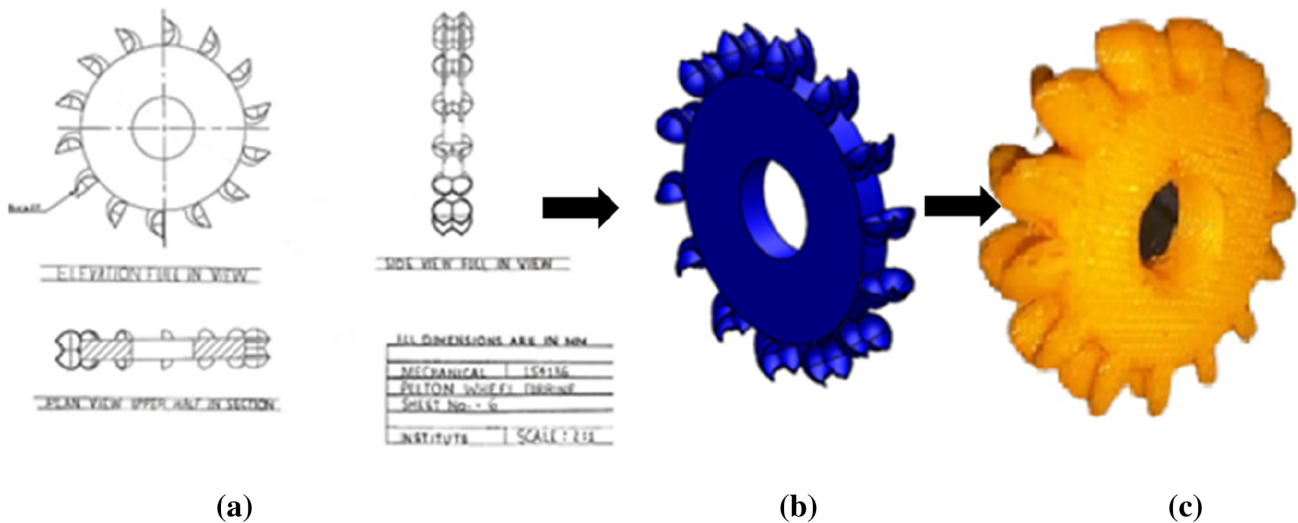
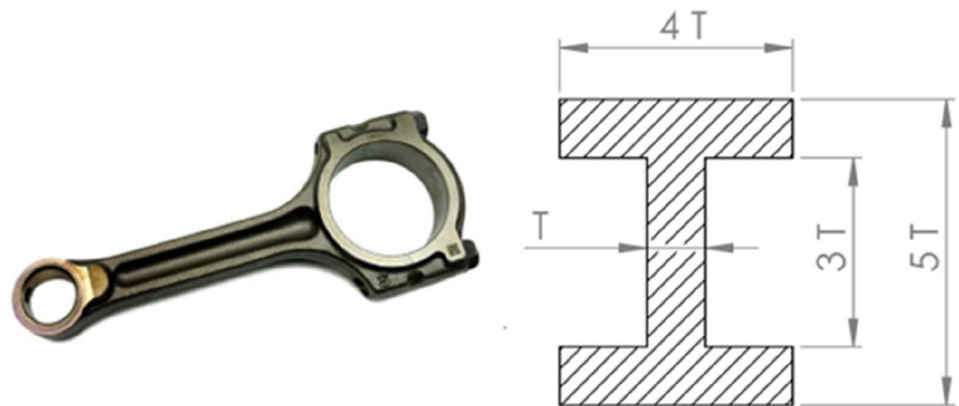


Fig. 15 Sequence of the designing a pelton wheel turbine **a** Engineering drawing of pelton wheel turbine **b** Solid works drawing of pelton wheel Turbine **c** 3D printed pelton wheel turbine

Fig. 16 Connecting Rod and Illustration of connecting rod section



can test the prototype with a nozzle apparatus to check the feasibility of the design in generating power. Prototyping also allows students to play with parameters like angle of jet deflection and analyze its impact on the wheel performance. This method provides a better grasp of concepts and helps students retain information effectively.

4.7 Case-7: Connecting rod

Connecting rod (Fig. 16) is an internal combustion piston engine component that converts the reciprocating motion of the piston into the rotatory motion of the crank shaft. It is connected to the piston through gudgeon pin on one end and the other end is connected to the crank. It is designed to sustain high speed loads encountered in an IC engine and is taught in courses like Machine Design 2 (MEM706), Machine Design Practice 2 (MEM707), Automobile Engineering (MEM603) and Theory of Machines 2 (MEM704).

4.7.1 Problem statement

To design an IC engine connecting rod having piston diameter of 0.1 m with maximum speed and piston pressure of engine equal to 2000 rpm and 3 MPa. The connecting rod and crank length are 400 mm and 100 mm respectively with the compression ratio for the cylinder equal to 6:1. The inertia force on the connecting rod is 10,000 N. The length and diameter for big end bearing are given as 60 mm and 45 mm, whereas the length and diameter for the small end bearing are given as 60 and 30 mm respectively. Two bolts of 12 mm diameter are used to fasten the big end cap to the connecting rod and the allowable stress for connecting rod material is taken as 100 MPa.

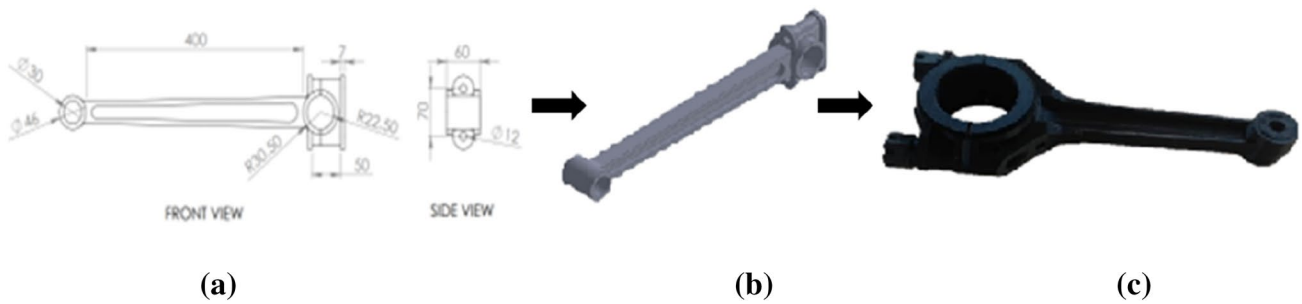


Fig. 17 Sequence of the designing a connecting rod **a** Engineering drawing of connecting rod **b** Solid works drawing of connecting rod **c** 3D printed connecting rod

4.7.2 Preliminary design

The mathematical formulas are used to determine the dimensions of the section of the connecting rod depending upon the permissible stress for the material and the operating conditions.

Piston diameter, $D = 100$ mm.

Piston Pressure, $P = 3$ MPa.

Length of Connecting Rod, $L = 400$ mm.

Allowable stress $= p = 100$ MPa.

The section of connecting rod is taken to be I-Shaped (Fig. 16) with the dimensions at the center of connection given as follows:

Thickness $= T$.

Height, $H = 5$ T.

Width, $W = 4$ T.

Moment of inertia about horizontal axis through center $= I_{XX} = 34.92 T^4$

Force on Connecting Rod, $F = \frac{\pi D^2}{4} \times P = 23,562$ N.

Now taking factor of safety as $\frac{5}{4}$, the buckling load is given as,

Buckling Load, $W = F \times 5 = 117,810$ N.

Radius of gyration for I Section, $K = 1.78$ T.

Using Rankine Formula, $W = \frac{\sigma A}{1 + a(\frac{L}{K})^2}$ where $\sigma = 320$ MPa.

Hence, we get $T = 6.2$ mm and we adopt the value of $T = 7$ mm.

Thus $H = 35$ mm and $W = 28$ mm.

Height at big End, $H_B = 1.2H = 42$ mm.

Height at Small End, $H_S = 0.85H = 30$ mm.

Thickness of big end cap $= t$ and width of big end cap $= 60$ mm

Section modulus for cap, $Z = 10 T^2$ and max bending moment for cap $= M = \frac{F \times S}{6}$

where $F =$ Inertia force $= 10,000$ and $S =$ distance between bolt center $= 70$ mm.

We know $p = \frac{M}{Z}$

$\rightarrow 100 = \frac{11666.67}{t^2}$ so we get $t = 11$ mm.

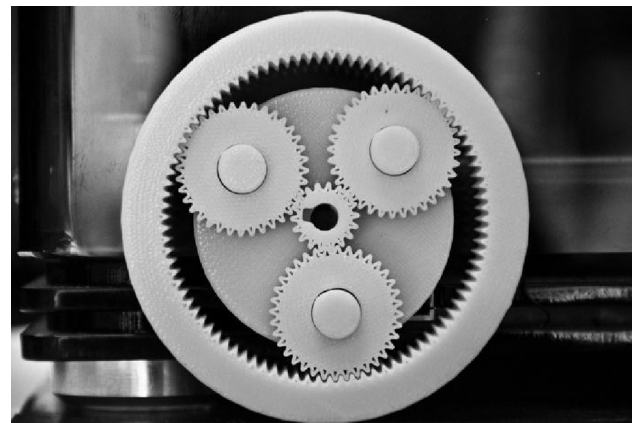


Fig. 18 Epicyclic gear train

After calculating all the dimensions of the Connecting Rod, a Two-Dimensional Drawing of the connecting rod assembly is drawn as shown below, Fig. 17a.

4.7.3 Modeling and prototyping

The two-dimensional drawing of the design is taken as a reference for creating a 3D CAD model, Fig. 17b, of the connecting rod. The motive behind creating a CAD model is to make students aware of the appearance and look of the part in 3D and to identify any errors in design, such as mismatch between the connecting rod and the cap, misalignment of bolt holes, etc. The CAD model helps students visualize the design and is further used for creating a prototype of the design using 3D printers. The 3D fabricated prototyping process for the connecting rod allows students to experience the final stage of product development. The exposure to 3D printed parts, Fig. 17c, allows students to alter the design parameters of the part to design improvement which is the objective of this task.

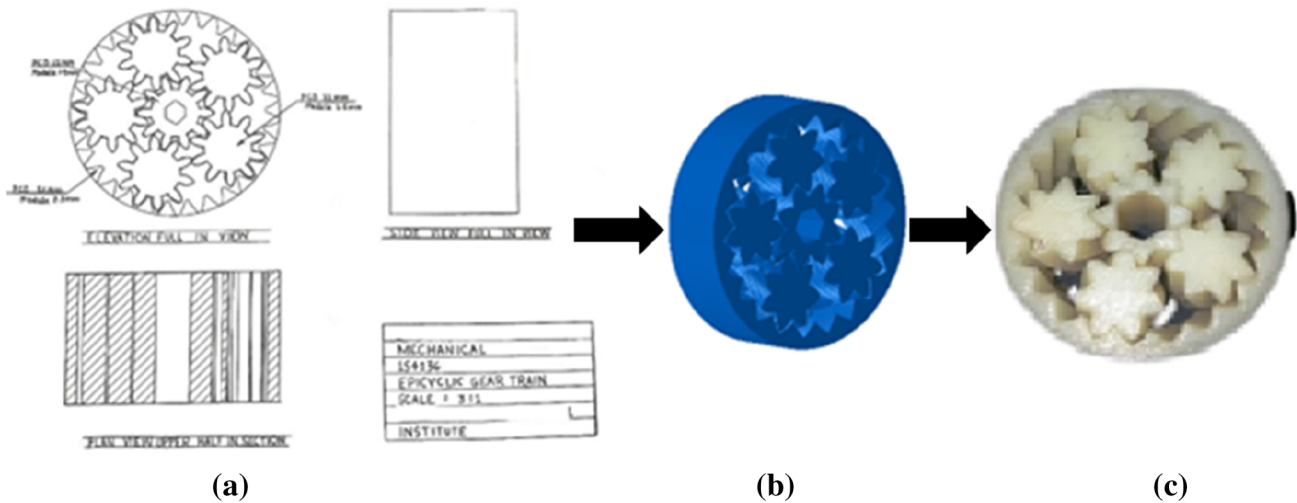


Fig. 19 Sequence of the designing a epicyclic gear train **a** Engineering drawing of epicyclic gear train **b** Solid works drawing of epicyclic gear Train **c** 3D printed epicyclic gear train

4.8 Case-8: Epicyclic gear train

Epicyclic gear train, Fig. 18, consists of sun gear, planet gear, and ring gear which is generally placed inside the box filled with lubricant and is used as a gear reducer. It is being taught to mechanical and manufacturing engineers in courses, namely, Machine Design 2 (MEM 706) and Theory of Machines (MEM704). The main advantage of the Epicyclic gear train is that it occupies very little space.

4.8.1 Problem statement

To design an Epicyclic gear train with herringbone gears for transmitting 180 N-mm torque at 50 rpm with 25° helix angle and 20° pressure angle with sun gear, planet gear, and ring gears have 8, 7 and 22 teeth respectively.

So, given Torque $T = 80$ N-mm, $Z_S = 8$, $Z_P = 7$, $Z_R = 22$, $\psi = 25^\circ, \theta = 20^\circ$

4.8.2 Mathematical modeling

In this stage, some parameters like torque, angular velocity, helix angle, and pressure angle are given, and students have to design the gear train with the help of mathematical equations.

Design for Sun gear,

$$\text{Tangential force on sun gear} = \frac{2T \cos \psi}{Z \cdot m} = F_T$$

Applying Lewis equation.

$$F_T = \frac{mbY\sigma}{\cos \psi}, \sigma = 25 \text{ MPa (for ABS)}, Y = 0.04\pi, b = 13m$$

Thus, on substituting these values.

We get the value of.

$$\text{Module } (m) = 1.5 \text{ mm.}$$

$$\text{PCD } (D) = m \times Z = 12 \text{ mm}$$

Design for Planet gear,

The module will be same for the meshing gears so Module $(m) = 1.5$ mm.

$$\text{PCD } (D) = m \times Z = 11 \text{ mm}$$

Design for Ring gear,

The tangential force acting on the gear will be the same and the Lewis equation will also remain the same except for the fact that Lewis form factor Y will get changed and its value will be 0.114π .

Applying Lewis equation.

$$F_t = \frac{mbY\sigma}{\cos \psi}, \sigma = 25 \text{ MPa (for ABS)}, Y = 0.14\pi, b = 13m$$

Thus, on substituting these values.

We get the value of.

$$\text{Module } (m) = 2.3 \text{ mm.}$$

$$\text{PCD } (D) = m \times Z = 50 \text{ mm}$$

After mathematical calculations, the 2D drawing is prepared. Figure 19a shows the basic 2-D drawing of Epicyclic Gear train.

4.8.3 CAD Modeling and Prototyping

The whole mathematical designing procedure and theoretical study of the element do not contribute to providing answers to all the questions, since students cannot figure out how the element looks like, how all the teeth come into contact and move with each other and whether the profile of the teeth of the gear will be manufactured as suggested in the design. For the purpose of finding out whether the part will be a success in practical cases or not, students prepare its CAD drawing (Fig. 19b) & further proceed to print this design via a 3D printer (Fig. 19c) which contributes to

Table 1 Summary of all Case studies including completion time and number of iterations

Cases	Courses	Completion time (Hours)	Failure rate (Times)
Hex nut	Graphic Science (MEM101), Engineering Drawing 2 (MEM203), Machine Design 1 (MEM601) And Machine Design Practice 1 (MEM602)	20	1
Knuckle joint	Machine Design 1 (MEM601), Machine Design Practice 1 (MEM602) And Village Industries (RDC681)	40	5
Roller bearing	Theory of Machines 1 (MEM404), Automobile Engineering (MEM603), Machine Design 2 (MEM706) And Machine Design Practice 2 (MEM707)	58	7
Venturi meter	Fluid Mechanics (MEM 501) and Hydraulic Machinery (MEM 818)	41	3
Spur gear	Theory of Machines 1 (MEM404), Automobile Engineering (MEM603), Machine Design 1 (MEM601), Machine Design Practice 1 (MEM602) And Machine Design 2 (MEM706)	52	4
Pelton Wheel Turbine	Applied Thermodynamics (MEM304) And Hydraulics Machinery (MEM818)	80	8
Connecting rod	Machine Design 2 (MEM706), Machine Design Practice 2 (MEM707), Automobile Engineering (MEM603) and Theory of Machines 2 (MEM704)	94	9
Epicyclic gear train	Machine Design 2 (MEM 706), Machine Design Practice 2 (MEM 707) and Theory of Machines 2 (MEM704)	97	10

learning different software for designing and the operation of the 3D printer.

After 3D printing the part, students can visually interpret how the part looks like, how the movement of all gear takes place at the same time, and how the teeth get engaged gradually without making any noises. Students can also find out the torque carrying capacity by performing strength-based tests and the critical dimensions where the part can fail and thus acquire complete knowledge of all the phases from designing to production. All these factors provide a better and overall understanding of the part which is not possible just by designing it on a piece of paper.

The process of product development for the above-mentioned case studies is a very novel method for students, as a result, this process turns out to be time-consuming for the students who require multiple iterations to develop the desired products. Thus, the students are introduced to only a single case study in each semester so that they are not burdened by this additional task and to ensure sufficient time for evaluation, feedback, and revision of the developed product. The data regarding the time spent per case study and the number of iterations required before developing a final product, on an average basis for the entire group of students taking part in this research, are provided in Table 1 as shown below:

The whole pattern of learning concepts, designing, and examining products by considering a particular case related to design needs in the industry in the real scenario help students understand the relevant information in a better way and allow them to visualize the design which enhances their imaginative abilities in solving real-life design problems. The process of designing under conventional method by performing calculations and creating 2D drawings is not of much help in the intellectual growth of students. Instead, the

method followed in the above case studies allows students to learn skills of CAD designing and 3D printing along with providing them with the opportunity to evaluate and improve their design through modern computational tools, resulting in a brief encounter of a product development cycle and its phases.

5 Assessment and results

To assess the effectiveness of this integrated learning model, several parameters, such as student performance in industry and institute, student motivation, student feedback, and placement data, were taken into consideration and evaluated against the data from conventional method of learning.

The aim of this research along with considering the immediate impact of this method was to track the long-term impact of this model on students learning outcomes. As the students are allocated design projects during each year of their studies, the follow-on problems or case studies were gradually made more challenging and time-consuming requiring a good grasp of engineering knowledge, skills of practice, and ability to link theory with practice. Several case studies were developed in such a manner to provide a broad perspective to students in a short time with a realistic context, helping them in studying the design process and the stages of a product life cycle through experiential learning. These case studies were based on the actual industrial problems related to the courses being studied by students during each semester. The research was carried out over a period of four years and one of the major findings from this research was the ability of this learning technique to nurture intrinsic motivation in students to promote deep learning of

the concerned subject matter by giving a greater emphasis on effective and innovative pedagogical interventions. The intrinsic motivation which is due to the pleasure of the task itself and the desire to excel in the task is essential for the continuous growth and success of the individual.

An integral part of the curriculum at our Institute is the incorporation of industrial training during each year of study for an engineering graduate to ensure that students are not bewildered in the industrial environment during the start of their professional practice. The objective of providing students with an experience of the industrial conditions, for a duration of one week to five months depending upon the year of graduation, is to help students keep up with the rapid development in the industry and provide them with a chance to evaluate their practical skills in addressing the actual workplace issues. To measure the usefulness of this experiential learning approach in preparing students for efficient performance in the industry, feedback was taken from the students who were experiencing this updated learning method after the successful completion of their training. They were asked to provide feedback regarding the usefulness of the content from the point of view of an industry, the ease with which the students were able to conceptualize and visualize the solution to a problem, how quickly or after how many attempts students were able to discover the optimum solution, the extent of utilization of the technical skills and software knowledge of students in the industry, etc. The response was quite positive with the majority of students being able to incorporate their knowledge and hands-on experience in their work as interns.

A special emphasis was given to the final year students who were a part of this experimental learning model to analyze the contribution of this method in developing industry-ready students. The data regarding the placement of these students were collected and evaluated against that of the entire batch, the results to which were phenomenal—all the 20 students who were part of this project were able to secure jobs with relative ease. It was reported by the students themselves that by being part of this research they were able to learn several software employed for CAD designing, analysis, 3D Printing, etc. which were a valuable addition to their skills and made their resume more engaging for the employers. With the advent of the Fourth Industrial Revolution (or Industry 4.0) that involves the use of modern technology to automate traditional practices in the industry, this skill set is highly desirable from the selectors' point of view as the proficiency in these software offers bright prospects for the employer and the employee.

Another effect of integrating 3D printing technology with the long-established method for teaching of designing, as observed in these 20 students, was the improvement in the efficiency of the students to deduce an optimum solution to the given problem. This was evident during the final year

of the involved students in that when working on a major project they felt more comfortable with software and tools used during modeling, were far more creative and imaginative, and were able to create projects of the level of professionally developed products. The understanding of the stages of product development and awareness of the issues encountered during these phases helped the students move on with their work in an orderly fashion with a lower number of failed attempts or setbacks before arriving at the optimum solution.

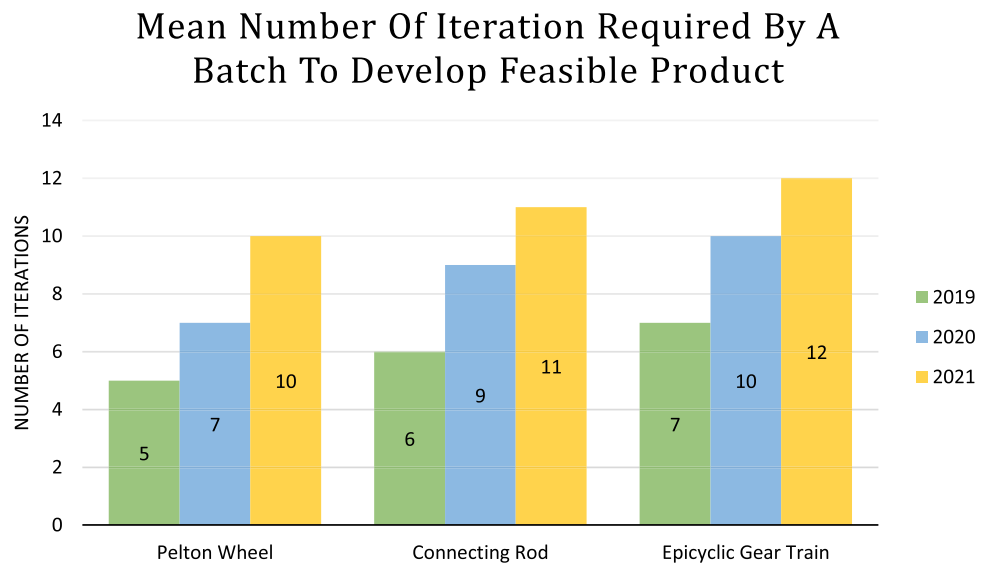
The students' 2019 batch who were a part of this research from the past three years, developed a better sense of understanding regarding mathematical modeling, CAD and prototyping of products. They were much aware of the issues and setbacks involved in the product design cycle and hence were able to arrive at the final feasible product in much less iterations as is evident from the data. Thus, they were able to save both time and resources which is a critical aspect of product design at a professional level. This difference in the average number of iterations required by a particular batch to develop a feasible product for different case studies, as shown in Fig. 20 is an important observation that points out the need to implement the additive manufacturing technology in the design courses from an early stage, preferably from the first year of education, to train students in designing a product in a highly optimized manner.

The learning method in this research was carefully worked out to ensure integration of the knowledge and practice in modeling, prototyping, and 3D printing with the existing model of learning in mathematical designing, as well as incorporate technical and contextual knowledge, competencies of practice, laboratory and design experience, professionalism, and ethics in the concerned students. Students who did not participate directly in this research involving the design and fabrication of projects through 3D Printing, expressed interest in engaging in other opportunities with 3D printing.

To this end, a survey was conducted for students working on case-based design problems. The survey was conducted in 2021 on all the 72 students which were a part of this research to get their feedback on this method. The students were asked to score their agreement and disagreement on a scale of 1 to 5 with 1. Strongly Disagree, 2. Disagree, 3. Neutral, 4. Agree, 5. Strongly Agree. The results of the survey are published below in a tabular form, Table 2, as follows:

According to the results, the questions present in the survey were taken as feedback of the research work from the students along with the responses of all the 72 students for each question. The results of the survey were very encouraging with 92.78% ratings falling under Agree (4) & Strongly Agree (5) categories and many students

Fig. 20 Graph depicting the mean number of iterations required by a batch to develop feasible product



commented that the whole learning experience felt more real & worthwhile. The above survey is a clear-cut indication of the success rate of the research work in integrating 3D printing with the conventional learning model.

This integrated learning model which was implemented simply with the intention to explore the possibilities of incorporating 3D printing technology into the conventional methodology for designing products which proved to be a game changer for the students and the institute, not only did it improve the performance of the students in the industrial environment but also enabled them to understand the concepts better than the others.

The evaluation of student's sensitivity and awareness to design and product development cycle-related issues and their knowledge of important design and manufacturing concepts like improvement through iterations of physical products, scaling of model for prototyping, manufacturing tolerances and surface finish constraints, guidelines and preparation of software file related to 3D printing technology, was done before and after participating in the research to measure the impact of the research on improving the design skills and knowledge of students.

The participating students (group of 72 students) were evaluated based on their knowledge of the above design and manufacturing concepts and their ability to implement these concepts in physical real-life design problems before and after exposure to the case study-based product development exercises. The evaluation was done through a short 20 question objective test taken before and after participation in the research for all the 72 students and the average score of the entire sample size out of 10 for each of the concepts is presented in a tabulated form in Table 3. The variation in the overall average score from student to student for each of the concepts is also indicated in Table 3 by means of the

standard deviation of the average score. The data point out that the students have improved their theoretical and practical skills related to design concepts and 3D printing, as being a part of this research.

The vast scope of 3D printing technology and flexibility of various parameters involved in the manufacturing of 3D printed parts has garnered a lot of attention from the students who are very much willing to learn and apply this technology in their design problems. Some students even took the initiative themselves and volunteered for learning modeling and 3D printing by taking out time from their curriculum to spend extra time to work on design problems using CAD and prototyping.

With such a high competition among engineering graduates, this state-of-the-art learning model involving virtual design and prototyping through 3D printing will provide a more hands-on approach to students, in which they will experience, hypothesize, assemble, and test actual physical products which result in a finer sense of the correlation between the design and fabricated product. In this way, each design iteration will be kept on improving which enables them to achieve the product they envision.

Therefore, using the proposed approach in this paper, students can be well prepared for a professional work environment, to replenish their minds with innovative ideas and feed them with technological curiosity which will help them to make their mark among a plethora of engineers graduating each year.

Table 3 Evaluation of conceptual knowledge and implementation skills Pre and post exposure to additive manufacturing-based design learning

Design and manufacturing concepts	Evaluation of conceptual knowledge and ability to implement in practical problems	
	Before participating in research	After participating in research
Improvement of physical products through iterations	Mean = 5 Standard Deviation = 0.7	Mean = 8 Standard Deviation = 1.1
Scaling of model for prototyping	Mean = 4 Standard Deviation = 0.9	Mean = 9 Standard Deviation = 0.8
Manufacturing Tolerances and surface finish	Mean = 5 Standard Deviation = 1.0	Mean = 7 Standard Deviation = 0.9
Guidelines, constraints, and preparation regarding 3D printing	Mean = 3 Standard Deviation = 1.2	Mean = 8 Standard Deviation = 0.7

6 Conclusion

The outcomes of this research provided valuable data regarding the impact of 3D printing on the cognitive processes of students for learning design courses. These data can be used to promote the integration of 3D printing into the present teaching methods of design courses that not only challenge the students to critically reflect on the wider impacts of their work but also inculcate real-world skills that are extremely crucial for their professional success.

The effective and promising results of this research have impressed the institute authorities as well as the students to such an extent that at present we have successfully embedded the 3D printing technology for prototyping and modeling in various courses being taught at the university, such as Theory of Machines 1 (MEM404), Automobile Engineering (MEM 603), Machine Design 1 (MEM 601), Machine Design Practice 1 (MEM 602) and Machine Design 2 (MEM

706), Applied Thermodynamics (MEM 304) and Hydraulics Machinery (MEM 818), etc.

This gradual shift in the mechanical engineering pedagogy away from the conventional approach enabled students to develop a deeper sense of understanding in terms of conceptual and practical knowledge. The proposed method in this work is a tool that can be used to transform students' concepts of design into reality with relative convenience. Desktop 3D printing helps educators to engage technically sharp-witted students and ease their design effort.

The inclusion of 3D printing of models to conventional design methods made students understand better various aspects of the design process in a completely different way. Faculty members in the department found 3D printing a positive addition to the curriculum with students reporting the 3D printing process was easier than their expectation. A positive culture change toward engineering designs and engineering was noted and student engagement encouraged the expansion and refinement of the design courses.

Table 2 Result of feedback survey

Survey Questions	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
The work helped me in better understanding of lecture	0	1	9	16	46
The prototyping helped me in better visualization of product	0	0	2	29	41
Being a part of research work improved my creativity	0	1	9	22	40
Being a part of research work improved my theoretical knowledge	0	1	10	25	36
This method of learning should be adopted in the curriculum	0	0	2	19	51
The design work helped me learn new skills	0	0	1	33	38
The use 3D Printing technology was relatively easy	0	0	3	28	41
The product development exercise helped me in industry during internship	0	2	5	40	25
The work has improved my confidence on my designing skills	0	0	4	31	37
The learning method involved in research was engaging and innovative	0	0	3	28	41
Being a part of research work helped understand certain design aspects that other were unaware, such as surface finish, tolerances, etc.	0	1	1	20	50
The designing by this method results in product with accurate functionality	0	0	4	43	25
It is easy to adapt to the learning method involved in research work	0	2	8	32	30
I would adopt this methodology for my future projects	0	1	6	29	36
The course is highly effective in improving design learning experience	0	0	2	24	46

The most important factor that 3D designing will enhance is the confidence among students when they engage in a real-world design problem through prior experiences. It provides a “hands-on learning” approach where students are provided with a realistic experience in designing and developing models for a real-world problem using computational tools. The integration of 3D printing into the design course will improve the grasp of students undertaking the course in simulation, prototyping, and analysis.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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