

## Chapter 2

# Template-Based Integrated Design: A Case Study

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**Abstract** This chapter discusses the application of concurrent engineering principles in the product development phase to achieve maximum cost reduction by foreseeing the manufacturability constraints and solving perceived problems beforehand in the concept-generation phase itself. This would entail integrating the different phases, namely, design calculation, computer-aided design, and process planning. This design methodology is applied to the process of shaft design and bearing selection in the product development phase of a motor. The design calculations include a force analysis and also bearing life calculations. The output from these design calculations is used to develop drawings in integrated design and engineering analysis software (I-DEAS). These designs are then used to carry out a time and cost analysis.

## 2.1 Introduction

The increased globalization of the manufacturing industry opened up new markets with varying customer requirements and also increased competition with more number of companies by introducing low-cost products. This caused an acceleration in the rate of product change which forced engineers and managers to respond with products having lower cost, better quality, and shorter development times. As a result, companies started reinventing their product development methodologies. One of the areas that have gained importance due to this is concurrent engineering. Concurrent engineering techniques have gained wide acceptance in the high volume manufacturing companies such as automotive and consumer electronics markets. It has also gained importance in the low volume, high innovation industry of aerospace. Concurrent engineering is defined as an integrated and systematic approach to the design of products and their related processes, including manufacture and support.

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This approach causes designers to consider the whole product life cycle from conception through disposal while selecting a design [22]. One of the main reasons for concurrent engineering to gain broad acceptance was its impact on time. Second, it got the manufacturing and marketing departments involved early in the product development process. This enabled them to influence the design and obtain a cost-effective and high performance product. It also made full use of latest advances in information technology to develop libraries with complex accumulations of detailed design. Because of this, knowledge gained during the development of one product could be passed on to subsequent product developments [20].

## **2.2 Problem Description**

Any manufacturing process starts with the product development phase. In a sequential engineering approach the design process and the actual manufacturing are considered as mutually independent. The design department develops a product depending on the customer requirements and design constraints and provides engineering drawings to manufacturing. Here the design department does not take into consideration the manufacturing capabilities and the process limitations on the shop floor. The manufacturing department then carries out a manufacturability analysis of the design and returns it back to the design section with a list of manufacturing concerns. Here each department passes the design or drawings back and forth until they achieve functional success. In the concurrent engineering approach, this back and forth movement of drawings is completely eliminated since manufacturability concerns are addressed in the design phase itself.

Once the design is finalized, resources have to be assigned for manufacturing the product. This is carried out in the process planning phase. In a manual process planning environment, each process plan reflects primarily the experience and skills of the individual process planner; hence it is difficult to maintain consistency and discipline in the planning process [5]. It also acts as a significant break in the automated flow of data from CAD to CAM. Hence it is necessary to automate process planning along with the design phase and allow smooth integration of the two. Advances in information technology and increase in the processing speed of computers help to develop libraries which contain all the data required for manufacturing. This also eliminates the need to develop a new process plan from scratch if a similar product component has already been manufactured.

## **2.3 Problem Solution**

Modifications made to the product in the design phase have maximum impact on the cost and functionality of the product [15]. Hence, we would be concentrating on applying concurrent engineering principles in the product development stage

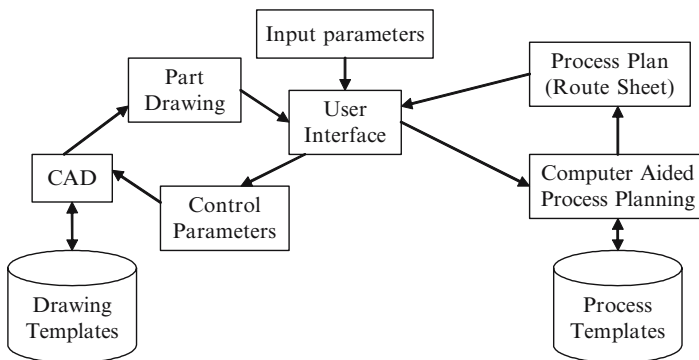
and thus achieve maximum cost reduction by foreseeing the manufacturability constraints and solving perceived problems beforehand in the concept-generation phase itself.

In an integrated CAD/CAM environment, parts are detailed using a computer graphics system. The system stores the geometric information necessary to create process plans. These process plans determine the machining processes, tools, and machines required to convert a part from its initial form to the desired form. To apply this methodology, we have to interlink the different phases of the manufacturing process. The template-based system can be divided into three different parts:

1. Design calculations.
2. Drafting.
3. Process planning.

The system schema is illustrated in Fig. 2.1. The user requirements are analyzed and converted into input parameters for the design calculation phase. The output from the design calculations is utilized as the control parameters for selecting feasible drawings from the CAD system. The process planning module uses the CAD data and then generates route sheets as well as a cost analysis of feasible designs. This enables the designer to study the impact on the design on the basis of cost and manufacturing capability.

The template-based design methodology is used for the bearing selection and shaft design process of an electric motor. The input parameters are speed, power of motor, and also the minimum life of bearing required. This information is then used to obtain the parameters for CAD models. The CAD modeler then returns feasible part drawings which act as the input to the process planning phase. The process planning module prepares the route sheet and carries out a time and cost analysis for different feasible part drawings and returns it to the user.



**Fig. 2.1** Basic system schema

## 2.4 Electric Motor

An electric motor converts electrical energy to mechanical energy. Alternating current motors are classified into polyphase synchronous motor, and single-phase or polyphase induction (asynchronous) motors. In polyphase synchronous motors, magnetic field associated with the rotor results from a rotor winding (electric field) excited by direct current via slip rings or from permanent magnets on the rotor structure. In single-phase or polyphase induction motors, the rotor magnetic field is created by electromagnetic induction effects [9]. There are two common features for all types of motors. The first feature is that, for an average torque to be produced, magnetic fields of the stator and the rotor must be stationary with respect to each other. The second feature is, for a specific rotor length, air gap diameter, and speed, there is a maximum average power output rating.

In induction motors, power is transferred from the stationary part (stator) to the rotating part (rotor) [10]. The stator is made of a stack of steel laminations with insulated slots opening to the inside diameter and holding stator coils or windings. The rotor is also made up of slotted steel laminations. The rotor conductors and end rings are formed using a die cast process. The rotor stack length is approximately equal to the length of the stator stack and its outside diameter is smaller than the inside diameter of the stator packet by twice the air gap. This rotor packet is fitted on the shaft. The shaft is supported on the bearings. The end of the shaft where the power is transferred through a pulley or coupler is called the drive end. The other end is called the nondrive end. An external fan is mounted on the nondrive end of the shaft for external cooling.

The proposed design methodology is applied to bearing selection and shaft design of electric motors. The inputs to design calculations are speed, power of the motor, type of drive, and minimum life of bearing required. This information is used to calculate and select the minimum diameter of shaft drive end and also to select the bearings required. Dimensions of the bearings and shaft extension dimensions are then used as the control parameters for CAD template retrieval. The process planning module then carries out a cost analysis for the modified product and returns the minimum cost machine to the user.

## 2.5 Design Calculations

Power ( $P$ ) and speed ( $N$ ) are inputs to the design calculation process. The torque ( $T$ ) acting on the shaft is given by

$$T_{(Nm)} = [1000 \times 60 \times (P_{(kW)} / N_{(rpm)})] / (2\pi) \quad (2.1)$$

The tangential force ( $F_t$ ) is calculated as

$$F_{t(N)} = [T_{(Nm)} / (D_{(m)} / 2)] \quad (2.2)$$

where  $D$  is the nominal diameter of the pulley or the coupler [16].

Based on the types of transmission, the radial force ( $F_r$ ) and the axial force ( $F_a$ ) acting on the shaft at the point of mounting is determined [21]. Forces generated at the elements mounted on the shaft produce bending moments and the power transmitted produces shearing stresses. A shaft force analysis is then carried out for the section at which transmission element is mounted. This analysis includes both the maximum shear stress theory and the distortion energy theory [14].

The stresses acting on the surface of a solid shaft are given as follows:

$$\sigma_x = 32M/\pi d^3 + 4F/\pi d^2 \quad (2.3)$$

$$\tau_{xy} = 16T/\pi d^3 \quad (2.4)$$

Assuming that the axial force produces the same kind of stress as the bending moment,

$$\tau_{\max} = (2/\pi d^3)[(8M + Fd)^2 + (8T)^2]^{0.5} \quad (2.5)$$

$$\sigma' = (4/\pi d^3)[(8M + Fd)^2 + 48T^2]^{0.5} \quad (2.6)$$

From the maximum shear stress theory, the allowable shear stress is given by

$$\tau_{\text{all}} = S_y/2n \quad (2.7)$$

From the distortion energy theory, the normal stress is given by

$$\sigma'_{\text{all}} = S_y/n \quad (2.8)$$

where  $d$  – diameter of the shaft;  $F$  – axial force;  $M$  – bending moment;  $n$  – factor of safety;  $S_y$  – yield strength;  $T$  – twisting moment;  $\tau_{\max}$  – maximum shear stress;  $\sigma'$  – normal stress;  $\tau_{\text{all}}$  – allowable shear stress; and  $\sigma'_{\text{all}}$  – allowable normal stress.

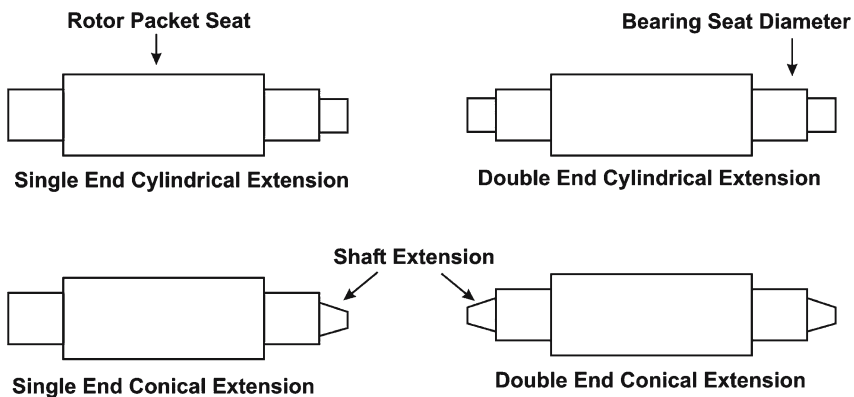
The factor of safety for maximum shear stress is taken as 1.5 and for maximum normal stress is taken as 2. The material used for the shaft is alloy steel C1045 with density 7830 kg/m<sup>3</sup>, whose allowable shear stress is equal to 60 kpsi and allowable normal stress is 92.5 kpsi [7]. Equating  $\tau_{\max}$  with  $\tau_{\text{all}}$  and  $\sigma'$  with  $\sigma'_{\text{all}}$ , the minimum required diameter of shaft extension is calculated. The shaft is primarily supported at the bearings. Elements mounted on the shaft include the rotor and the transmission device. A free body analysis of this shaft is carried out and the radial and axial forces acting on the bearings determined. A search heuristic is developed to select all the feasible combinations of bearings from the bearing database that will provide the required life. The process retrieves the bearing dimensions for each bearing and its associated cost. The bearings considered are deep groove ball bearings and roller bearings. The length and diameter of the bearing seat would be the same as the inner diameter and width of bearings used. The power and speed required for the application determine the electrical

design of stator and rotor. A database of electrical specifications is created which contains the rotor packet dimensions and its corresponding weight for each combination of power and speed.

## 2.6 CAD Modeler

Integrated design and engineering analysis software (I-DEAS) is used to generate and store shaft design templates. The shaft consists of the drive end and nondrive end shaft extensions, the drive end and nondrive end bearing seats, and the rotor packet seat. The different dimensions of the shaft are obtained from the design calculations. They include the minimum shaft extension and bearing seat dimensions. The rotor seat dimension is obtained from the electrical design database. The drawings are classified on the basis of the shaft ends as shown in Fig. 2.2. It is either cylindrical or conical. Second classification depends on whether the shaft has extensions on both ends or only one shaft extension. Both end shaft extensions are used either to run a tachometer or to run an external blower at the nondriving end.

Further classifications are based on the applications: low speed high torque and high speed low torque applications. Once the template is selected, necessary changes are made in the dimensions and also additional features like undercuts and threading are incorporated. All the changes made to the template are recorded. These modifications are passed on to the process planning stage.



**Fig. 2.2** Shaft classifications

## 2.7 Process Planning

Process planning is the development of a set of work instructions to convert a part from its initial form to the required final form [6, 11, 12, 19]. In the proposed system, the process plan provides detailed description of the manufacturing processes and machine tools required to make the part. This detailed information includes the list of different machines that are used, specific cutting energy for the work material, cost per hour of operation, standard setup and tear down times, and the number of tools utilized for the process. The process plans are saved in the system database. A search heuristic is developed for selecting the process plan. If the process plan does not exist in the database then a new process plan is generated by selecting machines on the basis of the features, dimensions, and tolerance required for the finished product. The process plan information is used to obtain the time required for manufacturing and also for cost estimation.

## 2.8 Cost and Time Analysis

Each process plan is linked to a cost analysis chart which gives the costs incurred in the manufacturing process. If a new process plan is generated then a detailed analysis for cost estimation is carried out. The time required for manufacturing a part can be classified into productive and nonproductive time [2, 4]. The productive time consists of roughing and finishing operations. Roughing operations are carried out at maximum power and the time taken is given by:

$$t_{mp} = (60r_v p_s W)/(paW^b) = ((60r_v p_s)/(pa)) W^{(1-b)} \quad (2.9)$$

where  $r_v$  – proportion of initial volume of workpiece to be removed by machining,  $p_s$  – specific cutting energy,  $\rho$  – density of work material,  $W$  – initial weight of work material in pounds, and  $a, b$  – constants for machine tool type.

The time taken for the facing operation at maximum power condition ( $t_{mpf}$ ) is given by

$$t_{mpf} = 60 V_m p_s / P_m \quad (2.10)$$

where  $V_m$  – volume of material removed and  $P_m$  – maximum machining power.

The time taken for the finishing operation depends on the surface generation rate  $R_{sg}$  for the material. It is the product of speed and feed and is the rate at which machined surface is generated.  $R_{sg}$  for alloy steel work piece and high speed steel tool is found to be equal to 23.7 in.<sup>2</sup>/min [3]. The finished machining time is given by

$$t_{mc} = (60A_m)/R_{sg} \quad (2.11)$$

where  $A_m$  – surface area to be generated.

The tool replacement time is accounted for by modifying the roughing and finishing time equations as

$$t'_{mp} = t_{mp} [1 + (n/(1-n)) (t_{mc}/t_{mp})^{(1/n)}] \quad (2.12)$$

when  $t_{mc}/t_{mp} < 1$ , and

$$t'_{mc} = ((60A_m)/R_{sg}) (1/(1-n)) \quad (2.13)$$

where  $n$  is the Taylor tool life index and depends on the material of the tool. Value of  $n$  is taken as 0.123 for high speed steel tool [4]. The nonproductive time is calculated as

$$t_{np} = (t_{sa} + n_t t_{sb})/B_s = t_{ln} + n_o t_{pt} \quad (2.14)$$

where  $t_{sa}$  – basic setup time,  $t_{sb}$  – setup time per tool,  $B_s$  – batch size,  $t_{ln}$  – loading and unloading time,  $t_{pt}$  – tool positioning time, and  $n_o$  – number of operations.

The loading and unloading time depends on the weight of the workpiece and is given by

$$t_{ln} = c d W \quad (2.15)$$

where  $c$  and  $d$  are constants and have values 38 and 1.1, respectively, for a lathe [8].

The total rate for the machine and the operator is given by

$$R_t = (k_m e W^f)/(2 n_y n_s) = k_o R_o \quad (2.16)$$

where  $R_o$  – direct labor rate,  $k_m$  – factor for machine overhead,  $k_o$  – factor for operator overhead,  $e, f$  – constants for a given tool,  $n_y$  – amortization period for the cost incurred, and  $n_s$  – number of shifts.

The total cost of manufacturing can then be calculated by multiplying the cost rate with the total time required for the process. The manufacturing cost  $C_{man}$  is given by

$$C_{man} = R_o (t_{mp} + t'_{mc} + t_{np}) \quad (2.17)$$

when  $t_{mc}/t_{mp} \geq 1$ , and

$$C_{man} = R_o (t'_{mp} + t'_{mc} + t_{np}) \quad (2.18)$$

when  $t_{mc}/t_{mp} < 1$ .

Bearings are normally procured from a vendor. If the bearing required can be found in the bearing database then its corresponding cost is retrieved and used in calculating the total cost. If the bearing cost is not available in the database, then the relative cost of the bearing is determined using polynomials [17]:



$$P_3(X) = a_3X^3 + a_2X^2 + a_1X^1 + a_0 \quad (2.19)$$

where  $a_3, a_2, a_1, a_0$  – coefficients,  $X$  – standardized dimension, and  $P_3(X)$  – third-degree standardized cost function.

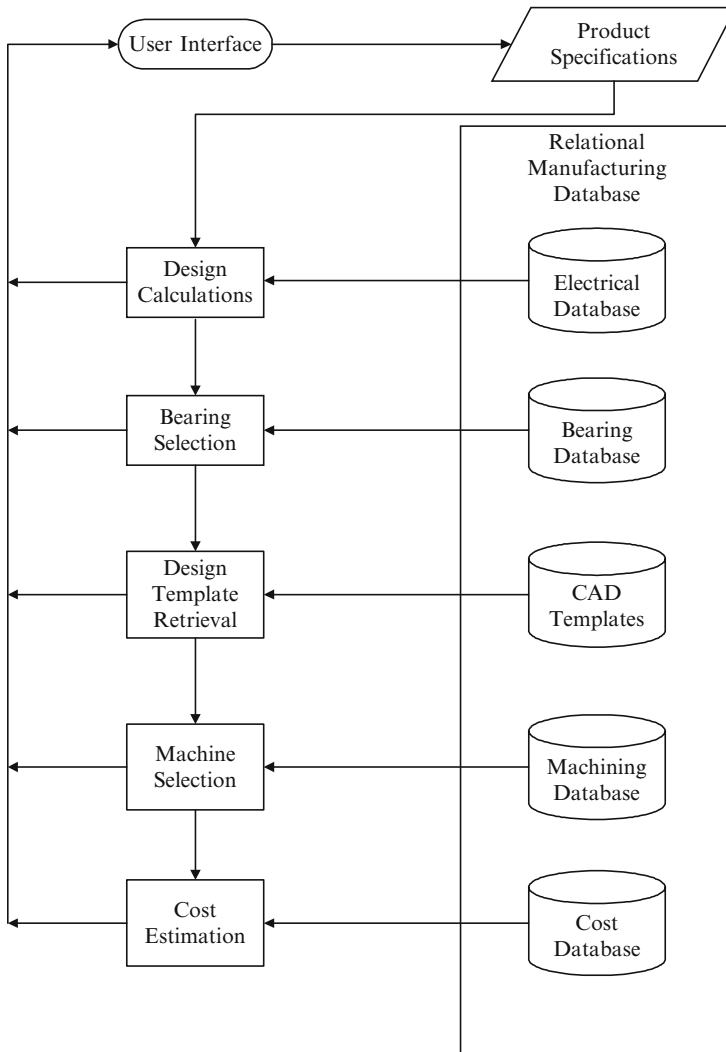
The coefficients  $a_3, a_2, a_1$ , and  $a_0$  are obtained from the following set of equations.

The total cost for the design including the bearing procurement cost and the manufacturing cost is reported for all the machines that can be utilized to manufacture the shaft. This estimate helps the designer to select the minimum cost alternative along with the machine information on which it can be processed.

$$\begin{pmatrix} \sum_{i=0}^M \left( \frac{X_i^{2n}}{Y_i^2} \right) & \sum_{i=0}^M \left( \frac{X_i^{2n-1}}{Y_i^2} \right) & \text{K} & \text{K} & \sum_{i=0}^M \left( \frac{X_i^n}{Y_i^2} \right) \\ \sum_{i=0}^M \left( \frac{X_i^{2n-1}}{Y_i^2} \right) & \sum_{i=0}^M \left( \frac{X_i^{2n-2}}{Y_i^2} \right) & \text{K} & \text{K} & \sum_{i=0}^M \left( \frac{X_i^{n-1}}{Y_i^2} \right) \\ \text{M} & \text{M} & & & \text{M} \\ \sum_{i=0}^M \left( \frac{X_i^n}{Y_i^2} \right) & \sum_{i=0}^M \left( \frac{X_i^{n-1}}{Y_i^2} \right) & \text{K} & \text{K} & \sum_{i=0}^M \left( \frac{1}{Y_i^2} \right) \end{pmatrix} \begin{pmatrix} \alpha_n \\ \alpha_{n-1} \\ \text{M} \\ \alpha_0 \end{pmatrix} = \begin{pmatrix} \sum_{i=0}^M \left( \frac{X_i^n}{Y_i^2} \right) \\ \sum_{i=0}^M \left( \frac{X_i^{n-1}}{Y_i^2} \right) \\ \text{M} \\ \sum_{i=0}^M \left( \frac{1}{Y_i^2} \right) \end{pmatrix} \quad (2.20)$$

## 2.9 System Components

The structure of the system is divided into four major components: design calculations, bearing selection, design template retrieval, and machine selection with process cost estimation. These components are illustrated in Fig. 2.3. In this system, the product specifications are the input for carrying out design calculations. The external forces acting on the bearings and the shaft extension is calculated. The design calculations also retrieve the electrical design data for rotor packet from the database. A search heuristic is implemented for selecting a minimum cost bearing which can withstand the external forces acting on it. The features required and dimensions of the bearings, rotor packet, and shaft extension are used to retrieve the CAD templates. The template information is used for selecting the machine and carry out a process cost analysis. The output from each component is reported back to the user interface. The system is implemented on a personal computer equipped with a Pentium-4 processor and Windows XP operating system. The graphical user interface, search heuristics, and design calculations are developed in Microsoft Visual Basic (.NET platform). The relational database is developed in Microsoft Access 2003. The 3-D models are generated in I-DEAS and imported into Visual Basic which acts as the drawing templates.



**Fig. 2.3** System structure

## 2.10 Design Calculations

The power and speed entered in the user interface is used to search the electrical database to retrieve specifications of the rotor packet. These specifications are used to calculate the radial and axial magnetic forces acting on the shaft [1]. The radial force acting on the shaft is given by:

$$F_{mr} = (0.1 + 0.005SID) [(0.25RL \cdot SID) / (5AG)] \quad (2.21)$$

where  $F_{mr}$  – radial magnetic force, SID – inner diameter of stator packet, RL – rotor packet length, and AG – air gap.

The axial force is given by:

$$F_{ma} = (35A.T)/SID \quad (2.22)$$

where  $F_{ma}$  – axial magnetic force, SID – inner diameter of stator packet,  $A$  – skew angle,  $T$  – torque, and AG – air gap.

The skew angle is the angle made by the rotor packet slots with the axis of rotation. Skew angle is provided in some motors to reduce noise levels. Skew angles are generally kept as small as possible since higher skew angles reduce motor performance. A free body analysis of the forces acting on the shaft is carried out to find the external radial and axial forces acting on the bearings as shown in Fig. 2.4. At equilibrium conditions, resultant moment  $\Sigma M = 0$ , resultant horizontal forces  $\Sigma F_{hor} = 0$ , and resultant vertical forces  $\Sigma F_{vert} = 0$ .

So taking moments about the drive end bearing, the radial force acting on the nondrive end is given by:

$$F_{nde} = (-1)[(F_{r2} + G_2 \cos \theta)(l_2 + L) + (F_{mr} + G \cos \theta)l_i - (F_{r1} + G_1 \cos \theta)l_1]/L \quad (2.23)$$

The radial force acting on the drive end is calculated as:

$$F_{rde} = F_{r2} + G_2 \cos \theta - F_{nde} + G \cos \theta + F_{r1} + G_1 \cos \theta \quad (2.24)$$

The resultant axial force is calculated as:

$$F_{ade} + F_{ande} = F_{a1} + F_{a2} + G_1 \sin \theta + G_2 \sin \theta + G \sin \theta \quad (2.25)$$

$F_{r1}$  – radial force acting on the drive end.

$F_{a1}$  – axial force acting on the drive end.

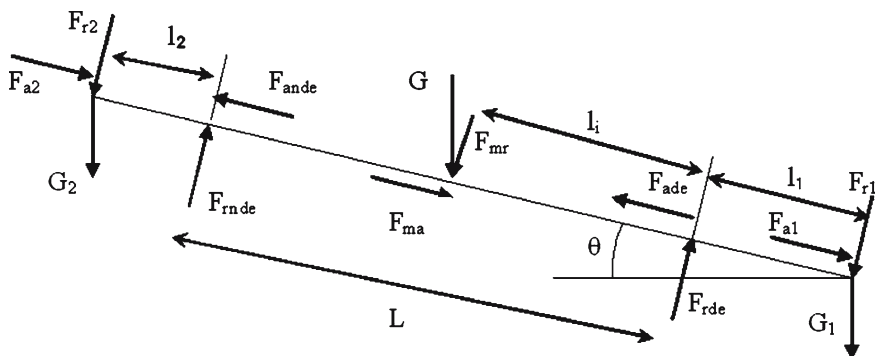


Fig 2.4 Free body diagram

- $G_1$  – weight of drive end transmission device.
- $F_{r2}$  – radial force acting on the nondrive end.
- $F_{a2}$  – axial force acting on the nondrive end.
- $G_2$  – weight of nondrive end transmission device.
- $F_{mr}$  – radial magnetic force.
- $F_{ma}$  – axial magnetic force.
- $F_{rde}$  – radial force acting on drive end bearing.
- $F_{ade}$  – axial force acting on drive end bearing.
- $F_{rnde}$  – radial force acting on nondrive end bearing.
- $F_{ande}$  – axial force acting on nondrive end bearing.
- $L$  – distance between bearings.
- $l_1$  – distance between the drive end transmission device and the drive end bearing.
- $l_2$  – distance between the nondrive end transmission device and the nondrive end bearing.
- $l_i$  – distance between the center of the rotor packet and the drive end bearing.
- $\theta$  – angle made by the shaft with the horizontal plane.

The external forces acting on the bearings and the minimum shaft extension diameter obtained from stress calculations are then called from the design calculations module into the bearing selection module which returns the minimum cost bearings that can be used for the application.

## 2.11 Bearing Selection

The different types of bearings considered are spherical ball bearings (62 and 63 bearings), cylindrical roller bearings (NU2 and NU3 bearings), and angular contact bearings (72 and 73 bearings) manufactured by Svenska Kullagerfabriken (SKF), Inc. The bearing life required for all applications is 100,000 h. For each of the bearing types, a search is carried out to select the minimum cost bearing. The bearing life calculations for each type of bearing are described in the following sections [18].

### 2.11.1 Bearing Life Calculations for Spherical Ball Bearings

The equivalent load ( $P_{eq}$ ) acting on spherical bearings is given by:

$$P_{eq} = XF_r + YF_a \quad (2.26)$$

where  $F_r$  – external radial force acting on the bearing and  $F_a$  – external axial force acting on the bearing.

$$If [(F_a/F_r) > 0.505 (F_a/C_o)^{0.231}] \text{ then } X = 0.56 \text{ and } Y = 0.84 (C_o/F_a)^{0.24} \quad (2.27)$$

or else  $X = 1$  and  $Y = 0$ .

where  $C_o$  – static capacity of the bearing,

The bearing life ( $L$ ) in hours is given by:

$$L = 10^6 (C_{dyn}/P_{eq})^3 / (60 N) \quad (2.28)$$

where  $C_{dyn}$  – dynamic capacity of the bearing and  $N$  – speed in revolutions per minute.

### 2.11.2 Bearing Life Calculations for Cylindrical Roller Bearings

Roller bearings cannot withstand axial forces but can withstand very high radial forces. The bearing life for cylindrical roller bearings is given by:

$$L = 10^6 (C_{dyn}/P_{Fr})^{10/3} / (60 N) \quad (2.29)$$

### 2.11.3 Bearing Life Calculations for Angular Contact Bearings

The equivalent load ( $P_{eq}$ ) acting on angular contact bearings is given by:

$$P_{eq} = XF_r + YF_a \quad (2.30)$$

where  $F_r$  – external radial force acting on the bearing and  $F_a$  – external axial force acting on the bearing.

For 72 bearings,

if  $[(F_a/F_r) > 1.14]$  then  $X = 0.35$  and  $Y = 0.57$  or else  $X = 1$  and  $Y = 0$ .

For 73 bearings,

if  $[(F_a/F_r) > 1.14]$  then  $X = 0.35$  and  $Y = 0.93$  or else  $X = 1$  and  $Y = 0.55$ .

The bearing life ( $L$ ) is given as

$$L = 10^6 (C_{dyn}/P_{eq})^3 / (60 N) \quad (2.31)$$

## 2.12 Bearing Search

The search function retrieves the minimum cost bearing from each type for drive end and nondrive end. The constraints for the search are that selected bearings should be able to provide a minimum of 100,000 h and the inner diameter of the bearing should be greater than the minimum shaft extension diameter required. The minimum cost bearings of each type are displayed in the user interface. Also the combination of bearings for the drive end and the nondrive end which has minimum

combined cost is chosen and displayed as the recommended bearings. The following pseudo code describes the search function.

**Begin**

**For** *each type of bearing*

*Sort bearings in descending order of their cost*

**Do while** *inner diameter of bearing  $\geq$  minimum shaft extension diameter*

**If** *bearing life calculated  $\geq$  100,000 hours and*

*Cost of bearing  $\leq$  minimum cost bearing then*

*Select bearing dimensions and*

*Initialize minimum cost = bearing cost*

**End Do Loop**

*Select minimum cost combination for drive end and non drive end bearing*

**End**

The dimensions and cost of the bearings are transferred from this module to the design template retrieval module.

## 2.13 Design Template Retrieval

The 3-D models are generated in I-DEAS and are then imported as image files into Visual Basic. The graphical user interface in Visual Basic prompts the user to specify the type of shaft extension. It also asks if threading is required and also the minimum tolerance to be achieved on the shaft. The features considered in the case study are based on the shaft extension. The different options are single- or double-shaft extensions, conical shaft extensions, and threaded shaft extensions. The system retrieves the dimensions of the rotor packet, which are the internal diameter and the length of the rotor packet, and shaft extension dimensions from the design calculation module. It also retrieves the drive end and nondrive end bearing dimensions, which are the inner diameter and the length of the bearings, from the bearing search module. Drawing templates are retrieved on the basis of the features specified by the user. The selected features and the minimum tolerance to be achieved are then used by the system to choose the appropriate machines. The dimensions of the bearings, shaft extension dimensions, and rotor packet dimensions dictate the final dimensions of the shaft and are passed on to the machine selection and the process cost estimation module. The final dimensions and the features to be processed on the shaft form the basis for the final process cost estimation.

## 2.14 Machine Selection and Process Cost Estimations

The dimensions and features from the design module are obtained and are used to select a machine and estimate the cost of production. The system searches through the existing process plans in the database to obtain a shaft with matching features

and dimensions. If a similar shaft has been previously manufactured, the system returns the machine on which it was manufactured as well as the time and cost required for manufacturing. The pseudo code shown below is used to search through the process plan database.

### ***Process Plan Search***

**Begin**

**Do While** *processplanreader.Read()*

**If**

*New shaft dimensions = processplanreader (dimensions)*

*And New shaft features = processplanreader (features)*

*And New shaft tolerance = processplanreader (tolerance)*

**Then**

*machine = processplanreader (Machine)*

*cost = processplanreader (Cost)*

**End If**

**End While Loop**

**End**

If a process plan is not found in the database, a detailed analysis is carried out to select the machine and obtain the cost to manufacture. The flowchart for machine selection and cost estimation is given in Fig. 2.5. The system searches for a suitable raw material. The raw material database consists of various sizes of available cylindrical billets. The raw material used in the case study is alloy steel C1045. The machine selection module computes the total length and the maximum diameter of the designed shaft from the dimensions retrieved from the design module. It then searches the raw material database to select the billet, such that minimum material removal will be required for obtaining the final shape. This reduces the processing cost as well as the raw material cost. The following pseudo code describes the raw material search process.

### ***Raw Material Search***

**Begin**

*Sort material data in decreasing order of size*

**Do While** *Rawmaterialreader.Read( )*

**If** *rawmaterial length > total length of designed shaft*

**And**

*Rawmaterial diameter > maximum diameter of designed shaft*

**Then**

*select raw material*

**End If**

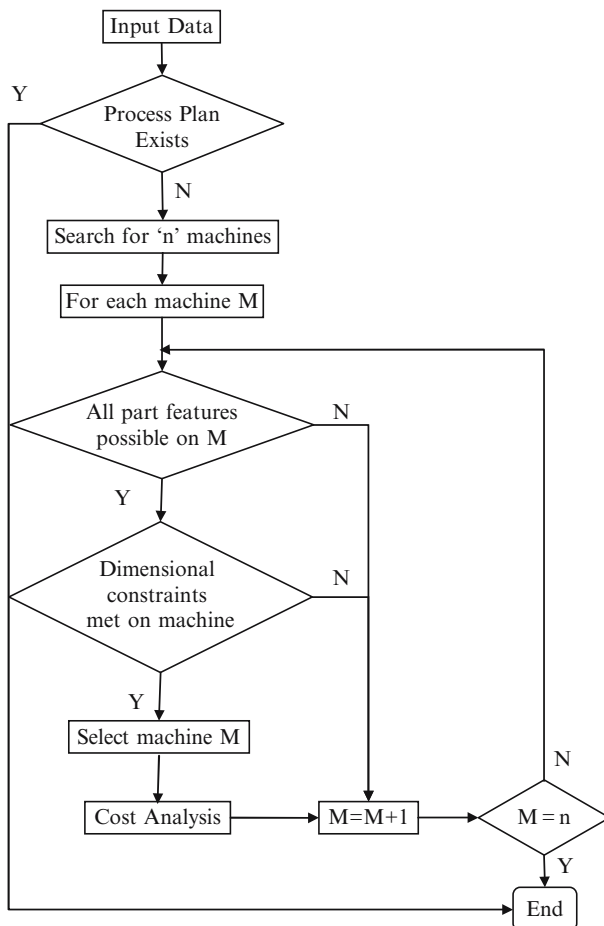
**Go to next smaller raw material**

*cost = processplanreader (Cost)*

**End While Loop**

**End**

The basic machining processes considered for this system are facing, rough turning, finish turning, taper, and threading. The system selects machines that can



**Fig. 2.5** Machine selection module

process the user-defined features on the shaft. The other two constraints for machine selection are the minimum tolerance required and the capacity of the machine. For each machine selected, the time required for machining is calculated. The nonproductive time ( $t_{np}$ ) required for the process is found by assigning values to the number of operations ( $n_o$ ) and the number of tools ( $n_t$ ) required for the machining process which depends on the features to be machined. The setup times for the machine ( $t_{sa}$ ), the setup time per tool ( $t_{sb}$ ), and the tool positioning time ( $t_{pt}$ ) are obtained from the machine database. The batch size is directly obtained from the user interface. The loading and unloading time depends on the weight of the work piece ( $W$ ), which is obtained from the raw material database. For roughing operations, which are carried out at maximum power conditions, the specific cutting energy ( $p_s$ ) is found to be 1.3 hp/(in.3/min) for alloy steel work piece and high speed steel tool [3]. The values for tool constants ( $a$ ,  $b$ ) are obtained from the machine database.



The time required for finishing operations is found by calculating the surface area generated in the machining surface. The surface area generated depends on the geometry and dimensions obtained from the design template. Tool replacement costs are accounted for by incorporating the Taylor's tool life index in the roughing and finish machining time equations. The factors " $k_m$ ," " $k_o$ ," " $e$ ," and " $f$ " are retrieved from the machine database to calculate the machine rate. The total time required for machining is then multiplied with the machine rate to obtain the cost for machining.

The module then returns the list of machines that can be used with the machining cost for each machine along with the selected machine. Even if the process plan exists in the database, the system runs a detailed cost analysis to verify the cost. This ensures that any changes made to the machine database after the existing process plan was created would be considered for the evaluation. If there is any change in the cost of machining, the modified value can be incorporated in the process plan database.

## 2.15 Case Studies

In this section, two examples are presented to demonstrate the integrated system and illustrate the operation procedure for the system. The user interface consists of four different windows, each representing a single module. The executable file is coded in Visual Basic and is connected to MS Access databases. The 3-D models are imported as image files and are retrieved by the system [13].

### 2.15.1 Case Study 2.1

The data required for the design procedure is input in the user interface as shown in Fig. 2.6. In the example, the power required is 100 kW at 1500 rpm. The motor is at an incline of 10 degrees with the horizontal plane. It is a double-ended motor with transmission equipment at both ends. The transmission equipments are spur gear with a nominal diameter of 350 mm and weight 30 kg and direct coupling with a nominal diameter of 300 mm and weight 30 kg. The number of units required is 10, which is considered as the batch size for process cost estimation.

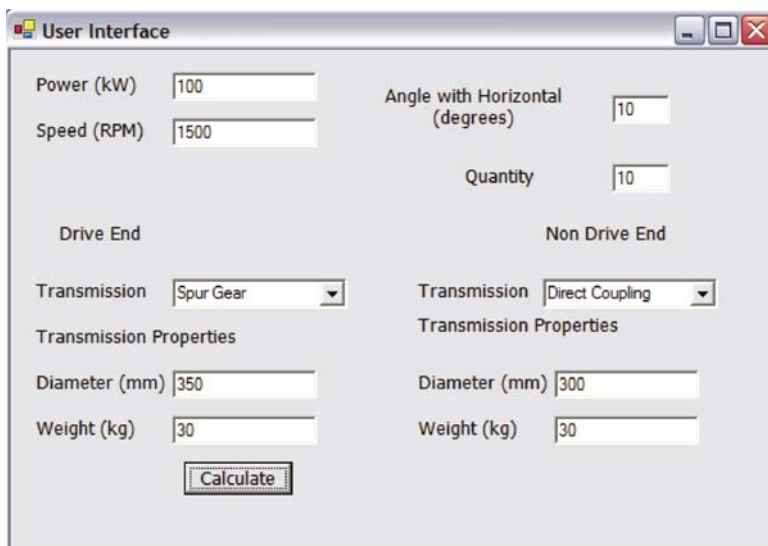
When the "Calculate" button is pressed, the system finds the resultant forces acting on the bearings, which are given below.

Resultant radial force on the drive end = 12,093.16 N

Resultant radial force on the nondrive end = 2,230.44 N

Resultant axial force = 161.87 N

These values are then passed on to the bearing selection module which displays the minimum cost bearings for each type that will provide the required bearing life. This screen is displayed in Fig. 2.7. The bearings recommended by the system are



The image shows a software window titled "User Interface" with standard Windows window controls (minimize, maximize, close). The window is divided into two main sections: "Drive End" on the left and "Non Drive End" on the right. Each section contains input fields for "Power (kW)", "Speed (RPM)", "Angle with Horizontal (degrees)", "Quantity", "Transmission" (a dropdown menu), "Transmission Properties", "Diameter (mm)", and "Weight (kg)". A "Calculate" button is located at the bottom center of the window.

Drive End		Non Drive End	
Power (kW)	100	Angle with Horizontal (degrees)	10
Speed (RPM)	1500	Quantity	10
Transmission	Spur Gear	Transmission	Direct Coupling
Transmission Properties		Transmission Properties	
Diameter (mm)	350	Diameter (mm)	300
Weight (kg)	30	Weight (kg)	30
[Calculate]			

**Fig. 2.6** User interface for Case Study 2.1

NU219 with a cost of \$248.98 for the drive end and 6217 with a cost of \$120.59 for the nondrive end. When the “Manufacture” button is clicked, the dimensions of these bearings are passed on to the design module where the user is prompted to specify the features and the minimum tolerance required as shown in Fig. 2.8. In the design template module, the user specifies the shaft end feature as “Double cylindrical shaft end” and clicks the “Template” button to retrieve the template. The user also specifies that no threading is required on the shaft ends. Also the closest tolerance required is specified as 2  $\mu\text{m}$ . This information is transferred to the machine selection module when the “Machine” button is clicked. The machine selection and process cost estimation menu is shown in Fig. 2.9. If a shaft with similar features and dimensions has already been processed, then its corresponding process plan along with the cost is retrieved. The machine selection module displays a list of machines and the corresponding machining costs. The system selects the machine “M3” with the least machining cost “\$ 31.66.” It also retrieves the raw material cost from the raw material database and the bearing cost from the bearing search module and calculates the total cost as “\$ 642.79.” This cost can then be compared with that of the existing process plan.

### 2.15.2 Case Study 2.2

In this example, the power required is 220 kW at a speed of 750 rpm. It is a single shaft end motor with a conical shaft end with a flexible coupling as the transmission device. The nominal diameter of the flexible coupling is 400 mm and the weight of

Bearings				
Bearing Type	Drive End Bearing	Cost	Non Drive End Bearing	Cost
62	<input type="text" value="0"/>	<input type="text" value="\$0.00"/>	<input type="text" value="6217"/>	<input type="text" value="\$120.59"/>
63	<input type="text" value="0"/>	<input type="text" value="\$0.00"/>	<input type="text" value="6317"/>	<input type="text" value="\$221.02"/>
72	<input type="text" value="7238"/>	<input type="text" value="\$622.00"/>	<input type="text" value="7217"/>	<input type="text" value="\$171.94"/>
73	<input type="text" value="7328"/>	<input type="text" value="\$758.99"/>	<input type="text" value="7317"/>	<input type="text" value="\$344.29"/>
NU2	<input type="text" value="NU219"/>	<input type="text" value="\$248.98"/>	<input type="text" value="0"/>	<input type="text" value="\$0.00"/>
NU3	<input type="text" value="NU317"/>	<input type="text" value="\$401.54"/>	<input type="text" value="0"/>	<input type="text" value="\$0.00"/>
Recommended	<input type="text" value="NU219"/>	<input type="text" value="\$248.98"/>	<input type="text" value="6217"/>	<input type="text" value="\$120.59"/>
<input type="button" value="Manufacture"/>				

Fig. 2.7 Bearings for Case Study 2.1

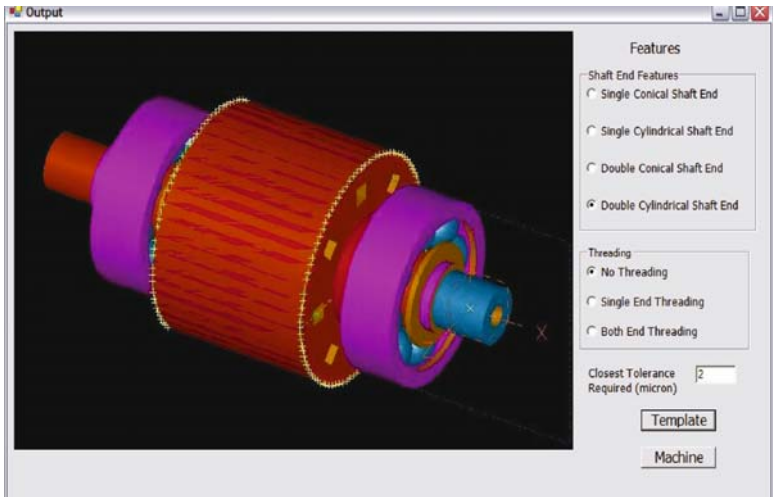


Fig. 2.8 Design template for Case Study 2.1

the coupling is 40 kg. The user interface is shown in Fig. 2.10. The resultant forces acting on the bearings are as given below:

- Resultant radial force on the drive end = 4,796.10 N.
- Resultant radial force on the nondrive end = 14,649.16 N.
- Resultant axial force = 0 N.

Based on these values, the system selects bearings NU219 with a cost of \$248.98 and 6219 with a cost of \$183.43. This is shown in Fig. 2.11. The bearing dimensions are then transferred to the design template module. The single conical shaft end with the threading option is chosen and the tolerance is input as 3  $\mu\text{m}$ . The design template menu is shown in Fig. 2.12.



Fig. 2.9 Machine selection and cost estimation for Case Study 2.1

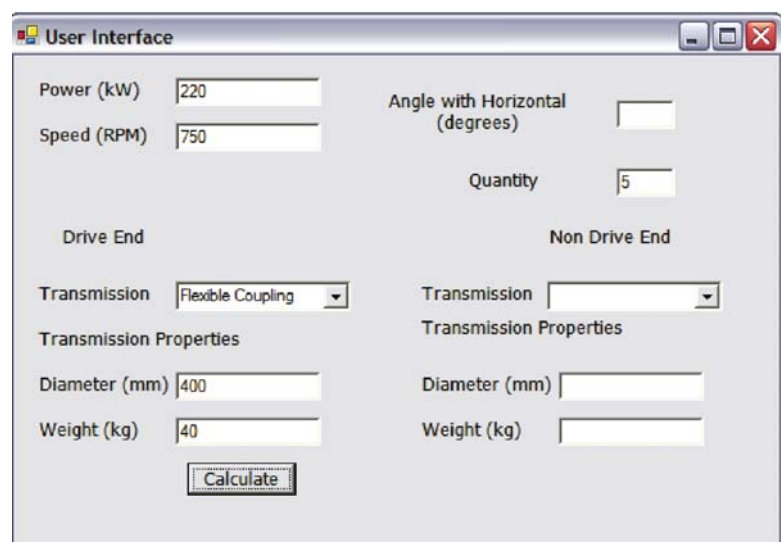


Fig. 2.10 User interface for Case Study 2.2

Based on the input from design template, the system retrieves three machines and calculates the total cost of manufacturing. The machine selection module is shown in Fig. 2.13. In Case Study 2.1, four machines were retrieved instead of three in Case Study 2.2, even though the tolerance was closer in Case Study 2.1. This is because not all machines have threading capabilities. The system was not able to find an existing process plan for the new shaft so the existing plan does not return any value. The machine selected is “M4” with a machining cost of “\$41.96.” The total cost is found to be “\$715.93.”

Bearing Type	Drive End Bearing	Cost	Non Drive End Bearing	Cost
62	0	\$0.00	6219	\$183.43
63	0	\$0.00	6319	\$241.21
72	7236	\$614.31	7219	\$265.87
73	7326	\$740.43	7319	\$526.60
NU2	NU219	\$248.98	0	\$0.00
NU3	NU319	\$498.76	0	\$0.00
Recommended	NU219	\$248.98	6219	\$183.43

**Manufacture**

Fig. 2.11 Bearings for Case Study 2.2

**Output**

**Features**

Shaft End Features:

- ☒ Single Conical Shaft End
- ☐ Single Cylindrical Shaft End
- ☐ Double Conical Shaft End
- ☐ Double Cylindrical Shaft End

Threading:

- ☐ No Threading
- ☒ Single End Threading
- ☐ Both End Threading

Closest Tolerance Required (micron): 3

**Template**

**Machine**

Fig. 2.12 Design template for Case Study 2.2

**Final Cost**

**Existing Plan**

Machine:

Machining Cost:  Total Cost:

Raw Material:

Raw Material Cost:

Bearing Cost:

**Suggested Plan**

Machine:

Machining Cost:  Total Cost:

Raw Material:

Raw Material Cost:

Bearing Cost:

Machine	Machining cost
M1	\$55.57
M4	\$41.96
M8	\$47.73

Fig. 2.13 Machine selection and cost estimation for Case Study 2.2

## 2.16 Conclusion

In this chapter, the implementation of an integrated design based on templates is presented. Concepts used in developing the system are independent of the software used. This system is thus focused on the small- and mid-segment industries which do not have enough resources for costly software upgradations. By using templates, the time required for new product development is drastically reduced. At the same time, incorporating computer-aided process planning into the system gives the designer a better understanding of the cost implications of the modified design with respect to manufacturing. The primary objective was to develop an integrated product and process design through a template-based approach. This system would thus act as an effective tool to reduce cost by foreseeing manufacturability constraints in the concept-generation phase itself. The concurrent engineering approach is applied to product and process development and thus the different phases of manufacturing are integrated together. The system developed has four main components, which are the design calculations, bearing search, and machine selection with process cost estimation. All these four components are connected to the relational manufacturing database. This database contains all the manufacturing information required for product and process development. Each component of the system is developed as a stand-alone module which interacts with the other modules and exchanges information when required. Each module provides the user with an output which acts as the feedback at each stage of product and process development. Since each component is independent of each other, they can be modified without affecting the other components.

The major challenge in implementing this system is that any changes in the manufacturing facility have to be incorporated in the process plans stored. This can be a tedious job but can be overcome by using the hybrid process planning approach instead of the variant-based approach.

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