Chapter 1: Introduction

1.1 Integrated Product Design and Concurrent Engineering

Companies both in manufacturing or service have to be restructured or re-organised in order to overcome challenges of the 21st century in which customers are not only to be satisfied, but also to be delighted. Global competition and escalating market efficiency are driving engineering businesses to adopt design philosophies which reduce product design cycle time. Figure 1.1 shows some notable changes in manufacturing industry, based on literature [1, 2]. The learning is that in this competitive environment, organization should use flexible, adaptive and responsive processes. For this, it has to use some enabling technologies and tools. One such design philosophy is “Concurrent Engineering”. Concurrent Engineering (CE) is “the systematic approach to the simultaneous, integrated design of products and their related processes, such as manufacturing, testing and support” [2]. Conceptually, CE is intended to
shorten the design cycle time by allowing engineering processes to run in parallel, rather than in series. This approach is intended to result in consideration of all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements. Put more simply, it is the concurrent design of products and their related processes, including manufacture and support [3].

A similar concept is that of Integrated Product Development (IPD), which is a philosophy that systematically builds teams across functional disciplines to integrate and concurrently apply the processes necessary to produce an effective and efficient product, that satisfies customer needs. This covers not just the design of the product, but also the prototyping of the product, product testing, design of the production process, design of instruction and support manuals, design of maintenance procedures, and the design of review and updating procedures.

The goal of both methodologies is to make significant reductions in design and development cycle time for new products. Reduction claimed reductions are of the order of 30 per cent to 70 per cent of total product development cycle time. Faster development, and a reduction in time-to-market, gives:

- competitive advantage over competitors who take longer to respond to market changes, customer needs, new technologies, or premium prices before competitors offer customers a choice.
- faster return on the development investment and therefore a lower financial risk.
- longer life cycle for the product.
- higher return on the total investment.

In addition to reductions in development cycle times, there are other benefits from such a rigorous and systematic approach to design and development. There are significantly fewer changes in specification of the components
during the lifecycle of the product because the initial design work is both thorough and done with the manufacturing and support process in mind. Attention to effective design also results in higher quality and consistency of components and of the final product, i.e., quality is designed into the product, not inspected onto it. Attention to process design results in higher productivity of the manufacturing process.

The above discussion shows that concurrent engineering can have much far-reaching effects on a business and therefore it must be considered as a strategic initiative. Leading innovative companies have always treated product development as a strategic process because they have always recognised it as a key component of their competitive strategy. If they are real product innovators, it is in effect their key business strategy.

In a global marketplace, where competition is everywhere, cutting product development cycle times may be the difference between creating a market and missing a market. The concept of concurrent engineering is simple. However, it does require fundamental changes in ways of working. First it requires a fundamental shift in organisation structure and culture to break down the barriers (and they do exist) between R&D, design, and manufacturing. By the very nature of the process, these departments have to start working together bringing their particular expertise to the table simultaneously rather than sequentially. They must respect each other’s expertise and attack issues and problems jointly. Most importantly, they must also address to design and manufacturing process from a customer standpoint.

The essence of CE is the integration of product design and process planning into one common activity. Concurrent design helps improve the quality of early design decisions and has a tremendous impact on life cycle cost of the product.
CE can be visualized as illustrated in Figure 1.2. In this, figure the designer is represented by the hub of the wheel. Designers coordinate the inputs and re-design suggestions from each of the domain experts (shown in the circumference). One can think of Concurrent Engineering (CE) as accomplishing this purpose using five interrelated elements:

1. Careful analysis and understanding of the fabrication and assembly processes. This allows the designers to predict the performance of the product and select production schemes from alternative processes.
2. Strategic product design conceived to support a specific strategy for making and selling the product. The product should be made to marketing specifications for market value, shelf life, and usability.
3. Rationalized manufacturing system design coordinated with product design.
4. Economic analysis of design and manufacturing alternatives to permit rational choices among design alternatives.
5. Product and system designs characterised by robustness. Robustness means resistance to unpredicted noise or errors in production and in use. In other words, the product’s performance is as resistant as possible to variations in dimensions within the tolerance.

The goals of CE within these elements are:

- Avoiding component features that are unnecessarily expensive to produce, e.g., specification of surfaces smoother than necessary, wide variations in wall thickness of an injection-moulded component, too-small fillet radius in a forged component, or internal apertures too close to the bend line of a sheet metal component.
- Reducing costs of making, by the optimum choice of materials and processes e.g. can the component be cold-headed and finish-machined rather than machined from bar stock?

This approach encourages the designers to consider interactively all elements of the product’s development process from the design through to the disposal (including customer requirements, product quality,
manufacturing costs and production time) [4]. Despite wide acceptance of
the CE approach, an implementation rate of around only 50% is reported
[5]. The main barrier to implementation is the lack of tools and techniques
available to assist in implementing the approach. This is the area chosen for
work in this thesis.

![Diagram of Concurrent Engineering](image)

**Figure 1.2 The Concept of Concurrent Engineering**

Most of the CE research to date has focused on combining production
considerations with product design issues [6, 7, 8, 9]. CE applications were
reported to achieve a 30 to 60% reduction in time-to-market, 15 to 50%
reduction in life cycle costs and a 55 to 95% reduction in engineering
change requests. It is well established that over 70% of the total
development cost of a product is frozen during the design phase, though this
phase accounts for less than 7% of the total value [10].

Over the last two decades, a significant shift has taken place in the source of
competitive advantage for manufacturing companies. Traditionally, firms
made use of economies of scale to produce highly standardized products to
satisfy massive and large homogeneous markets. Nowadays, to stay
competitive, firms need the capability to produce a broad variety of high
quality products, and must exhibit rapid responsiveness to dynamic and
increasingly fragmented markets by introducing new products frequently at

In complex products, changes in the design requirements to meet rising performance targets can result in the need for radical changes to component material properties, configuration and geometry. Consequently, new manufacturing technology processes need to be developed to achieve these geometries. Thus, a key feature in a new product introduced in this sector is the ability to integrate knowledge of manufacturing technology innovations into the design process in a timely and appropriate way. To mitigate risk it is necessary to make this knowledge available as early in the design process as possible [12].

Currently, most of the research focuses on job and batch production, whose objective is to produce customized parts while trying to maintain minimum manufacturing cost by use of standard cutters, fixtures and machine tools. An important step toward establishing manufacturing planning platforms for mass customization is the development of planning methodologies that provide easy access to information in the previous manufacturing plans. Due to the similarity / commonality among production systems or among specific customized products, the concept of reuse presents itself as a natural choice to facilitate increasingly efficient and cost effective product development. That is, a new manufacturing plan that reuses a previous plan at some level or to some extent will be less expensive to develop than a plan that is designed from scratch. By reusing prior plans, an engineer can save design time and cost by leveraging previously worked-out solutions. Figure 1.3 shows the roles and issues relating to manufacturing planning in the production cycle, which is composed of three stages: design, manufacturing planning and production.
The product data model is central to CE and can be defined as the sum of all the information needed to define a product, consisting of both geometric and non-geometric information. In order to make CE possible, a product data model needs to be made at the beginning of the design cycle. Geometric and limited non-geometric information are defined with Computer-Aided Design (CAD) tools. Geometry defined in CAD can then be exported to downstream engineering applications where additional non-geometric information, called attributes, are assigned and attached to the geometry before other engineering tasks are performed [13].

1.2 Manufacturing Information Modelling

To meet market challenges, manufacturers trying to improve their efficiency in areas of product development and resource utilization. In the manufacturing industry domain, the development and manufacture of products requires, a wide range of information to support the decision-making processes, during different stages of the product lifecycle (especially, in engineering design). A knowledge-intensive process is needed for many tasks, such as conceptual design, detailed design,
engineering analysis, assembly design, process design, and performance evaluation. Each task is carried out using multiple areas of knowledge and experience. Engineering designers have to access and retrieve information from numerous design resources to make decisions. Research shows that engineering designers spend as much as 30% of their working time on searching and accessing information. Hence, to improve product development decisions and to obtain a competitive advantage, an industry should effectively organize, store, and retrieve such knowledge and experience [14].

Knowledge Management (KM) can be used to capture code, store and retrieve information. It has been used in manufacturing enterprises during the last decade in a variety of decision-making processes, and continues to be the focus of research interest. As the notion of KM matures, it is increasingly clear that KM is not just about technology. It cannot be realized simply through information systems. The challenge of managing knowledge in an organizational context lies in effectively harnessing multiple knowledge sources into coherent business intelligence, and embedding the intelligence into the organization’s memory (OM).

In many companies, product and process design are fragmented and difficult to manage and coordinate. CAD/CAE tools automate the design and development process but, in many cases, cause the rapid proliferation of designs without regard to the impact on the rest of the organization. These tools are integrated to varying degrees. Often these systems are used to create an item's geometry on paper to communicate with other functional areas of a company [15].

One survey indicated that the typical company re-creates an item's geometry five or more times in areas such as customer proposals or marketing specifications, conceptual design, detail design, finite element analysis, other engineering analysis, detail drafting, fabrication or assembly sketches,
work cell device programming, tooling and fixture design, and training and service manuals. Each time part geometry or product design information are independently maintained in a separate system or independently created on paper, another source of redundant design information are created, which needs to be managed. Non-integrated systems also require additional effort to transfer data from one system to another. This allows errors to creep into the process and data can be mis-handled or lost. Delays are inherent in this process and extra effort is required to coordinate activities. Technology and information integration represent one dimension of overcoming these traditional problems. Integrated design and manufacturing automation systems and databases are the basis for the engineering blueprint of the future. This will allow manufacturers to “cost-effectively improve product and process design”, while facilitating the integration of design activities with the production process.

Product and process design will be greatly enhanced using integrated databases and information systems to maintain and optimize the use of design information. Product and process design information are treated as a corporate-wide resource. This information must be stored and maintained in a logical, consistent, non-redundant and usable manner. A shift is required to definition-oriented design information that can directly drive downstream processes with little or no human interpretation and planning.

Evolving standards such as the Standard for the Exchange of Product Model Data (STEP) will provide a more complete set of product data in a neutral format. This design information has to be distributed to workstations, controllers and other systems as per requirement. Changes to product and process design data to be managed in accordance with the company's data access and configuration management procedures. By focusing on maintaining product and process design information electronically, paper-based representations of this data are minimized. As paper drawings are
avoided, there will be reduced manual handling and storage of documents, reduced time to access the most current design of a part, and prevention of errors from avoiding the use of outdated drawing information. Design and administrative activities can be streamlined. When design information is maintained electronically, design can be readily analyzed and improved, so that more mature and manufacturable designs are developed more quickly. Most importantly, this is the basis for definition-oriented designs.

1.2.1 Knowledge Management

The sharing of design and manufacturing knowledge across the product introduction process can be viewed as a knowledge management problem. Features are a popular method of exchanging design and manufacturing knowledge in CAD/CAM platforms to assist the decisions of designers [12]. A feature is defined as a collection of geometry to which some engineering significance can be assigned. Such representation enables knowledge pertaining to that feature to be structured and represented for different life cycle domains, such as design or manufacturing. However, the domain-specific nature of features limits their ability to be used in knowledge sharing, across different domains. Techniques such as multifeature view mapping, where features from one domain are translated into a second domain, have been developed to overcome this problem. However, this results in a number of different product models being stored. A further limitation is that the geometric nature of a feature requires the product design to have reached a stage of maturity (typically detail design) for the technique to be successfully deployed. This limits their use to later life cycle domains.

Therefore, in developing information systems to share manufacturing and design knowledge for re-use, the preferred approach is to create knowledge models to structure and represent knowledge and information to be shared, in the form of a product model and in cases of manufacturing knowledge, an
additional process model. Often represented as class-based UML diagrams, these models enable different domains to be modeled and translated.

It is also reported in literature that, manufacturing constraints represented as rules and parameters are mainly related to the selected configuration and material of the component. The manufacturing options are compared by cost with no assessment of manufacturing capability. A knowledge management database has to be developed, to support manufacturing knowledge in design, using a feature-based product model and an integrated process model [16].

The development of such an information system requires, an effective integration of the key variables involved in manufacture planning and user-friendly interface. This research deals the development of such an information system, with a focus on the data model and the user interface design undermining its operation [17].

Knowledge management involves the identification and analysis of available and required knowledge, and subsequent planning and control of actions to develop knowledge assets to fulfill organizational objectives. Knowledge assets are the knowledge regarding markets, products, technologies and organizations, that a business owns or needs to own which enable its business processes to generate profits [18]. There are four kinds of knowledge management. They are: (1) creating knowledge repositories in which knowledge can be stored and retrieved easily; (2) improving knowledge access to facilitate its transfer between individuals; (3) enhancing a knowledge environment to conduct more effective knowledge creation, transfer and use; (4) managing knowledge as an asset and concern about how to increase the effective use of knowledge assets over time.
### 1.2.2 Concurrent Engineering

The systematic approach to the design process is indicative of the methodological approach adopted widely in Europe and the US [12]. The sequential nature of this process can be a problem in that the design may reach a stage of maturity before its manufacturability has been assessed. This can lengthen development times and lead to inefficient or unnecessarily costly manufacturing processes.

In an effort to help designers better assess the downstream life cycle impacts of their design choices, manufacturing companies and researchers have developed many design decision support tools referred to as Design for X (DFX) methodologies [19]. Concurrent engineering (CE) and associated techniques such as design for manufacture (DFM) aim to reduce the cost of the component and its developmental lead time by considering a proposed design solution in terms of ease of manufacture as early as is practicable. Such techniques have resulted often in substantial lead-time reductions and cost reductions. However, the DFM technique does not account for other design requirements, which may be required simultaneously during the embodiment stage. A further line of a DFM is that there is an assumption that all the manufacturing processes selected are capable and proven [20].

Successful implementations of CE techniques are usually been team-based, using methods such as IPTs (integrated product teams). Researchers have recognized the opportunity to develop Integrated Computer Technologies (ICTs) to support this team-based approach by providing quality of data. The challenge in developing such systems is ensuring that the information is structured in such a way as to make it communicable between systems [21].

### 1.3 Process Planning systems and Some New Approaches

Process planning translates design information into the, process steps and instructions, to effectively manufacture the products. Many computer-aided
tools support design process. Computer-aided process planning (CAPP) has evolved to simplify and improve process planning, and to achieve effective use of manufacturing resources [15].

1.3.1 Process Planning

Process planning encompasses the activities and functions required to prepare a detailed set of plans and instructions to produce a part. This planning begins with engineering drawings, specifications, parts or material lists and a forecast of demand. The results of planning are:

- Routings, which specify operations, operation sequences, work centers, standards, toolings and fixtures. This routing becomes a major input to the manufacturing resource planning system to define operations for production control purposes and define required resources for capacity requirements planning purposes.
- Process plans, which typically provide more detailed systematic work instructions including: dimensions related to individual operations, machining parameters, set-up instructions, and quality assurance checkpoints.
- Fabrication and assembly drawings to support manufacture (as opposed to engineering drawings to define the part).

Manual process planning is based on a manufacturing engineer's experience and knowledge of production facilities, equipment, their capabilities, processes, and tooling. Process planning is very time-consuming and the results vary based on the person doing the planning.

1.3.2 Computer Aided Process Planning

Manufacturers have been pursuing an evolutionary path to improve and computerize process planning, which has gone through the following five stages:

Stage I - Manual classification; standardized process plans
Stage II - Computer maintained process plans
Stage III - Variant CAPP
Stage IV - Generative CAPP
Stage V - Dynamic, generative CAPP

Prior to CAPP, manufacturers attempted to overcome the problems of manual process planning by basic classification of parts into families and developing somewhat standardized process plans for part families (Stage I). When a new part is introduced, the process plan for that family is to be manually retrieved, marked-up, and retyped. While this improved productivity, it did not improve the quality of the planning of processes, and it did not easily take into account the differences between parts in a family or improvements in production processes.

Computer-aided process planning initially evolved as a means to electronically store a process plan once it was created, retrieve it, modify it for a new part and print the plan (Stage II). Other capabilities of this stage were table-driven cost and standard estimation systems.

This initial computer-aided approach evolved into what is now known as "variant" CAPP. However, variant CAPP is based on a Group Technology (GT) coding and classification approach to identify a larger number of part attributes or parameters. These attributes allow the system to select a baseline process plan for the part family and accomplish about ninety percent of the planning work. The planner will add the remaining ten percent of the process modifying or fine-tuning the process plan. The baseline process plans stored in the computer were manually entered using a super planner concept that is, developing standardized plans based on the accumulated experience and knowledge of multiple planners and manufacturing engineers (Stage III).

The next stage of evolution is toward generative CAPP (Stage IV). In this stage, process planning decision rules are built into the system. These decision rules will operate based on a part's group technology or features
technology coding to produce a process plan that will require minimal manual interaction and modification (e.g., entry of dimensions).

While CAPP systems are moving more and more towards being generative, a pure generative system that can produce a complete process plan from part classification and other design data is the goal for the future. This type of purely generative system (in Stage V) will involve the use of artificial intelligence type capabilities, to produce process plans as well as to be fully integrated in a CIM environment. A further step in this stage is dynamic generative CAPP, which would consider plant and machine capacities, tooling availability, work center and equipment loads, and equipment status (e.g., maintenance downtime) in developing process plans.

The process plan developed with a CAPP system at Stage V would vary over time depending on the resources and workload in the factory. For example, if a primary work center for an operation(s) were overloaded, the generative planning process would evaluate work involving that work center, to be released alternate processes and the related routings. The decision rules would result in process plans that would reduce the overloading on the primary work center by using an alternate routing that would have the least cost impact. Since finite scheduling systems are still in their infancy, this additional dimension to production scheduling is still a long way off.

Dynamic, generative CAPP also implies the need for online display of the process plan on a workorder-oriented basis to insure that the appropriate process plan is provided to the shop floor. Tight integration with a manufacturing resource planning system is needed to track shop floor status, load data, and assess alternate routings vis-a-vis the schedule. Finally, this stage of CAPP would directly feed shop floor equipment controllers or display assembly drawings online in conjunction with process plans in a less automated environment.
1.3.3 Some of the New Approaches in Process Planning

In many companies, product and process design are fragmented and difficult to manage and coordinate. CAD/CAE tools automate the design and development process but, in many cases, cause the rapid proliferation of designs without regard to the impact on the rest of the organization. While these tools are integrated to varying degrees, often these systems are used to create an item's geometry on paper to communicate with other functional areas of a company [15].

As mentioned earlier a company recreates an item geometry many times in different departments. This allows errors to creep into the process and data is mis-handled or lost. Delays are inherent in this process and extra effort is required to coordinate activities. Technology and information integration represent one dimension of overcoming these traditional problems. Integrated design and manufacturing automation systems and databases are the basis for the engineering blueprint of the future. This will allow manufacturers to cost-effectively improve product and process design, while facilitating the integration of design activities with the production process.

Product and process design will be greatly enhanced with integrated databases and information systems to maintain and optimize use of design information. Product and process design information must be treated more as a corporate-wide resource. This information must be stored and maintained in a logical, consistent, non-redundant and usable manner.

The automation of manufacturing planning activities presents many challenges, since it involves a multitude of conflicting criteria and competing objectives and also requires a great deal of expertise and knowledge, both of which are not easy to model and codify. For example, minimizing product costs and keeping on a tight delivery time schedule is always a dilemma, and it is hard to fulfill these two objectives
simultaneously. Hence, some research in production planning support systems focus on isolated portions of planning activities, especially on the improvement of manufacturing process performance such as: selection of cutters and optimal machining parameters; and the generation of optimal cutting toolpaths, etc. However, several questions in CAMP remain unanswered and many issues must still be resolved. Some of the new approaches in these areas such as feature based process planning, solid model based process planning, static and dynamic process planning are discussed in Chapter 3.

1.4 The Work in the Thesis

Using present design approaches and tools, there is incomplete knowledge of the required manufacturing steps to produce the part, and inadequate consideration of the variety of other downstream influences that shape time to market, market acceptance, and product longevity. In the part design stage many important constraints relative to the product and its process of manufacture often neglected. These flaws lead to a multitude of costly and time-consuming design reworks or difficult process modifications as unanticipated problems must be rectified.

The work in this thesis was to develop an Integrated Product and Process Planning Information System (IPPPIS) for a machine tool manufacturing firm. For this, analysis of the fundamental elements necessary for modeling manufacturing and process planning framework used in machine tool manufacturing was done. Then a model for collaborative design has been developed for a machine tool manufacturing firm. The workability of this approach was tested using a prototype of the system developed. Case study is presented to demonstrate the feasibility of the approach and brings out the benefits.
1.5 Organization of the Thesis

Chapter 2: This chapter is devoted to discussion on research issues, research objectives, and research methodology after conducting a literature survey on information systems, database application for decision-making.

Chapter 3: This chapter is used to present a discussion on CE, design for manufacturing, process planning systems, databases and GT classification in the context of a machine tool manufacturing company.

Chapter 4: Concepts used for developing a classification and coding system in the context of a machine tool manufacturing company are discussed in this chapter.

Chapter 5: Process design, process planning and information modeling using object-oriented system analysis approach in the IPPPIS are detailed in this chapter.

Chapter 6: Information modeling of the process, manufacturing activity, manufacturing resource, manufacturing cost and time, manufacturing plan is detailed in this chapter.

Chapter 7: A case study dealing with product and process design of small parts for a machine tool company is presented in this chapter.

Chapter 8: In this last chapter conclusion, limitations of this work and scope for future work are presented.